Sustainable Agriculture
in California and Mediterranean Climates

Evidence for the effects of selected interventions

Gorm E. Shackelford, Rodd Kelsey, Rebecca J. Robertson, David R. Williams & Lynn V. Dicks

SYNOPSES OF CONSERVATION EVIDENCE SERIES

Sustainable Agriculture in California and Mediterranean Climates

Evidence for the effects of selected interventions

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David R. Williams, and Lynn V. Dicks

Synopses of Conservation Evidence Series

Attribution should include the following information:

Shackelford, G. E., Kelsey, R., Robertson, R. J., Williams, D. R., and Dicks, L. V. (2017) *Sustainable Agriculture in California and Mediterranean Climates: Evidence for the effects of selected interventions*. Synopses of Conservation Evidence Series. University of Cambridge, Cambridge, UK.

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Contents

1. About this book 10

2. Crops 21

Crop and soil management: Effects on crop production *21*

2.1. Add compost to the soil: Crop production (8 studies) 21

2.2. Add manure to the soil: Crop production (2 studies) 23

2.3. Add sewage sludge to the soil: Crop production (1 study) 24

2.4. Add slurry to the soil: Crop production (6 studies) 25

2.5. Use organic fertilizer instead of inorganic: Crop production (11 studies) 26

2.6. Grow cover crops in arable fields: Crop production (25 studies) 30

2.7. Plant or maintain ground cover in orchards or vineyards: Crop production (14 studies) 39

2.8. Use crop rotations: Crop production (9 studies) 45

2.9. Use no tillage in arable fields: Crop production (23 studies) 48

2.10. Use no tillage instead of reduced tillage: Crop production (15 studies) 55

2.11. Use reduced tillage in arable fields: Crop production (26 studies) 60

Habitat management: Effects on crop production *70*

2.12. Plant flowers: Crop production (3 studies) 70

2.13. Plant hedgerows: Crop production (1 study) 71

Livestock management: Effects on crop production *72*

3. Soil 73

Crop and soil management: Effects on soil *73*

3.1. Add compost to the soil: Soil (24 studies) 73

3.2. Add manure to the soil: Soil (11 studies) 83

3.3. Add sewage sludge to the soil: Soil (6 studies) 87

3.4. Add slurry to the soil: Soil (14 studies) 89

3.5. Use organic fertilizer instead of inorganic: Soil (26 studies) 94

3.6. Grow cover crops in arable fields: Soil (29 studies) 105

3.7. Plant or maintain ground cover in orchards or vineyards: Soil (22 studies) 120

3.8. Use crop rotations: Soil (14 studies) 131

3.9. Use no tillage in arable fields: Soil (40 studies) 136

3.10. Use no tillage instead of reduced tillage: Soil (20 studies) 153

3.11. Use reduced tillage in arable fields: Soil (40 studies) 160

Habitat management: Effects on soil *176*

3.12. Plant buffer strips: Soil (1 study) 176

3.13. Plant hedgerows: Soil (1 study) 177

3.14. Restore habitat along watercourses: Soil (2 studies) 177

Livestock management: Effects on soil *178*

3.15. Exclude grazers: Soil (6 studies) 178
3.16. Use fewer grazers: Soil (2 studies) 180

4. Water 182

Crop and soil management: Effects on water *182*
4.1. Add compost to the soil: Water (6 studies) 182
4.2. Add manure to the soil: Water (5 studies) 184
4.3. Add sewage sludge to the soil: Water (3 studies) 186
4.4. Add slurry to the soil: Water (7 studies) 187
4.5. Use organic fertilizer instead of inorganic: Water (11 studies) 190
4.6. Grow cover crops in arable fields: Water (19 studies) 193
4.7. Plant or maintain ground cover in orchards or vineyards: Water (21 studies) 201
4.8. Use crop rotations: Water (4 studies) 210
4.9. Use no tillage in arable fields: Water (15 studies) 211
4.10. Use no tillage instead of reduced tillage: Water (10 studies) 216
4.11. Use reduced tillage in arable fields: Water (17 studies) 219

Habitat management: Effects on water *226*
4.12. Plant buffer strips: Water (5 studies) 226
4.13. Restore habitat along watercourses: Water (1 study) 228

Livestock management: Effects on water *229*
4.14. Exclude grazers: Water (6 studies) 229
4.15. Use fewer grazers: Water (1 study) 231
4.16. Use seasonal grazing: Water (1 study) 231

5. Pest regulation 233

Crop and soil management: Effects on pest regulation *233*
5.1. Add compost to the soil: Pest regulation (3 studies) 233
5.2. Use organic fertilizer instead of inorganic: Pest regulation (2 studies) 235
5.3. Grow cover crops in arable fields: Pest regulation (19 studies) 236
5.4. Plant or maintain ground cover in orchards or vineyards: Pest regulation (13 studies) 244
5.5. Use crop rotations: Pest regulation (2 studies) 251
5.6. Use no tillage in arable fields: Pest regulation (12 studies) 251
5.7. Use no tillage instead of reduced tillage: Pest regulation (8 studies) 256
5.8. Use reduced tillage in arable fields: Pest regulation (10 studies) 259

Habitat management: Effects on pest regulation *263*
5.9. Plant flowers: Pest regulation (8 studies) 263
5.10. Plant hedgerows: Pest regulation (3 studies) 267
5.11. Restore habitat along watercourses: Pest regulation (1 study) 269

Livestock management: Effects on pest regulation *270*

5.12. Exclude grazers: Pest regulation (1 study)....270

6. Pollination....271

Crop and soil management: Effects on pollination....271

6.1. Plant or maintain ground cover in orchards or vineyards: Pollination (1 study) 271

6.2. Use no tillage in arable fields: Pollination (1 study)....271

Habitat management: Effects on pollination....272

6.3. Plant flowers: Pollination (8 studies)....272

6.4. Plant hedgerows: Pollination (8 studies)....275

6.5. Restore habitat along watercourses: Pollination (1 study)....279

Livestock management: Effects on pollination....280

7. Other biodiversity....281

Crop and soil management: Effects on other biodiversity....281

7.1. Add compost to the soil: Other biodiversity (5 studies)....281

7.2. Add manure to the soil: Other biodiversity (1 study)....283

7.3. Add sewage sludge to the soil: Other biodiversity (2 studies)....283

7.4. Use organic fertilizer instead of inorganic: Other biodiversity (1 study)....285

7.5. Plant or maintain ground cover in orchards or vineyards: Other biodiversity (3 studies)....286

Habitat management: Effects on other biodiversity....287

7.6. Plant flowers: Other biodiversity (3 studies)....287

7.7. Plant hedgerows: Other biodiversity (3 studies)....289

7.8. Restore habitat along watercourses: Other biodiversity (24 studies)....290

Livestock management: Effects on other biodiversity....299

7.9. Exclude grazers: Other biodiversity (45 studies)....299

7.10. Use fewer grazers: Other biodiversity (12 studies)....317

7.11. Use grazers to manage vegetation: Other biodiversity (18 studies)....322

7.12. Use rotational grazing: Other biodiversity (2 studies)....330

7.13. Use seasonal grazing: Other biodiversity (8 studies)....331

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We thank the following people for advising on the scope and content of this synopsis:

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Sasha Gennet, The Nature Conservancy
Louise Jackson, University of California, Davis
Daniel Karp, University of California, Davis
Christina Kennedy, The Nature Conservancy
Claire Kremen, University of California, Berkeley
Sara Kross, California State University
Jeffrey Mitchell, University of California, Davis
Katharina Ullmann, The Xerxes Society for Invertebrate Conservation
Stephen Wood, Yale University and The Nature Conservancy

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Acknowledgements

We thank William Sutherland, Rebecca Smith, and Nancy Ockendon for their advice. Funding for this project was provided by a 2016 Science Catalyst Fund grant to Rodd Kelsey from The Nature Conservancy of California.

1. About this book

The purpose of Conservation Evidence synopses

Conservation Evidence synopses **do**	Conservation Evidence synopses **do not**
• Bring together scientific evidence captured by the Conservation Evidence project (over 5,000 studies so far) on the effects of interventions to conserve biodiversity and ecosystem services	• Include evidence on the basic ecology of species or habitats, or threats to them
• List realistic interventions for the subject in question, regardless of how much evidence for their effects is available	• Make any attempt to weight or prioritize interventions according to their importance or the size of their effects
• Describe each piece of evidence, including methods, as clearly as possible, allowing readers to assess the quality of evidence	• Weight or numerically evaluate the evidence according to its quality
• Work in partnership with conservation practitioners, farm advisors, policymakers, and scientists to develop the list of interventions and ensure we have covered the most important literature	• Provide recommendations for conservation problems, but instead provide scientific information to help with decision-making

Who is this synopsis for?

If you are reading this, we hope you are someone who makes decisions about how to sustainably manage agricultural landscapes. You might be a farmer, a land manager, a conservationist in the public or private sector, a campaigner, an advisor or consultant, a policymaker, a researcher, or someone taking action to protect your own local wildlife. Our synopses summarize scientific evidence relevant to your conservation objectives and the actions you could take to achieve them.

We do not aim to make your decisions for you, but to support your decision-making by telling you what evidence there is (or isn't) about the effects that your planned actions could have.

When decisions have to be made with particularly important consequences, we recommend carrying out a systematic review, as the latter is likely to be more comprehensive than the summary of evidence presented here. Guidance on how to carry out systematic reviews can be found from the Centre for Evidence-Based Conservation at the University of Bangor (www.cebc.bangor.ac.uk).

The Conservation Evidence project
The Conservation Evidence project has four parts:

(1) An online, **open access journal** *Conservation Evidence* that publishes new pieces of research on the effects of conservation management interventions. All our papers are written by, or in conjunction with, those who carried out the conservation work and include some monitoring of its effects.

(2) An ever-expanding **database of summaries** of previously published scientific papers, reports, reviews or systematic reviews that document the effects of interventions.

(3) **Synopses** of the evidence captured in parts one and two on particular species groups, habitats, or ecosystem services. Synopses bring together the evidence for each possible intervention. They are freely available online and available to purchase in printed book form.

(4) ***What Works in Conservation*** is an assessment of the effectiveness of interventions by expert panels, based on the collated evidence for each intervention for each species group, habitat, or ecosystem service covered by our synopses.

These resources currently comprise over 5,000 pieces of evidence, all available in a searchable database on the website (www.conservationevidence.com).

The Nature Conservancy

The Nature Conservancy works collaboratively in 69 countries on innovative protection, management, and financing solutions to protect the lands and waters on which all life depends. Key to achieving its mission is finding ways to protect and restore nature in human-dominated landscapes, while meeting the challenge of feeding a growing world. This includes incentivizing farmers and ranchers to implement practices that add value economically and ecologically. Such practices need to have a strong basis in the best available scientific evidence for what works for both nature and people. This synopsis of evidence was designed to meet this need by providing guidance for the design and implementation of incentives that promote sustainable management of farmlands in Mediterranean regions around the world.

The scope of this synopsis
This synopsis includes evidence for the effects of interventions on six **targets**:

(1) Crop production
(2) Soil
(3) Water
(4) Pest regulation
(5) Pollination
(6) Biodiversity conservation

Some of these targets are **ecosystem services** (crop production, pest regulation, pollination, and biodiversity conservation), and some of these targets include multiple ecosystem services (soil fertility, climate regulation through carbon storage and greenhouse gases in soils, water availability, and water quality).

These targets could be measured using many different metrics. With the help of our Advisory Team (see above), we defined a **list of metrics** (Table 1) to set the scope for this synopsis. These metrics are shown in bold text throughout the synopsis, and the key messages for each intervention are grouped by metric. **This synopsis only includes evidence on these metrics.**

The abundance and diversity of living organisms — biodiversity — is a relevant metric for several of these targets (for example, soil organisms, natural enemies of crop pests, and crop pollinators). Therefore, in the list of metrics, we defined "biodiversity conservation" as **"other biodiversity"**, to differentiate it from the biodiversity that is listed as a metric for other targets.

This synopsis only includes studies from farmland, riparian areas, and grazed areas in California and other Mediterranean ecosystems. We used the Mediterranean Forests, Woodlands, and Scrub biome from the Terrestrial Ecoregions of the World (https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world) to define the geographic extents of Mediterranean ecosystems around the world (Figure 1). We also included evidence from studies anywhere in California and anywhere described as Mediterranean by the authors of the studies.

Figure 1. Mediterranean ecosystems: the Mediterranean Forests, Woodlands, and Scrub biome from the Terrestrial Ecoregions of the World

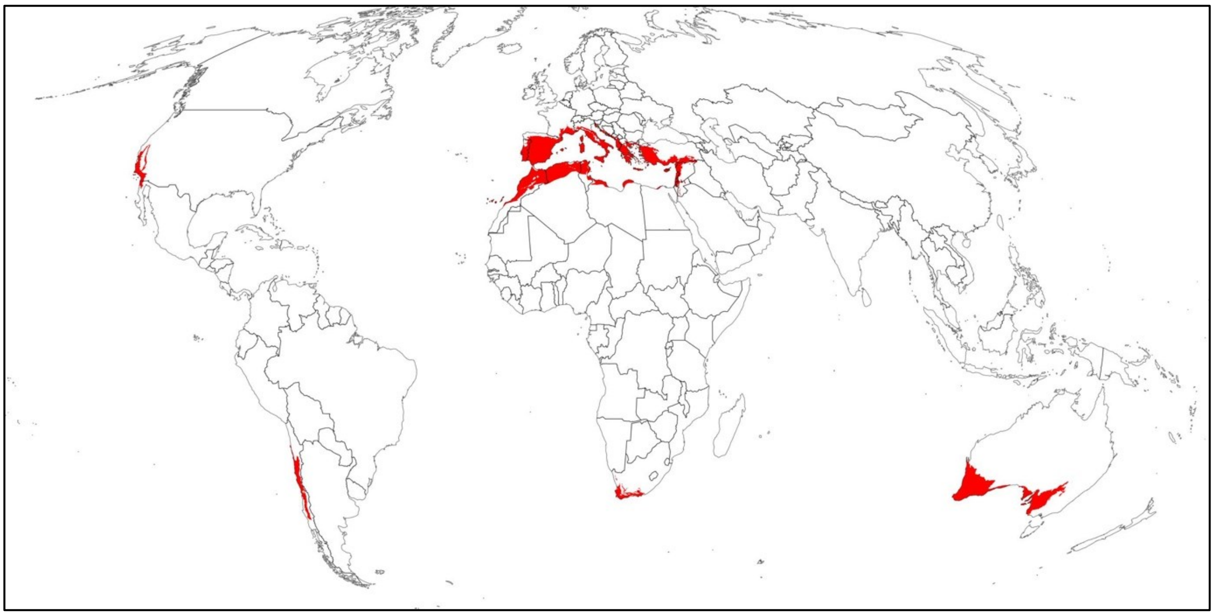

Table 1. List of metrics for which evidence is summarized in this synopsis

Target	Metric
Crop production	**Crop yield**
Crop production	**Crop quality**
Pest regulation	**Pest regulation** (by natural enemies; e.g., parasitism rates)
Pest regulation	**Crop damage** (by pests and diseases)
Pest regulation	**Ratio of natural enemies to pests**
Pest regulation	**Pest numbers**: abundance and diversity of weeds and other pests, and disease prevalence and severity
Pest regulation	**Natural enemy numbers**: abundance and diversity
Pollination	**Pollination**: changes in the yield and quality of crops (including fruit set and seed set) that are attributable to pollination
Pollination	**Flower visitation** (by pollinators)
Pollination	**Pollinator numbers**: abundance and diversity
Soil	**Organic matter**: soil organic matter, including (organic) carbon
Soil	**Nutrients**: nitrogen (N), nitrate (NO_3), ammonium (NH_4), phosphorus (P), phosphate (PO_4), and pH
Soil	**Soil organisms**: abundance and diversity (including microbial biomass, bacteria, fungi, nematodes, earthworms, and mites)
Soil	**Soil erosion and aggregation**: soil lost to wind or water, and aggregate stability
Soil	**Greenhouse gases** (emitted from soil or measured in soil, including soil respiration): carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)
Water	**Water use** (including water-use efficiency: crop yield per volume of water)
Water	**Water availability**: soil water content, infiltration, and porosity
Water	**Nutrients** (in water or leaching from soil): N, NO_3, P, PO_4
Water	**Pathogens and pesticides** (in water or leaching from soil)
Water	**Sediments** (in water)
Other biodiversity	Biodiversity (e.g., **Birds** or **Plants**) not reported in other targets (e.g., not pollinators, which are reported in "Pollination"): abundance, species richness, and other diversity metrics (e.g., evenness, beta diversity)

Table 2. List of interventions for which evidence is summarized in this synopsis, and the Natural Resources Conservation Service (NRCS) Conservation Practices to which this evidence could be relevant

	Intervention	Conservation Practice
Crop and soil management	Add compost to the soil	Nutrient Management, Waste Recycling
	Add manure to the soil	Nutrient Management, Waste Recycling
	Add sewage sludge to the soil	Nutrient Management, Waste Recycling
	Add slurry to the soil	Nutrient Management, Waste Recycling
	Use organic fertilizer instead of inorganic	Nutrient Management, Waste Recycling
	Grow cover crops in arable fields	Cover Crop
	Plant or maintain ground cover in orchards or vineyards	Cover Crop
	Use crop rotations	Conservation Crop Rotation
	Use no tillage in arable fields	Residue and Tillage Management: No Till, Residue and Tillage Management: Reduced Till
	Use no tillage instead of reduced tillage	Residue and Tillage Management: No Till, Residue and Tillage Management: Reduced Till
	Use reduced tillage in arable fields	Residue and Tillage Management: Reduced Till
Habitat management	Plant buffer strips	Filter Strip, Contour Buffer Strip
	Plant flowers	Field Border, Conservation Cover
	Plant hedgerows	Hedgerow Planting, Field Border, Conservation Cover, Tree/Shrub Establishment
	Restore habitat along watercourses	Riparian Forest Buffer, Riparian Herbaceous Cover, Stream Habitat Improvement and Management, Critical Area Planting, Tree/Shrub Establishment
Livestock management	Exclude grazers	Prescribed Grazing, Fence
	Use fewer grazers	Prescribed Grazing
	Use grazers to manage vegetation	Prescribed Grazing, Fence, Herbaceous Weed Management
	Use rotational grazing	Prescribed Grazing, Fence
	Use seasonal grazing	Prescribed Grazing

How we decided which interventions to include in this synopsis

We created a list of interventions, based in part on the list of "National Conservation Practice Standards" published by the Natural Resources Conservation Service (NRCS) of the United States Department of Agriculture (USDA NRCS: http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/cp/ncps/). We modified the list based on input from other staff at The Nature Conservancy and the Advisory Team. We then searched for published studies of these interventions. When we found studies of interventions that were not on the list, we added these interventions to the list. We then sorted the list into high and low priorities. **We summarized the evidence only for the interventions that were our highest priorities (Table 2).**

How we reviewed the literature for this synopsis

We used four methods to search for studies to include in this synopsis:

(1) We used keywords (Table 3) to search the Web of Knowledge database (www.webofknowledge.com), and we read the titles and abstracts of the resulting studies. For Searches 1–2, we used keywords related to the metrics on our list (Table 1). For Search 3, we used keywords related to names of the NRCS Conservation Practices on our list for which we had found few or no studies in Searches 1–2. For Searches 4–5, we used keywords related to riparian restoration.
(2) We read the titles and abstracts of studies that were published in *Agriculture, Ecosystems & Environment*, *Ecological Applications*, or *Journal of Applied Ecology* (the top three journals recommended by our Advisory Team) in 2006–2015 or *California Agriculture* in 2000–2015.
(3) We searched for "California" in annotated bibliographies about conservation practices in agricultural landscapes in the USA. These bibliographies were keyworded by state, and they were published by the Water Quality Information Center, National Agricultural Library, Agricultural Research Service, USDA, Beltsville, Maryland:
    - Maderik, R.A., Gagnon, S.R., Makuch, J.R. (2006) *Environmental Effects of Conservation Practices on Grazing Lands: A Conservation Effects Assessment Project (CEAP) Bibliography* (**1,303 citations**)
    - Maderik, R.A., Gagnon, S.R., Makuch, J.R. (2006) *Wetlands in Agricultural Landscapes: A Conservation Effects Assessment Project (CEAP) Bibliography* (**1,225 citations**)
    - Gagnon, S.R., Makuch, J.R., Harper, C.Y. (2008) *Effects of Agricultural Conservation Practices on Fish and Wildlife, A Conservation Effects Assessment Project (CEAP) Bibliography* (**2,285 citations** in two volumes)
(4) We asked our Advisory Team to recommend additional studies.

The criteria for the inclusion of studies were as follows:

- There must have been an intervention that farmers or conservationists would do.
- The effects of the intervention must have been monitored quantitatively.

These criteria exclude studies of historical land-use patterns that were not the result of a conservation intervention (for example, studies that compared biodiversity in farms that were surrounded by semi-natural forest or deforested areas). Such studies can suggest that an intervention could be effective (for example, conserving forest), but they cannot provide direct evidence of a causal relationship between the intervention and the observed effect.

Table 3. Literature searches in Web of Knowledge. We used one "Publication Name" field with the names of all the journals agreed to by our Advisory Team (Table 4) or the name of one journal (for example, *Restoration Ecology* in Search 5). We also used one "Year Published" field. For Searches 1–5, we used up to three "Topic" fields ("Topic" includes titles, abstracts, and keywords). All fields were joined with "AND" (for example, Publication Name AND Year Published AND Topic 1 AND Topic 2). The "*" symbol represents any number of letters. The "$" symbol represents one letter or no letters.

Search	Publication Name	Year Published	Topic 1	Topic 2	Topic 3	Results
1	[List of journals]	2000-2015	California* OR Mediterranean	abundance OR biodiversity OR divers* OR evenness OR species OR conservation OR sustainab* OR "ecosystem service*" OR "biological control" OR "pest regulation" OR "natural pest control" OR "natural enem*" OR predat* OR pollinat* OR erosion OR soil* OR irrigat* OR water	agricultur* OR agro-ecosystem* OR agroecosystem* OR crop* OR farm* OR orchard* OR vineyard* OR rangeland* OR meadow* OR pasture* OR graz*	2,227
2	[List of journals]	1990-1999	California*	abundance OR biodiversity OR divers* OR evenness OR species OR conservation OR sustainab* OR "ecosystem service*" OR "biological control" OR "pest regulation" OR "natural pest control" OR "natural enem*" OR predat* OR pollinat* OR erosion OR soil* OR irrigat* OR water	agricultur* OR agro-ecosystem* OR agroecosystem* OR crop* OR farm* OR orchard* OR vineyard* OR rangeland* OR meadow* OR pasture* OR graz*	188
3	[List of journals]	2000-2015	California* OR Mediterranean	"alley cropping" OR "buffer strip*" OR "conservation cover" OR "critical area planting" OR "field border*" OR "field margin*" OR "filter strip*" OR "forage harvest management" OR "grassed water$way*" OR "habitat management" OR hedge$row* OR "herbaceous wind barrier*" OR "range planting" OR "riparian forest buffer*" OR "riparian forest buffer" OR "riparian herbaceous cover" OR "sediment trap*" OR shelter$belt* OR silvo$pastur* OR stock$pond* OR strip$crop* OR "vegetative barrier*" OR "vegetative treatment area" OR "wetland creation" OR wild$flower* OR wind$break*		109
4	[List of journals]	2000-2015	California* OR Mediterranean	riparian OR river* OR stream* OR wetland	buffer* OR enhance* OR improve* OR manag* OR restor*	522
5	*Restoration Ecology*	1995-2015	California*			157
6	*Agriculture, Ecosystems & Environment*	2006-2015				2,496
7	*Ecological Applications*	2006-2015				1,919
8	*Journal of Applied Ecology*	2006-2015				1,617
9	*California Agriculture*	2000-2015				434

Table 4. List of journals (75 journals with alternative spellings)

"Agricultural Systems"
OR "Agriculture, Ecosystems and Environment"
OR "Agriculture Ecosystems and Environment"
OR "Agriculture, Ecosystems & Environment"
OR "Agriculture Ecosystems & Environment"
OR "Agriculture Ecosystems Environment"
OR "Agroforestry Systems"
OR "Agronomy Journal"
OR "Animal Conservation"
OR "Annals of Botany"
OR "Annual Review of Ecology and Systematics"
OR "Annual Review of Ecology & Systematics"
OR "Annual Review of Entomology"
OR "Applied Environmental Microbiology"
OR "Applied Soil Ecology"
OR "Austral Ecology"
OR "Basic and Applied Ecology"
OR "Basic & Applied Ecology"
OR "Biocontrol"
OR "Biodiversity and Conservation"
OR "Biodiversity & Conservation"
OR "Biological Conservation"
OR "Biological Control"
OR "Biological Reviews"
OR "Biology and Fertility of Soils"
OR "Biology & Fertility of Soils"
OR "BioScience"
OR "Biotropica"
OR "California Agriculture"
OR "Conservation Biology"
OR "Conservation Letters"
OR "Crop Protection"
OR "Ecological Applications"
OR "Ecological Entomology"
OR "Ecological Indicators"
OR "Ecological Restoration"
OR "Ecology"
OR "Ecology Letters"
OR "Entomologia Experimentalis et Applicata"
OR "Environmental Conservation"
OR "Environmental Entomology"
OR "Environmental Management"
OR "European Journal of Soil Science"
OR "European Journal of Wildlife Research"
OR "Frontiers in Ecology and the Environment"
OR "Frontiers in Ecology & the Environment"
OR "Functional Ecology"
OR "Global Change Biology"
OR "Human Wildlife Interactions"
OR "Human Wildlife Conflicts"
OR "Journal for Nature Conservation"
OR "Journal of Animal Ecology"
OR "Journal of Applied Ecology"
OR "Journal of Applied Entomology"
OR "Journal of Ecology"
OR "Journal of Economic Entomology"
OR "Journal of Environmental Management"
OR "Journal of Rangeland Management"
OR "Journal of Raptor Research"
OR "Journal of Tropical Ecology"
OR "Journal of Wildlife Management"
OR "Journal of Raptor Research"
OR "Journal of Zoology"
OR "Landscape Ecology"
OR "Nature"
OR "New Zealand Journal of Zoology"
OR "Oecologia"
OR "Oikos"
OR "Oryx"
OR "Pacific Conservation Biology"
OR "Pest Management Science"
OR "Plant and Soil"
OR "PLoS One"
OR "Proceedings of the National Academy of Sciences of the United States of America"
OR "Proceedings of the Royal Society B Biological Sciences"
OR "Rangeland Ecology and Management"
OR "Rangeland Ecology & Management"
OR "Restoration Ecology"
OR "Science"
OR "Soil and Tillage Research"
OR "Soil & Tillage Research"
OR "Soil Biology and Biochemistry"
OR "Soil Biology & Biochemistry"
OR "Soil Science Society of America Journal"
OR "Systematic Reviews"
OR "Trends in Ecology and Evolution"
OR "Trends in Ecology & Evolution"

How we summarized the evidence

The evidence is summarized in **six sections**: one section for each of the six targets (crop production, soil, water, pest regulation, pollination, and other biodiversity).

For each study, there is one summary paragraph for each combination of an intervention and a target (for example, "Soil: Use no tillage in arable fields" or "Water: Use no tillage in arable fields"). Thus, for each study, there could be up to six paragraphs for each intervention: one paragraph for each of the six targets. If the effects of multiple interventions on multiple targets were reported in a single study, then there is a separate paragraph for each (for example, "Soil: Use no tillage in arable fields" and "Soil: Grow cover crops in arable fields").

For each intervention, the **key messages** from all summarized studies are reported as bullet points. Each of the bullet points is one of the metrics on our list (Table 1), and the number of summarized studies for which we found evidence for each metric is in parentheses. For example:

- **Crop yield (8 studies)**

  …

- Crop quality (0 studies)

The key messages are not intended to be a form of "vote counting" (a count of the number of positive effects vs negative or non-significant effects for that metric), but they are intended to be an index that directs the reader to the relevant evidence for that metric. If we did not find evidence for a metric, the name of the metric is followed by "(0 studies)" to show that this is a gap in the evidence.

Terminology used to describe evidence

Unlike systematic reviews of particular conservation questions, we do not quantitatively assess the evidence or weight it according to quality within synopses. However, to allow you to interpret evidence, we make the size and design of each trial we report clear. The table below defines the terms that we have used to do this. The strongest evidence comes from randomized, replicated, controlled trials with paired sites and before-and-after monitoring.

Term	Meaning
Site comparison	A study that considers the effects of interventions by comparing sites that have historically had different interventions or levels of intervention.
Replicated	The intervention was repeated on more than one plot or site. In conservation and ecology, the number of replicates is much smaller than it would be for medical trials (when thousands of individuals are often tested). When the replicates are plots or sites, as is often the case with agricultural management interventions, pragmatism

	dictates that between five and ten replicates is a reasonable amount of replication, although more would be preferable. We provide the number of replicates wherever possible.
Controlled	Plots or sites treated with the intervention are compared with control individuals or sites not treated with the intervention.
Paired sites	Sites are considered in pairs, when one was treated with the intervention and the other was not. Pairs of sites are selected with similar environmental conditions, such as soil type or surrounding landscape. This approach aims to reduce environmental variation and make it easier to detect a true effect of the intervention.
Randomized	The intervention was allocated randomly to plots or sites. This means that the initial condition is less likely to bias the outcome.
Before-and-after trial	Monitoring of effects was carried out before and after the intervention was imposed.
Review	A conventional review of literature. Generally, these have not used an agreed search protocol or quantitative assessments of the evidence.
Systematic review	A systematic review follows an agreed set of methods for identifying studies and carrying out a formal '**meta-analysis**'. It will weight or evaluate studies according to the strength of evidence they offer, based on the size of each study and the rigour of its design. Environmental systematic reviews are available at: www.environmentalevidence.org/index.htm
Study	If none of the above apply, for example a study that was not controlled.

Taxonomy

Taxonomy has not been updated but has followed that used in the original paper. Where possible, common names and Latin names are both given the first time each species is mentioned within each synopsis. Latin names are not given for the crops in this synopsis.

Significant results

Throughout the synopsis we have quoted results from papers. Unless specifically stated, these results reflect statistical tests performed on the results by the authors of these papers.

Multiple interventions

Some studies investigated several interventions at once. When the effects of different interventions were separated, then the results are discussed separately in the relevant sections. When the effects of multiple interventions cannot be separated (e.g., growing cover crops in arable fields and using no tillage), then the results are followed by "It was not clear whether these results were a direct effect of [practice X or practice Y]".

How you can help to change conservation practice

If you know of evidence that is not included in this synopsis, we invite you to contact us, via our website, www.conservationevidence.com. If you have new, unpublished evidence, you can submit a paper to the *Conservation Evidence* journal. We particularly welcome papers submitted by conservation practitioners.

2. Crops

Crop and soil management: Effects on crop production

2.1. Add compost to the soil: Crop production (8 studies)

- **Crop yield (8 studies):** Three replicated, controlled studies (two randomized) from Italy[4], Spain[7], and the USA[8] found higher crop yields in plots with added compost, compared to plots without added compost, in some comparisons[4,7] or all comparisons[8]. Two replicated, randomized, controlled studies from Italy[6] and the USA[2] found inconsistent differences in crop yields (sometimes higher, sometimes lower) between plots with or without added compost. Three replicated, randomized, controlled studies from Spain[3,5] and the USA[1] found similar crop yields in plots with or without added compost. Of two replicated, randomized, controlled studies from Spain[3,5], one study[3] found higher yields of barley straw in plots with added compost, compared to plots without added compost, and one study[5] did not.
- Crop quality (0 studies)
- **Implementation options (1 study):** One replicated, randomized, controlled study from the USA[1] found similar crop yields in plots with added compost that did or did not also have added fertilizer.

A replicated, randomized, controlled study in 1995 in a broccoli field in the Salinas Valley, California, USA (1), found similar broccoli yields in plots with or without added compost. **Crop yield:** Similar broccoli yields were found in plots with or without added compost (13–15 Mg/ha). **Implementation options:** In plots with added compost, similar broccoli yields were found with or without added fertilizer (13–15 vs 14–15 Mg/ha). **Methods:** There were four plots for each of three compost treatments (0, 22, or 44 Mg/ha). Fertilizer (165 kg ammonium nitrate/ha) was added to half (6.1 x 7.7 m) of each plot. The compost was made from green wastes (>30%), cow manure (>20%), spoiled hay (>15%), clay soil (>5%), and crop processing residues. Crops were harvested and weighed on 10, 14, and 17 November 1995.

A replicated, randomized, controlled study in 1998–2000 in an irrigated vegetable field in the Salinas Valley, California, USA (2), found inconsistent differences in crop yields between plots with or without added compost. **Crop yield:** Higher lettuce yields were found in plots with added compost, compared to plots without added compost, in one of six comparisons (410 vs 390 g dry weight/m^2), but lower lettuce yields were found in two of six comparisons (280–390 vs 310–430). No differences in broccoli yields were found between plots with or without added compost (620–640 vs 610–630 g dry weight/m^2). Larger lettuce or broccoli plants were found in plots with added compost, compared to plots without added compost, in four of eight comparisons (lettuce: 1,080–1,150 vs 1,030–1,100 g fresh weight/plant; broccoli: 240–270 vs 210–220), but smaller lettuces were found in two of six comparisons (750–1,050 vs 790–1,110). **Methods:** There were four plots (0.52 ha), for each of four treatments (minimum tillage or conventional tillage, with or without added organic matter). In plots with added organic matter, compost was added two times/year, and a cover crop (Merced rye) was grown every autumn or winter. The compost was made from municipal yard waste, salad packing plant waste, horse manure, clay, straw, and other compost. Lettuce or broccoli crops were grown in raised beds. Sprinklers and drip irrigation were used in all plots. Crops were collected in two 2 m^2 areas/plot. It was not clear whether these results were a direct effect of adding compost or growing cover crops.

A replicated, randomized, controlled study in 2002–2005 in a barley field in Toledo, Spain (3), found no difference in grain yields, but found higher straw yields, in barley plots with added compost, compared to barley plots without added compost. **Crop yield:** Similar grain yields were found in barley plots with or without added compost (0.7–1.9 vs 1.2–1.6 t dry weight/ha). Higher straw yields were found in barley plots with added compost, compared to plots without added compost (3.3–3.4 vs 1.3–1.8 t dry weight/ha). **Methods:** The compost was made from sewage sludge. There were four plots (10 x 3 m) for each of four fertilizer treatments (20 or 80 t compost/ha, applied once in three years or once/year) and one control (no fertilizer). Plots were fertilized in mid-September and planted in mid-October. Barley plants were harvested (1 m^2/plot), in June 2005.

A replicated, randomized, controlled study in 2001–2009 in an irrigated orchard in Italy (4) found higher nectarine yields in plots with added compost, compared to plots without added compost. **Crop yield:** Higher yields were found in plots with added compost, in one of six comparisons (38 vs 26 kg/tree). **Methods:** There were four plots for each of three compost treatments (5 t/ha in May, 5 t/ha split into two applications, in May and September, or 10 t/ha split into two), and there were four control plots (no fertilizer; plot size not reported). The compost was made from domestic organic waste and urban pruning material (50% each). Compost was tilled into the soil (25 cm depth). Yield was measured in the four central trees of each plot, every year.

A replicated, randomized, controlled study in 2006 in a barley field in the Henares river basin, Spain (5), found similar barley yields in plots with or without added compost. **Crop yield:** Similar barley yields were found in plots with or without added compost (1,879 vs 1,825 kg grain and straw/ha). **Methods:** Composted municipal solid waste (125 kg available N/ha) was added to three treatment plots, but not to three control plots, in January. Plots were 30 m^2. Plots were cultivated (5 cm depth) to incorporate the compost into the soil. Barley was planted in January and harvested in June.

A replicated, randomized, controlled study in 2009–2011 on two farms in the Salerno district, Italy (6), found higher crop yields in plots with added compost, compared to plots without added compost, in most crop cycles. **Crop yield:** Higher crop yields were found in plots with added compost, compared to plots without added compost, in 12 of 14 crop cycles (38–39% higher), but lower yields were found in 2 of 14 crop cycles (23–25% lower). **Methods:** On each of two farms, there were three plots (7 x 5 m) for each of four treatments (30 or 60 Mg organic matter/ha/year, with a carbon-to-nitrogen ratio of 15:1 or 25:1) and there were three control plots (no organic matter). Organic matter was added in February 2009, February 2010, and June 2011. It was made from the composted organic fraction of municipal solid waste, and it was mixed with wood scraps to control the carbon-to-nitrogen ratio. Between the two farms, one pepper, three melon, four kohlrabi, and six lettuce crops (14 crop cycles) were grown in plastic tunnels. It was not clear whether these results were a direct effect of adding composted municipal waste or wood scraps.

A replicated, randomized, controlled study in 2013 in greenhouses in southeast Spain (7) found higher fruit yields in tomatoes with added compost, compared to tomatoes without added compost. **Crop yield:** Higher fruit yields were found in tomatoes with added compost, compared to tomatoes without added compost, in one of four comparisons (compost R1, with low doses of mineral fertilizer: 5.8 vs 4.2 kg fresh weight fruit/ha). **Methods:** There were four replicates for each of four treatments (50.5 t/ha of compost R1 or 40 t/ha of compost R2, with low or medium doses of mineral fertilizer) and two controls (low or medium doses of mineral fertilizer). Mineral fertilizer (Hoagland's solution) was added in two of three waterings (medium dose) or one of five waterings (low dose). Compost R1 was made from sheep and goat manure. Compost R2 was made from alperujo (olive-mill waste), manure, and olive prunings. Ripe red fruits were harvested each week (91- to 161-day-old plants).

A replicated, controlled study in 2014 in 29 organic vegetable fields on the Central Coast, California, USA (8), found higher lettuce yields in plots with added compost, compared to plots without added compost. **Crop yield:** Larger lettuces were found in plots with added compost, compared to plots without added compost (65 g larger, fresh weight). **Methods:** In each of 29 vegetable fields, compost was added to one plot, but not to one adjacent plot (5 x 5 m plots), 1–2 months before lettuces were planted (25 t compost/ha, made from cow, chicken, and green manures). Lettuces were planted in spring (5–28 March) and summer (30 May–5 July). Lettuce weights were measured at maturity in one 1 x 1 m quadrat/plot.

(1) Stamatiadis, S., Werner, M. & Buchanan, M. (1999) Field assessment of soil quality as affected by compost and fertilizer application in a broccoli field (San Benito County, California). *Applied Soil Ecology*, 12, 217-225.

(2) Jackson, L.E., Ramirez, I., Yokota, R., Fennimore, S.A., Koike, S.T., Henderson, D.M., Chaney, W.E., Calderón, F.J. & Klonsky, K. (2004) On-farm assessment of organic matter and tillage management on vegetable yield, soil, weeds, pests, and economics in California. *Agriculture, Ecosystems & Environment*, 103, 443-463.

(3) Fernández, J.M., Plaza, C., García-Gil, J.C. & Polo, A. (2009) Biochemical properties and barley yield in a semiarid Mediterranean soil amended with two kinds of sewage sludge. *Applied Soil Ecology*, 42, 18-24.

(4) Baldi, E., Toselli, M., Marcolini, G., Quartieri, M., Cirillo, E., Innocenti, A. & Marangoni, B. (2010) Compost can successfully replace mineral fertilizers in the nutrient management of commercial peach orchard. *Soil Use and Management*, 26, 346-353.

(5) Meijide, A., Cárdenas, L.M., Sánchez-Martín, L. & Vallejo, A. (2010) Carbon dioxide and methane fluxes from a barley field amended with organic fertilizers under Mediterranean climatic conditions. *Plant and Soil*, 328, 353-367.

(6) Bonanomi, G., D'Ascoli, R., Scotti, R., Gaglione, S.A., Caceres, M.G., Sultana, S., Scelza, R., Rao, M.A. & Zoina, A. (2014) Soil quality recovery and crop yield enhancement by combined application of compost and wood to vegetables grown under plastic tunnels. *Agriculture, Ecosystems & Environment*, 192, 1-7.

(7) Hernández, T., Chocano, C., Moreno, J.-L. & García, C. (2014) Towards a more sustainable fertilization: Combined use of compost and inorganic fertilization for tomato cultivation. *Agriculture, Ecosystems & Environment*, 196, 178-184.

(8) Karp, D.S., Moses, R., Gennet, S., Jones, M.S., Joseph, S., M'Gonigle, L.K., Ponisio, L.C., Snyder, W.E. & Kremen, C. (2016) Agricultural practices for food safety threaten pest control services for fresh produce. *Journal of Applied Ecology*, 53, 1402-1412.

2.2. Add manure to the soil: Crop production (2 studies)

- **Crop yield (2 studies):** One replicated, randomized, controlled study from Greece[1] found higher maize yields in plots with added manure, compared to plots without added manure, in two of three comparisons. One replicated, randomized, controlled study from Italy[2] found similar nectarine yields in plots with or without added manure.

- Crop quality (0 studies)

A replicated, randomized, controlled study in 2002–2005 in an irrigated maize field in Greece (1) found higher maize yields in plots with added manure, compared to plots without added manure. **Crop yield:** Higher maize yields were found in plots with added manure, compared to plots without added manure, in two of three comparisons (11–14 vs 10–12 Mg/ha). **Methods:** Plots (5.6 x 8 m) had liquid cow manure (80 Mg/ha/year) or no added fertilizer (six plots each). The manure was incorporated into the soil with a disk harrow (12–15 cm depth) within two hours of application. Grain yield was measured at the end of October (two rows/plot, 12.8 m^2).

A replicated, randomized, controlled study in 2001–2009 in an irrigated nectarine orchard in Italy (2) found similar nectarine yields in plots with or without added manure. **Crop yield:** Similar nectarine yields were found in plots with or without added manure (33 vs 38 kg/tree). **Methods:** Four plots received 5–10 kg dry cow manure/ha, and four plots received no fertilizer. The manure was tilled into the soil (25 cm depth). Yield was measured in four trees/plot/year.

(1) Lithourgidis, A.S., Matsi, T., Barbayiannis, N. & Dordas, C.A. (2007) Effect of Liquid Cattle Manure on Corn Yield, Composition, and Soil Properties. *Agronomy Journal*, 99, 1041-1047.

(2) Baldi, E., Toselli, M., Marcolini, G., Quartieri, M., Cirillo, E., Innocenti, A. & Marangoni, B. (2010) Compost can successfully replace mineral fertilizers in the nutrient management of commercial peach orchard. *Soil Use and Management*, 26, 346-353.

2.3. Add sewage sludge to the soil: Crop production (1 study)

- **Crop yield (1 study):** One replicated, randomized, controlled study from Spain[1] found higher barley yields in plots with added sewage sludge, compared to plots without it.
- Crop quality (0 studies)
- **Implementation options (1 study):** One replicated, randomized, controlled study from Spain[1] found higher barley yields in plots with low amounts of added sewage sludge, but not high amounts, compared to plots without added sewage sludge.

A replicated, randomized, controlled study in 2002–2005 in a barley field in Toledo, Spain (1), found higher barley yields in plots with added sewage sludge, compared to plots without it. **Crop yield:** Higher grain yields were found in plots with added sewage sludge, compared to plots without it, in one of two comparisons (with low amounts of sewage sludge: 2.0 vs 1.2 t/ha). Higher straw yields were found in plots with added sewage sludge, compared to plots without it (2.7–4.2 vs 1.2 t/ha). **Implementation options:** Similar grain yields were found in plots with high amounts of added sewage sludge and plots without added sewage sludge (1.5 vs 1.2 t/ha). **Methods:** The sewage sludge was thermally dried at 75°C. There were four plots (10 x 3 m) for each of four fertilizer treatments (20 or 80 t sewage sludge/ha, applied once in three years or once/year) and there were four control plots (no fertilizer). Plots were fertilized in mid-September and planted in mid-October. Barley plants were harvested (1 m^2/plot), in June 2005.

(1) Fernández, J.M., Plaza, C., García-Gil, J.C. & Polo, A. (2009) Biochemical properties and barley yield in a semiarid Mediterranean soil amended with two kinds of sewage sludge. *Applied Soil Ecology*, 42, 18-24.

2.4. Add slurry to the soil: Crop production (6 studies)

- **Crop yield (6 studies):** Six replicated, randomized, controlled studies from Spain[1-6] found higher crop yields in plots with added pig slurry, compared to plots without it, in some comparisons.
- Crop quality (0 studies)
- **Implementation options (4 studies):** Two replicated, randomized, controlled studies from Spain[1,2] found similar crop yields in plots with digested pig slurry, compared to untreated pig slurry. One replicated, randomized, controlled study from Spain[5] found lower crop yields in plots with less pig slurry, compared to more, but another[6] found similar crop yields with different amounts of pig slurry.

A replicated, randomized, controlled study in 2009 in a rainfed barley field in Spain (1) found higher crop yields in plots with added slurry, compared to plots without it. **Crop yield:** Higher barley yields were found in plots with added slurry, compared to plots without it, in one of two comparisons (1,508 vs 972 kg/ha). **Implementation options:** Similar barley yields were found in plots with untreated slurry or digested slurry (1,125 vs 1,508 kg/ha). **Methods:** Plots (30 m^2) had no fertilizer or pig slurry (anaerobically-digested or untreated), which was applied in January 2006 (125 kg N/ha; three plots for each) and incorporated into the soil (0–5 cm depth) using a roto-cultivator. Phosphate and potassium (75 and 40 kg/ha, respectively) were added to all plots.

A replicated, randomized, controlled study in 2006 in a barley field in the Henares river basin, Spain (2), found higher crop yields in plots with added slurry, compared to plots without it. **Crop yield:** Higher barley yields were found in plots with added slurry, compared to plots without it, in one of two comparisons (digested slurry: 2,381 vs 1,825 kg grain and straw/ha). **Implementation options:** Similar barley yields were found in plots with digested slurry or untreated slurry (2,381 vs 2,117 kg grain and straw/ha). **Methods:** There were three plots (30 m^2) for each of two treatments (anaerobically digested thin fraction of pig slurry or untreated pig slurry) and there were three control plots (no slurry). Slurry was applied at a rate of 125 kg available N/ha, in January. Plots were cultivated (5 cm depth) to incorporate the slurry. Barley was planted in January and harvested in June.

A replicated, randomized, controlled study in 2000–2003 in an irrigated maize field in Spain (3) found higher crop yields in plots with added slurry, compared to plots without it. **Crop yield:** Higher maize yields were found in plots with added slurry, compared to plots without it, in two of three comparisons (7–12 vs 6–7 Mg/ha). **Methods:** Plots (3.8 x 2.5 m) had added slurry (30, 60, 90, or 120 Mg/ha) or no fertilizer (three plots for each). Maize was harvested in November each year.

A replicated, randomized, controlled study in 2000–2005 in an irrigated barley-maize field in Spain (4) found higher crop yields in plots with added slurry, compared to plots without it. **Crop yield:** Higher yields were found in plots with added slurry, compared to plots without it (4–6 vs 3 Mg/ha). **Methods:** Plots (3.8 x 2.5 m) had added slurry (30, 60, 90, or 120 Mg/ha) or no fertilizer (three plots for each) in 2000–2003. Phosphorus (120 kg P_2O_5/ha) and potassium (180 kg KCl/ha) were added to all plots in 2003 and 2004. Barley was sown in December 2003 and harvested in June 2004. Maize was sown in July 2004 and harvested in December.

A replicated, randomized, controlled study in 2010–2013 in rainfed barley fields in Spain (5) found higher crop yields in plots with added slurry, compared to plots without it. **Crop yield:** Higher barley yields were found in plots with added slurry (4,657–5,335 vs 2,359 kg/ha). **Implementation options:** Lower barley yields were found in plots with less slurry, compared to more slurry (4,657 vs 5,335 kg/ha). **Methods:** Plots (40 x 12 m) had added slurry (75 or 150 kg N/ha) or no fertilizer (three plots for each). Plots had conventional tillage (mouldboard plough: 25 cm depth; cultivator: 15 cm depth) or no tillage. Barley was harvested in June.

A replicated, randomized, controlled study in 2003–2004 in an irrigated maize field in Spain (6) found higher crop yields in plots with added pig slurry, compared to plots without it. **Crop yield:** Higher maize yields were found in plots with added pig slurry (16–18 vs 10 Mg/ha). **Implementation options:** Similar crop yields were found in plots with different amounts of added slurry (30, 60, 90, 120 Mg/ha) (16–18 Mg/ha). **Methods:** Plots (30 x 40 m) had pig slurry (30, 60, 90, or 120 Mg/ha) or no fertilizer (three plots for each). Slurry was immediately covered after application. Lysimeters (2.6 x 2 m; 1.5 m depth), were installed in each plot, five years before the study. Each lysimeter was drip-irrigated, simulating flood irrigation (May to mid-September, with 7–12 intervals). Soil samples were collected after harvest (0–120 cm depth).

(1) Meijide, A., García-Torres, L., Arce, A. & Vallejo, A. (2009) Nitrogen oxide emissions affected by organic fertilization in a non-irrigated Mediterranean barley field. *Agriculture, Ecosystems and Environment*, 132, 106-115.

(2) Meijide, A., Cárdenas, L.M., Sánchez-Martín, L. & Vallejo, A. (2010) Carbon dioxide and methane fluxes from a barley field amended with organic fertilizers under Mediterranean climatic conditions. *Plant and Soil*, 328, 353-367.

(3) Yagüe, M.R. & Quílez, D. (2010) Cumulative and residual effects of swine slurry and mineral nitrogen in irrigated maize. *Agronomy Journal*, 102, 1682-1691.

(4) Yagüe, M.R. & Quílez, D. (2013) Residual effects of fertilization with pig slurry: Double cropping and soil. *Agronomy Journal*, 105, 70-78.

(5) Plaza-Bonilla, D., Cantero-Martínez, C., Bareche, J., Arrúe, J.L. & Álvaro-Fuentes, J. (2014) Soil carbon dioxide and methane fluxes as affected by tillage and N fertilization in dryland conditions. *Plant and Soil*, 381, 111-130.

(6) Yagüe, M.R. & Quílez, D. (2015) Pig slurry residual effects on maize yields and nitrate leaching: A study in lysimeters. *Agronomy Journal*, 107, 278-286.

2.5. Use organic fertilizer instead of inorganic: Crop production (11 studies)

- **Crop yield (11 studies)**

- Food crops (10 studies): Four replicated studies (three controlled, two randomized; one site comparison) from Italy[5] and Spain[2,10,11] found higher yields in plots with organic fertilizer, compared to inorganic fertilizer, in some comparisons. Three replicated, randomized, controlled studies from Spain[8,9] and the USA[3] found lower yields in plots with organic fertilizer, compared to inorganic fertilizer, in some[8,9] or all[3] comparisons. Three replicated, randomized, controlled studies from Greece[1] and Spain[4,6] found similar yields in plots with organic or inorganic fertilizer.
- Forage crops (1 study): One replicated, randomized, controlled study from Spain[7] found higher alfalfa yields in plots with organic fertilizer, compared to inorganic, in one of two comparisons.

- Crop quality (0 studies)

A replicated, randomized, controlled study in 2002–2005 in a maize field in Greece (1) found similar crop yields in plots with organic or inorganic fertilizer. **Crop yield:** Similar maize yields were found in plots with organic or inorganic fertilizer (12–14 vs 12–13 Mg/ha). **Methods:** Plots (5.6 x 8 m) had organic fertilizer (liquid cow manure: 80 Mg/ha/year) or inorganic fertilizers (260 kg N ha/year and 57 kg P/ha/year) (six plots each). Fertilizers were incorporated into the soil with a disk harrow (12–15 cm depth) within two hours of application. Grain yield was measured in two rows (12.8 m^2) in each plot, at the end of October.

A replicated, randomized, controlled study in 2002–2005 in a barley field in Toledo, Spain (2), found higher grain and straw yields in plots with organic fertilizer, compared to inorganic fertilizer. **Crop yield:** Higher grain yields were found in plots with organic fertilizer, compared to inorganic fertilizer, in two of eight comparisons (with 20 t thermally dried sewage sludge/ha/year: 2.0 vs 1.6 t/ha; with 80 t composted sewage sludge/ha once in three years: 2.8 vs 1.6 t/ha), and higher straw yields were found in six of eight comparisons (2.7–4.2 vs 1.8 t/ha). **Methods:** There were four plots (10 x 3 m) for each of eight organic fertilizers (20 or 80 t thermally dried sewage sludge/ha, applied once in three years or once/year; 20 or 80 t composted sewage sludge/ha, applied once in three years or once/year) and one mineral fertilizer (15-15-15 NPK: 400 kg/ha/year). Plots were fertilized in mid-September and planted in mid-October. Barley was harvested in June 2005 (1 m^2/plot).

A replicated, randomized, controlled study in 2003–2004 in three maize-tomato fields near Davis, California, USA (3), found lower crop yields in organically-fertilized plots, compared to inorganically-fertilized plots. **Crop yield:** Lower maize yields were found in organically-fertilized plots, compared to inorganically-fertilized plots (4.1–6.7 vs 9.3–13.6 Mg grain/ha). **Methods:** Organic or inorganic fertilizer was used on six plots each (1.5 x 1.0 m plots). Urea was added to inorganically-fertilized plots (April: 60 kg N/ha; May: 200 kg N/ha). On organically-fertilized plots, inorganic fertilizer was replaced, every other year, with the residues of legume cover crops (100 kg N/ha). Maize was sown at different times (organically-fertilized plots: March; inorganically-fertilized plots: May), and different amounts of nitrogen were applied. It was not clear whether these results were direct effects of differences in the type of fertilizer (organic or inorganic), the amount of fertilizer, or the planting date.

A replicated, randomized, controlled study in 2009 in a rainfed barley field in Spain (4) found similar crop yields in plots with organic or inorganic fertilizer. **Crop yield:** Similar crop yields were found in plots with organic or inorganic fertilizer (1,032–1,508 vs 1,061 kg/ha). **Methods:** Plots (30 m^2) had no fertilizer, organic fertilizer (pig slurry, anaerobically-digested pig slurry, municipal solid waste, or composted crop residue with sludge), or inorganic fertilizer (urea), which was applied in January 2006 (125 kg N/ha; three plots for each fertilizer) and incorporated into the soil (0–5 cm depth) using a roto-cultivator. Phosphate and potassium (75 and 40 kg/ha, respectively) were added to all plots.

A replicated, randomized, controlled study in 2001–2009 in an irrigated nectarine orchard in Italy (5) found higher yield in plots with organic fertilizer added compared to inorganic fertilizers added. **Crop yield:** Higher nectarine yields were found in plots with organic fertilizer, compared to inorganic fertilizer, in one of eight comparisons (38 vs 28 kg/tree). **Implementation options:** Higher nectarine yields were found in plots with compost, compared to manure, in one of six comparisons (39 vs 33 kg/tree). **Methods:** There were four plots for each of four organic-fertilizer treatments (5 t compost/ha in May; 5 t/ha split into two applications, in May and September; 10 t/ha split into two; or 5–10 kg dry cow manure/ha), and there were four plots for inorganic fertilizer (70–130 kg N/ha, 100 kg P/ha, 200 kg K/ha; plot size not reported). The compost was made from domestic organic waste and urban pruning material (50% each). Fertilizers were tilled into the soil (25 cm depth).

A replicated, randomized, controlled study in 2006 in a barley field in the Henares river basin, Spain (6), found similar crop yield in plots with organic or inorganic fertilizer. **Crop yield:** Similar barley yields were found in plots with organic or inorganic fertilizer (1,879–2,381 vs 2,079 kg grain and straw/ha). **Methods:** There were three plots (30 m^2) for each of four organic fertilizers (anaerobically digested thin fraction of pig slurry, untreated pig slurry, composted municipal solid waste, or sewage sludge and composted crop residues) and one mineral fertilizer (urea), applied in January (125 kg available N/ha). Plots were cultivated (0–5 cm depth) to incorporate the fertilizers. Barley was planted in January and harvested in June.

A replicated, randomized, controlled in 2006–2008 in an irrigated field in Spain (7) found higher alfalfa *Medicago sativa* yields in plots with organic fertilizer, compared to inorganic fertilizer. **Crop yield:** Higher alfalfa yields were found in plots with organic fertilizer, compared to inorganic fertilizer, in one of two comparisons (21 vs 20 Mg/ha). **Methods:** Plots (5 m^2) had organic fertilizer (pig slurry: 170 or 340 kg N/ha/year) or inorganic fertilizer (phosphorous-potassium: 200 kg/ha/year; phosphorus pentoxide and potassium oxide: 150 kg/ha/yr). Yield was measured in each plot (mown to 8 cm height).

A replicated, randomized, controlled study in 2000–2003 in an irrigated maize field in northeast Spain (8) found lower crop yields in plots with organic fertilizer, compared to inorganic fertilizer. **Crop yield:** Lower maize yields were found in plots with organic fertilizer, compared to inorganic fertilizer, in one of four years (2003: 7–9 vs 10 Mg/ha). **Methods:** Plots (3.8 x 2.5 m) had inorganic fertilizer (150 kg N/ha) or organic fertilizer (pig slurry: 30, 60, 90, or 120 Mg/ha) (three plots for each). Maize was harvested in November each year.

A replicated, randomized, controlled study in 2000–2005 in an irrigated barley-maize field in Spain (9) found lower barley and maize yields in plots with organic fertilizer, compared to inorganic fertilizer. **Crop yield:** Lower yields were found in plots with organic fertilizer, compared to inorganic fertilizer (barley, in one of two comparisons: 4–6 vs 8 Mg/ha; maize: 4–6 vs 8 Mg/ha). **Methods:** Plots (3.8 x 2.5 m) had inorganic fertilizer (150 kg N/ha/year) or organic fertilizer (slurry: 30, 60, 90, or 120 Mg/ha/year) in 2000–2003. Phosphorus (120 kg P_2O_5/ha) and potassium (180 kg

KCl/ha) were added to all plots in 2003 and 2004. Barley was sown in December 2003 and harvested in June 2004. Maize was sown in July 2004 and harvested in December.

A replicated, randomized, controlled study in 2010–2013 in rainfed barley fields in Spain (10) found higher barley yields in plots with organic fertilizer, compared to inorganic fertilizer. **Crop yield:** Higher barley yields were found in plots with organic fertilizer, compared to inorganic fertilizer, in seven of 12 comparisons (2,755–5,335 vs 1,308–3,885 kg/ha). **Methods:** Plots (inorganic: 50 x 6 m or 40 x 6 m; organic: 40 x 12 m) had inorganic fertilizer (60, 75, 120, or 150 kg N/ha) or organic fertilizer (75 or 150 kg N/ha) (three plots for each). Plots had conventional tillage (mouldboard plough: 25 cm depth; cultivator: 15 cm depth) or no tillage. Barley was harvested in June.

A replicated, randomized, controlled study in 2003–2004 in an irrigated maize field in Spain (11) found higher crop yields in plots with organic fertilizer, compared to inorganic fertilizer. **Crop yield:** Higher crop yields were found in plots with organic fertilizer, compared to inorganic fertilizer, in four of 12 comparisons (16–18 vs 14 Mg/ha). **Methods:** Plots (30 x 40 m) had organic fertilizer (30, 60, 90, or 120 Mg slurry/ha) or inorganic fertilizer (0, 180, 240, or 300 kg N/ha) (three plots for each). Slurry was immediately covered after application. Each plot was drip-irrigated, simulating flood irrigation (May to mid-September, with 7–12 intervals). Barley was harvested at the end of 2004.

(1) Lithourgidis, A.S., Matsi, T., Barbayiannis, N. & Dordas, C.A. (2007) Effect of Liquid Cattle Manure on Corn Yield, Composition, and Soil Properties. *Agronomy Journal*, 99, 1041-1047.

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2.6. Grow cover crops in arable fields: Crop production (25 studies)

- **Crop yield (24 studies):** Six replicated, controlled studies (five randomized) from Spain[13] and the USA[4,5,7,10,15] found lower cash crop yields in plots with winter cover crops, compared to plots without them, in some comparisons. Three replicated, randomized, controlled studies from Italy[20] and the USA[3,6] found higher cash crop yields in plots with winter cover crops, compared to plots without them, in some comparisons. Eight replicated, randomized, controlled studies from Italy[12,19,22,23,25] and the USA[9,11,24] found inconsistent differences in cash crop yields (sometimes higher, sometimes lower) between plots with or without summer[9] or winter[11,12,19,22-25] cover crops. Seven controlled studies (six replicated, four randomized) from France[14], Israel[21], Spain[16], and the USA[1,2,17,18] found no differences in cash crop yields between plots with or without cover crops. One replicated, randomized, controlled study from the USA[6] found inconsistent differences in cash crop yields between plots with or without summer cover crops.
- **Crop quality (6 studies):** Three replicated, controlled studies (two randomized) from Italy[12], Spain[13], and the USA[5] found no differences in cash crop quality between plots with or without winter cover crops. Two controlled studies (one replicated and randomized) from the USA[15,18] found some differences in tomato quality between plots with winter cover crops or fallows. One replicated, randomized, controlled study from the USA[7] found inconsistent differences in cash crop quality between plots with or without winter cover crops.
- **Implementation options (9 studies):** Eight studies from Italy[8,12,19,20,23,25], Spain[13], and the USA[11] found higher cash crop yields in plots that had legumes as winter cover crops, compared to non-legumes. One study from the USA[5] found higher cash crop yields in plots that had a mixture of legumes and grasses, compared to legumes alone.

A replicated, randomized, controlled study in 1986–1988 in an irrigated lettuce field in the Salinas Valley, California, USA (1), found similar lettuce yields in plots with or without winter cover crops. **Crop yield:** Similar lettuce yields were found in plots with cover crops or fallows (210–664 g fresh weight/head). **Methods:** There were six plots (10.7 x 1.1 m raised beds) for each of two cover crops (broad beans or rye), and there were six control plots (bare fallow, maintained with herbicide). The cover crops were seeded in November 1986–1987, irrigated until emergence, and chopped, disked, and chisel ploughed in spring (25–30 cm depth). Lettuces were planted in May and July 1987 and March and August 1988, and were harvested in July and October 1987 and June and October 1988. The lettuces were irrigated (1–2 cm every 2–3 days until emergence, then 2 cm/week). Head weight was measured in 25 plants (autumn 1987) or all plants in 3 x 3 m quadrats (other harvests) in each plot.

A replicated, randomized, controlled study in 1989–1991 in an irrigated lettuce field in Salinas, California, USA (2), found similar lettuce yields in plots with winter cover crops or bare fallows. **Crop yield:** Similar lettuce yields were found in plots with cover crops or bare fallows (290–312 vs 252 g dry matter/m^2). **Methods:** In 1989–1990, six winter cover crops (*Raphanus sativus* oilseed radish, *Brassica hirta* white senf mustard, *Brassica alba* white mustard, *Lolium multiflorum* annual ryegrass, *Secale cereale* Merced rye, and *Phacelia tanacetifolia*) were grown on three plots each (two 12 m rows/plot), and bare fallows were maintained (with herbicide and hand cultivation) on three plots. In 1990–1991, two winter cover crops (*Secale cerale* Merced rye and *Phacelia tanacetifolia*) were grown on six plots each (two 8 m rows/plot), and bare fallows were maintained on six plots. Cover crops were tilled into the plots (15–20 cm depth in March 1990, depth not reported in February 1991). Lettuce was sown in April 1990–1991. All plots were irrigated and fertilized (56–85 kg N/ha, before sowing lettuce). Data on lettuce yields were reported for the harvest in July 1991.

A replicated, randomized, controlled study in 1992–1993 in an irrigated broccoli field in the Salinas Valley, California, USA (3), found higher broccoli yields in plots with winter cover crops, compared to bare fallows. **Crop yield:** Higher broccoli yields were found in plots with cover crops, compared to bare soil, in one of four comparisons (the first broccoli harvest, with phacelia as the winter cover crop: 957 vs 830 g dry weight/m^2). **Methods:** There were three plots for winter cover crops (half *Phacelia tanacetifolia* and half *Secale cereale* Merced rye, sown in November 1992 and mown in March 1993) and three control plots with bare soil in winter. All plots (252 x 24 m) were tilled in March 1993 (15 cm depth), and the cover crops were incorporated into the soil. Two broccoli crops were grown on raised beds (first crop: April–August 1993; second crop: August–November 1993). All plots were irrigated (440–450 mm/crop, subsurface drip irrigation) and fertilized (41–42 g N/m^2/crop). Broccoli biomass was measured in two 1 m^2 areas/plot.

A replicated, randomized, controlled study in 1991–1993 in an irrigated tomato field in the San Joaquin Valley, California, USA (4), found lower tomato yields in plots with winter cover crops, compared to winter fallows. **Crop yield:** Tomato yields were lower in plots with cover crops, compared to fallows, in one of two years (in 1991: 76–84 vs 97 t/ha). **Methods:** There were four plots (93 x 7 m plots) for each of three winter cover crops and one control (winter fallow). The cover crops were *Hordeum vulgare* barley, *Vicia dasycarpa* Lana woollypod vetch, or a barley-vetch mixture, seeded in October 1991–1992 and incorporated into the soil in March 1992–1993 (15–20 cm depth, rotary tiller). Tomato seeds were planted in April 1992–1993. All plots were fertilized (12 kg N/ha before planting the tomatoes), but only plots that had not been cover cropped with vetch were sidedressed (168 kg N/ha, when thinning the tomatoes). All plots were irrigated with saline water (at rates to replace evapotranspiration).

A replicated, controlled study in 1996–1998 in an irrigated tomato field in the San Joaquin Valley, California, USA (5), found lower tomato yields in plots with winter cover crops (and no tillage in spring), compared to plots with winter fallows (and tillage in spring). **Crop yield:** Lower tomato yields were found in plots with cover crops, compared to fallows, in four of 16 comparisons (27–36 vs 39–42 tons/acre). **Crop quality:** Similar amounts of soluble solids were found in tomatoes in the treatment and control plots (data not reported). **Implementation options:** Higher tomato yields were found in plots that were cover cropped with grass-legume mixtures, compared to legumes, in two of eight comparisons (36–38 vs 27 tons/acre). **Methods:** There were 12 plots (4.5 x 27.5 m plots) for each of four treatments (two grass-legume mixtures, or two legumes without grasses, as winter cover crops, sown in October 1996–1997, killed and retained as mulch, with no tillage, in March 1997–1998) and each of two controls (bare-soil fallows in winter, with or without herbicide, and conventional tillage in spring). Tomato seedlings were transplanted in April 1997–1998 and harvested in August 1997 and September 1998. The tomatoes were irrigated (two inches/week) and fertilized (0, 100, or 200 lb N/acre).

A replicated, randomized, controlled study in 1995–1998 in an irrigated tomato field in Davis, California, USA (6), found higher crop yields in plots with winter cover crops, compared to plots without cover crops, but summer cover crops had inconsistent effects on crop yields. **Crop yield:** Higher tomato yields were found in plots with winter cover crops, compared to plots without them, in one of four comparisons (1996–1997: 104 vs 94 t/ha). Higher tomato yields were found in plots with summer cover crops, compared to plots without them, in one of three comparisons (1996–1997: 108 vs 96 t/ha), but lower yields were found in one of three comparisons (1997–1998: 34 vs 45 t/ha). **Methods:** Cover crops were planted in different numbers of plots in different years (1995–1996: 16 plots with winter cover crops, eight plots with summer cover crops, 16 control plots without cover crops; 1996–1997: 12 winter, four summer, eight controls; 1997–1998: 28 summer and/or winter, four controls). Plots were 3–4 beds wide and 10 m long. Some summer cover crops were retained over winter, and some were mown and replaced with winter cover crops. Summer cover crops were mixtures of oats and legumes, planted in August–September. Winter cover crops were legumes (*Vicia sativa* common vetch), planted in November. In spring, cover crop residues were mown and either removed or evenly distributed among all plots and incorporated into the soil. Some plots were irrigated during the cover-cropping season. All plots were irrigated during the tomato-growing season. Herbicide was used on all plots, but no inorganic fertilizer was used.

A replicated, randomized, controlled study in 1998–2000 in an irrigated vegetable field in the Salinas Valley, California, USA (7), found lower lettuce yields in plots with winter cover crops, compared to plots without cover crops, but cover crops had inconsistent effects on crop quality. **Crop yield:** Lower lettuce yields were found in plots with cover crops, in one of four comparisons (281 vs 313 g dry weight/m^2). No differences in broccoli yields were found in plots with or without cover crops (625–644 vs 606–633 g dry weight/m^2). **Crop quality:** Larger lettuces were found in plots with cover crops, in two of four comparisons (1,080–1,140 vs 1,030–1,100 g fresh weight/plant), but smaller lettuces were found in one of four comparisons (750 vs 790). Larger broccoli plants were found in plots with cover crops (240–270 vs 210–220 g fresh weight/plant). **Methods:** There were four plots (0.52 ha), for each of four treatments (reduced tillage or conventional tillage, with or without added organic matter). In plots with added organic matter, compost was added two times/year, and a cover crop (*Secale cereale* Merced rye) was grown every autumn or winter. Lettuce or broccoli crops were grown on raised beds. Sprinklers and drip irrigation were used in all plots. Soils were disturbed to different depths (conventional tillage: disking to 50 cm depth, cultivating, sub-soiling, bed re-making, and bed-shaping; reduced tillage: cultivating to 20 cm depth, rolling, and bed-shaping). Crops were collected in two 2 m^2 areas/plot. It was not clear whether these results were a direct effect of adding compost or growing cover crops.

A replicated, randomized, controlled study in 1993–2001 in a rainfed cereal field in central Italy (8) found lower grain yields in plots that were cover cropped with rye, compared to clover. **Implementation options:** Lower grain yields were found in plots that were cover cropped with rye, compared to clover, in three of seven years (data not reported), but there were no differences in grain yields in two of three comparisons between species of cover crops. **Methods:** Winter cover crops (*Secale cereale* rye, *Trifolium subterraneum* subterranean clover, or *T. incarnatum* crimson clover) were grown on 72 treatment plots, but not on 24 control plots on which cereal crop residues were retained over winter (21 x 11 m sub-sub-plots, in a split-split-plot experimental design). In spring, the cover crops were flailed, half of the plots were tilled (30 cm depth), and half were not. Herbicide and fertilizer were used on all plots.

A replicated, randomized, controlled study in 1997–2001 in irrigated tomato fields at two sites in the Coachella and San Joaquin Valleys, California, USA (9), found lower tomato yields in plots with cover crops, compared to dry fallows, but found inconsistent differences in tomato yields between plots with cover crops and wet fallows. **Crop yield:** Lower tomato yields were found in plots with non-nematode-resistant cover crops, compared to plots with dry fallows, in some comparisons (e.g., in Experiment 1: 40,000 vs 61,000 kg/ha). Inconsistent differences in yields (sometimes higher, sometimes lower) were found between plots with cover crops or wet fallows (e.g., in Experiment 3, in 2 of 9 comparisons: 21,000 vs 59,000–69,000 kg/ha; in 1 of 9 comparisons: 143,000 vs 110,000). **Methods:** Six experiments compared plots with cover crops (cowpeas *Vigna unguiculata*: several nematode-resistant cultivars and one susceptible cultivar, sometimes incorporated into the soil, and sometimes not) to plots with fallows (dry or wet) between 1997 and 2001 (4–6 replicate plots/treatment/experiment). Some herbicide, but no fertilizer, was used. In the Coachella Valley, cover crops were sown in late July or early August and suppressed after 70–84 days. The following year, tomatoes were planted in late January or early March and harvested in June. In the Central Valley, cover crops were sown in May and suppressed after 83 days. The following year, tomatoes were planted in April and harvested in August.

A replicated, randomized, controlled study in 1999–2003 in an irrigated tomato-cotton field in the San Joaquin Valley, California, USA (10) (same study as (24)), found lower crop yields in plots with winter cover crops, compared to plots without winter cover crops. **Crop yield:** Lower tomato yields were found in plots with cover crops, compared to plots without cover crops, in one of two comparisons (with reduced tillage: 52 vs 58 t/ha). **Methods:** Sixteen plots (9 x 82 m) had six raised beds each. Rainfed winter cover crops (*Triticosecale* triticale, *Secale cereale* Merced rye, and *Vicia sativa* common vetch) were planted on eight plots, in October 1999–2002, and crop residues were chopped in March. Reduced tillage or conventional tillage was used on half of the plots, in 1999–2003. Different numbers of tillage practices were used for conventional tillage (19–23 tractor passes, including disk and chisel ploughing) and reduced tillage (11–12 tractor passes, not including disk and chisel ploughing). Tomato seedlings were transplanted in April 2000–2003. Fertilizer and herbicide were used on all plots, and the tomatoes were irrigated. Tomatoes were grown in rotation with cotton.

A replicated, randomized, controlled study in 2005–2007 in an irrigated tomato-maize field in Davis, California, USA (11), found lower tomato yields, but higher maize yields, in plots with winter cover crops, compared to bare fallows in winter. **Crop yield:** Lower tomato yields were found in plots with cover crops, compared to fallows (27–47 vs 68 Mg/ha). Higher maize yields were found in plots with cover crops, compared to fallows, for two of three mixtures of cover crops (mixtures with legumes: 30–31 vs 16 Mg/ha). **Implementation options:** Higher maize yields were found in plots that were cover cropped with legumes, compared to plots that were cover cropped with grains only (30–31 vs 16 Mg/ha). Similar tomato yields were found in plots with different mixtures of cover crops (27–47 Mg/ha). **Methods:** Three mixtures of winter cover crops (legumes only, legumes and grains, or grains only) were grown on five plots each, and five control plots were bare fallows on which weeds were controlled by burning (111 m^2 plots; six raised beds/plot). Tomatoes were grown in 2006, and maize was grown in 2007, without fertilizer.

A replicated, randomized, controlled study in 1999–2001 in two irrigated tomato fields in central Italy (12) found that winter cover crops had inconsistent effects on crop yields, which varied with the species of cover crop. **Crop yield:** Higher tomato yields were found in plots with mulched cover crops, compared to plots without cover crops or mulch, for three of four cover crops (86–100 vs 78 t/ha), but lower tomato yields were found for one of four cover crops (oats: 66 vs 78 t/ha). **Crop quality:** Tomato quality was similar with or without cover crops and mulch (pH 5.1–5.6, 4.3–4.9 cm diameter tomatoes). **Implementation options:** The highest yields were found in plots that were cover cropped and mulched with hairy vetch (100 t/ha, 181 fruits/m^2) and the lowest yields were found in plots that were cover cropped and mulched with oats (66 t/ha, 129 fruits/m^2). **Methods:** In September–May, cover crops were grown on 12 treatment plots, but not on three control plots, which were weeded with a disk cultivator (6 x 9 m plots). Cover crops were mown in May and used as mulch (6 cm depth, 80 cm width). All plots were irrigated and fertilized (100 kg P_2O_5/ha in September, 0–100 kg N/ha in June–July). Tomato seedlings were transplanted in May and harvested in August. It was not clear whether these results were a direct effect of growing cover crops or mulching.

A replicated, randomized, controlled study in 2006–2008 in an irrigated maize field in the Ebro river valley, Spain (13), found lower maize yields in plots with winter cover crops, compared to bare soils. **Crop yield:** Lower maize yields were found in plots with cover crops, compared to bare soils, in four of five comparisons (barley or winter rape as the cover crops: 14 vs 16–17 Mg/ha). **Crop quality:** Similar grain quality was found in plots with cover crops or bare soils (530–640 grains/ear; 0.25–0.29 g/kernel). **Implementation options:** Lower maize yields were found in plots that were cover cropped with non-legumes (barley or winter rape), compared to legumes (common vetch) (14 vs 18 Mg/ha). **Methods:** There were three plots (5.2 m^2) for each of three winter cover crops (*Hordeum vulgare* barley, *Brassica rapa* winter rape, or *Vicia sativa* common vetch, sown in October 2006–2007), and three control plots (bare soil in winter). Similar amounts of nitrogen were added to all plots (300 kg N/ha), but less of it came from mineral fertilizer in plots with cover crops, to compensate for the organic nitrogen that was added to these plots when the cover crop residues were tilled into the soil. All plots were tilled in spring (March 2007–2008) and autumn (October 2006–2007). All plots were irrigated twice/week (drip irrigation, based on evapotranspiration). Maize was planted in April and harvested in October 2007–2008.

A replicated, controlled study in 2004–2008 in an irrigated maize field in the Garonne River corridor, southern France (14), found similar maize yields in plots with or without winter cover crops. **Crop yield:** Similar maize yields were found in plots with cover crops or bare soil (11–13 vs 10–13 kg grain/ha). **Methods:** Winter cover crops (2006–2007: white mustard; 2004–2006 and 2007–2008: oats) were grown on six plots, and bare soil was maintained on six plots. The plots were 20 x 50 m. Maize was sown in April–May 2005–2008 and harvested in October 2005–2008. A centre-pivot sprinkler was used for irrigation (857–943 mm water/year, irrigation plus rainfall).

A replicated, randomized, controlled study in 2005–2006 in an irrigated, organic tomato field in Yolo County, California, USA (15), found lower tomato yields in plots with winter cover crops, compared to winter fallows. **Crop yield:** Lower tomato yields were found in plots with cover crops, compared to fallows (162 vs 234 g harvestable fruit/m^2). **Crop quality:** Tomatoes were not as red in plots with cover crops, compared to fallows (39.8 vs 38.9 L*a*b colour values), but firmer tomatoes were found in plots with cover crops (77% vs 75%). Tomato weight, soluble solids, pH, and titratable acidity did not differ between plots with cover crops or fallows (data not reported). **Methods:** The field was levelled and fertilized (17 Mg compost/ha). Eight plots had winter cover crops (mustard *Brassica nigra*, planted on 3 November 2005) and eight plots had winter fallows. Each plot was 16 x 9 m. Cover crops were mown on 26 April 2006, sprinkler irrigated, and tilled into the soil (10 cm depth) after 19 days, when fallow plots were also tilled. Plots were weeded and sulfur was used against mites and diseases. Tomatoes were furrow irrigated (approximately every 11 days: 88 mm/event). Tomatoes were transplanted on 18–19 May 2006 and harvested on 7–8 September 2006.

A replicated, randomized, controlled study in 2006–2009 in an irrigated maize field in the Tajo river basin, near Madrid, Spain (16), found similar crop yields in plots with winter cover crops or bare fallows. **Crop yield:** Similar maize yields were found in plots with cover crops or fallows (9,800–14,900 vs 8,400–14,400 kg grain/ha, dry weight). **Methods:** There were four plots (12 x 12 m plots) for each of two treatments (barley or vetch, as winter cover crops) and there were two control plots (bare fallow). Cover crops were sown in October 2006–2009 and maize was sown in April and harvested in October 2007–2009. The maize was irrigated (sprinklers) and fertilized (210 kg N/ha, split into two applications, 120 kg P/ha, and 120 kg K/ha).

A replicated, controlled study in 2007–2009 in an irrigated tomato field in Davis, California, USA (17), found similar crop yields in plots with winter cover crops or winter fallows. **Crop yield:** Similar tomato yields were found in plots with cover crops or fallows (28–34 vs 31–33 marketable t/acre). **Methods:** Conventional tillage or reduced tillage was used on four plots each (90 x 220 feet). Broadcast disking, subsoiling, land planing, and rebedding were used for conventional tillage. A Wilcox Performer was used for reduced tillage (two passes; beds were conserved). Winter cover crops (*Triticosecale* triticale) were grown on half of each plot, and the other half was fallow in winter. Sprinklers, furrow irrigation, and drip-tape (in furrows) were used to irrigate the tomatoes. All plots were fertilized.

A controlled study in 2005–2006 in an irrigated tomato field in the Sacramento Valley, California, USA (18), found some differences in tomato quality between the parts of the field that were cover cropped or fallow over winter. **Crop yield:** Similar tomato yields were found in each part of the field (55–67 Mg undamaged tomatoes/ha, fresh weight). **Crop quality:** More pink or split tomatoes were found in the cover-cropped part, compared to the fallow part (pink: 13 vs 11 Mg/ha; split: 6.8 vs 6.5), but similar numbers of green (22 vs 15 Mg/ha), sunburned (19 vs 20 Mg/ha), and mouldy or rotten (36 vs 27 Mg/ha) tomatoes were found in each part of the field (fresh weights). **Methods:** A field was divided into two parts: one part with a winter cover crop (mustard *Brassica nigra*, planted in autumn 2005, and disked into the soil in spring 2006), and one part fallow. Tomatoes were planted in both parts of the field in spring 2006. Tomatoes were sampled on 393 m transects (1 x 3 m quadrats every 30 m).

A replicated, randomized, controlled study in 2009–2011 in two irrigated pepper fields in central Italy (19) found that cover crops had inconsistent effects on crop yields. **Crop yield:** Higher pepper yields were found in plots with cover crops, compared to plots without cover crops, in 15 of 27 comparisons (9–41 vs 2–15 t/ha, fresh weight), but lower pepper yields were found in one of 27 comparisons (8 vs 15). **Implementation options:** Higher pepper yields were found in plots with hairy vetch as the winter cover crop (9–41 t/ha, fresh weight), compared to canola (3–26 t/ha) or oats (4–21 t/ha). Higher pepper yields were found in plots with canola as the winter cover crop, compared to oats, in two of nine comparisons (25–26 vs 8–10 t/ha, fresh weight), but lower yields were found in one of nine comparisons (14 vs 18). **Methods:** Three species of winter cover crops (*Vicia villosa* hairy vetch, *Brassica napus* canola, or *Avena sativa* oats) were sown on nine plots each (6 x 12 m plots) in September 2009–2010, and no cover crops were sown on nine plots (weeded, bare soil). The cover crops were mown and used as mulch (50 cm wide) in some plots, or were chopped and tilled into the soil in other plots, in May 2010–2011. Pepper seedlings were transplanted into these rows in May, and fruits were harvested twice/year in August–October 2010–2011. All plots were fertilized before the cover crops, but not after. All plots were irrigated.

A replicated, randomized, controlled study in 2009–2012 in two irrigated vegetable fields in central Italy (20) found higher crop yields in plots with winter cover crops, compared to plots with bare soil in winter. **Crop yield:** Higher crop yields were found in plots with cover crops, compared to bare soil, in one of three comparisons (in plots with hairy vetch as the winter cover crop: 17 vs 7 t/ha endive; 15 vs 4 t/ha savoy cabbage). **Implementation options:** Higher crop yields were found in plots with hairy vetch as the winter cover crop, compared to oats (endive: 17–23 vs 5–6 t/ha; cabbage: 15–23 vs 2–6 t/ha; fresh weights), or compared to oilseed rape, in five of six comparisons (endive: 17–23 vs 5–11; cabbage: 15–23 vs 2–6). Higher yields were found in plots with oilseed rape as the winter cover crop, compared to oats, in one of six comparisons (11 vs 4 t/ha endive, fresh weight). **Methods:** There were nine plots (6 x 4 m plots) for each of three treatments (hairy vetch, oats, or oilseed rape) and one control (bare soil, maintained with herbicide). Cover crops were sown in September 2009–2010 and suppressed in May 2010–2011 (chopped and incorporated into the soil with a mouldboard plough, 30 cm depth). Pepper seedlings were transplanted into these plots in May 2010–2011 and were last harvested in October 2010 and September 2011. After the pepper harvest, endive and savoy cabbage seedlings were transplanted into these plots, and they were harvested in December 2010 and November 2011 (endive) or March 2011 and February 2012 (cabbage). No fertilizer was added while the crops were growing, but the plots were irrigated.

A replicated, randomized, controlled study in 2011–2014 in irrigated potato fields in Israel (21) found similar crop yields in plots with or without cover crops. **Crop yield:** Similar potato yields were found in plots with or without cover crops (oats: 4.4–8.0 vs 4.9–8.0 kg/m^2; data not presented for other cover crops). **Methods:** Different plots were used in different years (2011–2012: 350 m^2 plots, 20 plots with cover crops, eight plots without cover crops; 2012–2013: 695 m^2 plots, 10 with, 10 without; 2013–2014: 1,800 m^2 plots, four with, four without). Different mixtures of cover crops were used in different years, but oats were used in all years, and triticale was used in Years 1 and 2 (2011–2013). Plots without cover crops were weeded (tilled bare; some plots in all years) or weedy (not tilled; some plots in Year 1). Herbicide and fertilizer were used on all plots. Potatoes were planted under mown cover crops. Potato yields were sampled in 5 m^2/plot.

A replicated, randomized, controlled study in 2011–2013 in two irrigated tomato fields in central Italy (22) (same study as (23)) found that cover crops had inconsistent effects on tomato yield. **Crop yield:** Higher tomato yields were found in plots that were cover cropped and mulched with hairy vetch, compared to control plots (5.4–5.9 vs 3.6–5.2 kg fresh weight/m^2), but lower yields were found in plots that were cover cropped and mulched with lacy phacelia or white mustard (2.4–4.3 kg). **Methods:** Three species of winter cover crops (*Vicia villosa* hairy vetch, *Phacelia tanacetifolia* lacy phacelia, or *Sinapis alba* white mustard) were sown on three plots each, in September, and winter weeds were controlled with herbicide on three control plots (18 x 6 m plots). The cover crops were mown and mulched (strips, 80 cm width) in May, and the control plots were tilled (depth not reported). Tomato seedlings were transplanted in May (transplanted into the mulch) and harvested in August. All plots were tilled (30 cm depth) and fertilized (100 kg P_2O_5/ha, harrowed to 10 cm depth) in September. Some plots were also fertilized (100 kg N/ha) in June–July. It was not clear whether these results were a direct effect of cover cropping, mulching, herbicide, or tillage.

A replicated, randomized, controlled study in 2012–2013 in two irrigated tomato fields in central Italy (23) (same study as (22)) found that cover crops had inconsistent effects on tomato yields. **Crop yield:** Higher tomato yields were found in plots that had been cover cropped and mulched with hairy vetch, compared to plots that had not (6.4–7 vs 3.2–5.3 kg/m^2). Lower tomato yields were found in plots that had been cover cropped and mulched with lacy phacelia (in one of two comparisons: 4.2 kg/m^2) or white mustard (2.1–3.5), compared to plots that had not (3.2–5.3). **Implementation options:** The highest tomato yields were found in plots with hairy vetch (6.4–7 kg/m^2) and the lowest were found in plots with white mustard (2.1 kg/m^2). **Methods:** Three species of winter cover crops (*Vicia villosa* hairy vetch, *Phacelia tanacetifolia* lacy phacelia, or *Sinapis alba* white mustard) were sown on three plots each, but not on three control plots (plot size not reported), in September. The cover crops were mulched in May, and the control plots were tilled (depth not reported). Tomato seedlings were transplanted in May (transplanted into the mulch) and harvested in August. All plots were tilled in September. It was not clear whether these results were a direct effect of cover cropping, mulching, or tillage.

A replicated, randomized, controlled study in 1999–2009 in an irrigated tomato-cotton field in the San Joaquin Valley, California, USA (24) (same study as (10)), found that winter cover crops had inconsistent effects on crop yields. **Crop yield:** Lower tomato yields were found in plots with cover crops, compared to plots without cover crops, in four of 10 years (95–118 vs 109–128 t/ha), but higher yields were found in one of 10 years (with conventional tillage: 142 vs 132 t/ha). **Methods:** Rainfed winter cover crops (*Triticosecale* triticale, *Secale cereale* Merced rye, and *Vicia sativa* common vetch) were planted on eight treatment plots, but not on eight control plots, in October 1999–2008. Crop residues were chopped in March. Reduced tillage or conventional tillage was used on half of these plots, in 1999–2009. The plots (9 x 82 m) had six raised beds each. Different numbers of tillage practices were used for conventional tillage (19–23 tractor passes, including disk and chisel ploughing) and reduced tillage (11–12 tractor passes, not including disk and chisel ploughing). Tomato seedlings were transplanted in April 2000–2009. Fertilizer and herbicide were used on all plots, and the tomatoes were irrigated. Tomatoes were grown in rotation with cotton.

A replicated, randomized, controlled study in 2009–2011 in an irrigated eggplant field in central Italy (25) found that winter cover crops had inconsistent effects on crop yield. **Crop yield:** Higher eggplant yields were found in plots with winter cover crops, compared to plots with bare soil in winter, in six of nine comparisons (18–38 vs 11–21 Mg/ha fresh weight), but lower yields were found in two of nine comparisons (7–14 vs 18–21). **Implementation options:** Higher eggplant yields were found in plots with hairy vetch as the winter cover crop (32–38 Mg/ha fresh weight), compared to oats (7–18 Mg/ha) or oilseed rape (18–25 Mg/ha). Higher eggplant yields were found in plots with oilseed rape as the winter cover crop, compared to oats, in two of three comparisons (20–25 vs 7–14 Mg/ha fresh weight). **Methods:** Three species of winter cover crops (*Vicia villosa* hairy vetch, *Brassica napus* oilseed rape, or *Avena sativa* oats) were sown on three plots each (6 x 12 m plots) in September 2009–2010, and no cover crops were sown on three plots (weeded, bare soil). The cover crops were mown and used as mulch (50 cm wide) in eggplant rows, in May 2010–2011. Eggplant seedlings were transplanted into the plots in May, and fruits were harvested four times/year in July–September 2010–2011. All plots were fertilized before the cover crops were grown, but not after. All plots were irrigated.

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2.7. Plant or maintain ground cover in orchards or vineyards: Crop production (14 studies)

- **Crop yield (11 studies)**
  - Grapes (8 studies): Two replicated, randomized, controlled studies from France[2] and the USA[1] found lower grape yields in plots that were seeded with grass between the vine rows, compared to plots with bare soil between the vine rows, in some comparisons[1] or all comparisons[2]. Six replicated, randomized, controlled studies from Italy[11], Portugal[4], Spain[12], and the USA[3,6,13] found similar grape yields in plots with or without ground cover between the vine rows.
  - Other crops (3 studies): Two replicated, randomized, controlled studies from Portugal[7,8] found higher chestnut yields in plots with resident vegetation, compared to plots without ground cover, but found no difference in chestnut yields between plots with seeded cover crops and plots without ground cover. One of these studies[7] also found higher mushroom yields in plots with resident vegetation, compared to plots without ground cover. One replicated, randomized, controlled study from Chile[9] found lower avocado yields in plots that were seeded with grasses and legumes, compared to plots with bare soil.
- **Crop quality (8 studies)**
  - Grapes (6 studies): Five replicated, randomized, controlled studies from Italy[11], Portugal[4], and the USA[3,6,13] found similar sugar contents in grapes with or without ground cover between the vine rows. Three of these studies[3,4,6] found similar pH levels, and two of these studies[3,11] found no differences in titratable acidity, but two of these studies[4,6] found lower titratable acidity in grapes with ground cover between the vine rows. One replicated, randomized, controlled study from the USA[13] found heavier grapes with ground cover between the vine rows, but two replicated, randomized, controlled studies from Italy[11] and Spain[12] did not. Two replicated, randomized, controlled studies from Portugal[4] and Spain[12] found other differences in grape quality with ground cover between the vine rows.
  - Other crops (2 studies): One replicated, randomized, controlled study from Portugal[7] found larger chestnuts in plots with ground cover, compared to plots without ground

cover. One replicated, randomized, controlled study from Chile[9] found no difference in avocado quality in plots with or without ground cover.

- **Implementation options (6 studies)**
  - Ground cover (5 studies)
    - Grapes (3 studies): One replicated, randomized, controlled study from the USA[10] found similar grape yields in plots with different types of ground cover. However, this study found lighter-weight clusters of grapes in plots with seeded cover crops, compared to resident vegetation, in one of three years, and found inconsistent differences in cluster weights between plots with different types of seeded cover crops. Two replicated, randomized, controlled studies from Spain[12] and the USA[14] found other differences in grape quality between plots with different types of ground cover.
    - Other crops (2 studies): Two replicated, randomized, controlled studies from Portugal[7,8] found lower chestnut yields in plots with seeded cover crops, compared to resident vegetation. One of these studies[8] also found smaller chestnuts and lower mushroom yields.
  - Tillage (2 studies): One replicated, randomized, controlled study from the USA[10] found higher grape yields, and heavier grape clusters, in plots without tillage between the vine rows, in one of six comparisons. Another replicated, randomized, controlled study from the USA[5] found similar grape yields, with or without tillage between the vine rows.

A replicated, randomized, controlled study in 1989–1990 in an irrigated vineyard in the San Joaquin Valley, California, USA (1), found lower crop yields in plots with cover crops, compared to bare soils, between the vine rows. **Crop yield:** Lower grape yields were found in plots with cover crops, compared to bare soils, in two of four comparisons (in 1990: 16–20 vs 23 Mg/ha). **Methods:** There were three plots (one vine row and two interrows, 183 m length) for each of two cover crops (*Bromus mollis* bromegrass as a winter cover crop, treated with herbicide and mulched in summer, or followed by resident vegetation as a summer cover crop), and there were three control plots (bare soil, maintained with herbicide throughout the year). The bromegrass was seeded in January and December 1989 (and reseeded in March 1989 because of poor establishment). All plots were furrow irrigated until the water had advanced to the end of the furrow (five times in March–September 1989–1990), and thus more water was given to plots with faster infiltration (plots with cover crops). Grapes were harvested in September 1989–1990.

A replicated, randomized, controlled study in 1998–2002 in a rainfed vineyard in southern France (2) found lower crop yields in plots sown with grass between vine rows, compared to bare soil. **Crop yield:** Lower grape yields were found in plots with grass between the vine rows, compared to bare soil (8 vs 12 t/ha). **Methods:** In 1998, grass seeds (*Festuca arudinacea* tall fescue) were sown between the vine rows in four treatment plots, and herbicide was used to control weeds between vine rows in four control plots (12 x 15 m plots). The grass was mown three times/year, in the summer. Grape yield was measured from 1999–2002 (three vines/plots).

A replicated, randomized, controlled study in 1996–2000 in an irrigated vineyard in the Sacramento Valley, California, USA (3), found no differences in grape yield or quality between plots with or without cover crops between the vine rows. **Crop yield:** Similar grape yields were found in plots with or without cover crops between the vine rows (18–

28 vs 19–30 kg/vine). **Crop quality:** No consistent differences in grape quality were found in plots with or without cover crops (see publication for data on Brix, pH, and titratable acidity). **Methods:** There were four plots for each of four cover crops (1.8 m width, between vine rows of 3.4 width), and there were four control plots (periodically disked between the vine rows). Each plot was 10 contiguous vines and two adjacent interrows. The cover crops were Californian native grasses (not tilled, mown), annual clover (not tilled, mown), barley and oats (mown and disked), or legumes and barley (mown and disked in spring and used as a green manure). The Californian native grasses were seeded between the vine rows in autumn 1996. The others were seeded in autumn 1997–1999. All plots were drip irrigated, fertigated (20 kg N/ha/year), and the grass cover crops were also fertilized with urea (45 kg N/ha/year). Herbicide was used under the vines. Grape quality was measured in 150 grapes/plot.

A replicated, randomized, controlled study in 2002–2004 in a rainfed vineyard in central Portugal (4) found similar grape yields, but differences in grape quality, in plots with ground cover (without tillage), compared to tilled soils (without cover crops), between the vine rows. **Crop yield:** Similar grape yields were found in plots with or without ground cover (2.9 kg/vine). **Crop quality:** Lower acidity (2004: 6.7–7.2 vs 8.1 g tartaric acid/litre), higher phenol content (data not reported), and higher anthocyanin content (2004: 1,182–1,269 vs 1,027 mg/litre) were found in grapes from plots with ground cover, but there were similar sugar contents (22 °Brix) and pH levels (pH 3.35). **Methods:** There were four plots for each of two ground-cover treatments (resident vegetation or sown cover crops, both without tillage between the vine rows), and there were four control plots (with tillage between the vine rows; depth not reported). The plots were four vine rows each (100 vines/row). The cover crops were 60% grasses (*Lolium* and *Festuca* spp.) and 40% legumes (*Trifolium* spp.), sown in March 2002. The interrows of all plots were mown (treatments: twice/year, to 15 cm, in February and May–June; controls: once/year, in February, height not reported). All plots were fertilized, and herbicide was used under the vines. Two-hundred grapes/plot were collected for measurements of crop quality.

A replicated, randomized, controlled study in 2002–2005 in an irrigated vineyard in the Napa Valley, California, USA (5), found similar grape yields in vine rows with ground cover, with or without tillage. **Implementation options:** Similar grape yields were found in vine rows with ground cover (either seeded cover crops or resident vegetation), with or without tillage (4.3–6.6 kg/vine). **Methods:** No tillage or conventional tillage was used on eight plots each, between the vine rows (three vine rows/plot). A disk plough was used for conventional tillage (15 cm depth, once/year in April–June). Four plots with conventional tillage had annual cover crops (seeded in October 2002–2004) and four plots had resident vegetation. Four plots with no tillage had annual cover crops (seeded in October 2002–2004), and four had perennial cover crops (seeded in October 2002). All plots were drip irrigated in July–October (85 kl/ha/week). Grapes were harvested from 18 vines/plot (September 2003–2004 and October 2005).

A replicated, randomized, controlled study in 2000–2005 in an irrigated vineyard in the Salinas Valley, California, USA (6), found similar crop yields and qualities in plots with or without cover crops, except for lower acidity in plots with cover crops. **Crop yield:** Similar grape yields were found in plots with or without cover crops (6–6.5 vs 6.1 kg/vine; 46–48 vs 47 cluster/vine, 130–139 vs 132 g/cluster). **Crop quality:** Similar sugar content and pH levels were found in grapes from plots with or without cover crops (24 °Brix, 3.4 pH), but lower titratable acidity was found in plots with cover crops, in one of two comparisons (7.0 vs 7.3 g/litre). **Methods:** There were nine plots for each of two treatments, and there were nine control plots. The treatments were triticale (X *Triticosecale*) or *Secale cereale* Merced rye, planted in November 2000–2004 as cover crops (32 inches width) between the vine rows (8 feet width), mown in spring, and disked into the soil in the following November. Bare soils were maintained in the controls through disking in spring and summer (depth not reported). Each plot had 100 vines and the adjacent areas between the vine rows. All plots were drip-irrigated in April–October. Grapes were harvested from 20 vines/plot (for crop yield), and 200 grapes/plot (for crop quality). It was not clear whether these results were a direct effect of cover crops or tillage.

A replicated, randomized, controlled study in 2001–2006 in a chestnut orchard in northeast Portugal (7) (same study as (8)) found higher chestnut yields in plots with resident vegetation (without tillage), compared to plots without ground cover (with conventional tillage). **Crop yield:** Higher chestnut yields were found in plots with ground cover, compared to plots without ground cover, in one of two comparisons (with resident vegetation: 27 vs 19 kg dry matter/tree). **Implementation options:** Lower chestnut yields were found in plots with seeded grasses and legumes, compared to resident vegetation (20 vs 27 kg dry matter/tree). **Methods:** There were three plots for each of two treatments (no tillage with ground cover: grasses and legumes, sown in 2001, or resident vegetation), and there were three control plots (conventional tillage, 15–20 cm depth, thrice/year). Each plot (600 m^2) had six chestnut trees (40 years old in 2001) and was fertilized but not irrigated. Chestnuts were collected thrice/plot in 2003–2006. It was not clear whether these results were a direct effect of ground cover or tillage.

A replicated, randomized, controlled study in 2001–2008 in a chestnut orchard in northeast Portugal (8) (same study as (7)) found higher mushroom and chestnut yields, and larger chestnuts, in plots with ground cover (without tillage), compared to plots with conventional tillage (without ground cover). **Crop yield:** Higher edible mushroom yields were found in plots with ground cover, compared to conventional tillage (43 vs 6 kg fresh weight/ha), and higher chestnut yields were also found in one of two comparisons (with resident vegetation: 27 vs 19 kg dry matter/tree). **Crop quality:** Larger chestnuts were found in plots with ground cover, compared to conventional tillage (10–11 vs 9 g/fruit; 26–27 vs 25 mm size index). **Implementation options:** Lower crop yields and smaller chestnuts were found in plots with seeded cover crops, compared to resident vegetation (edible mushrooms: 45 vs 59 kg fresh weight/ha; chestnuts: 20 vs 27 kg dry matter/tree; 11 vs 10 g/fruit; 26 vs 27 mm size index). **Methods:** There were three plots for each of two treatments (no tillage with ground cover: grasses and legumes, sown in 2001, or resident vegetation), and there were three control plots (conventional tillage, 15–20 cm depth, thrice/year). Each plot (600 m^2) had six chestnut trees (40 years old in 2001) and was fertilized but not irrigated. Chestnuts were sampled thrice/plot in 2003–2006. Mushrooms were collected in 2006–2008 (weekly in May–July and September–November, under three trees/plot). It was not clear whether these results were a direct effect of ground cover or tillage.

A replicated, randomized, controlled study in 2008–2011 in an irrigated avocado orchard in Chile (9) found lower crop yields in plots with cover crops, compared to bare soil. **Crop yield:** Lower avocado yields were found in plots with cover crops, compared to bare soil (1.3 vs 5 kg fruit/tree; 7 vs 27 fruits/tree). **Crop quality:** Similarly-sized avocados were found in plots with cover crops or bare soil. **Methods:** Cover crops were grown in five treatment plots, and bare soil was maintained with herbicide in five control plots, in an avocado orchard, on a 47% slope (10 x 50 m plots). The groundcover (*Lolium rigidum* ryegrass and a legume, *Medicago polymorpha*) was sown in August 2008 and mown in February 2009–2010 (residues were retained). All plots were fertilized and irrigated. Avocado yield and quality were measured in 2011.

A replicated, randomized, controlled study in 2008–2010 in an irrigated vineyard in the San Joaquin Valley, California, USA (10) (same study as (14)), found lighter-weight clusters of grapes in plots with seeded cover crops, compared to resident vegetation, but found similar crop yields. **Implementation options:** Similar grape yields were found in plots with cover crops or resident vegetation (8–19 vs 11–19 kg/vine). Similar grape yields were found in plots with different types of seeded cover crops (oats only, or oats and legumes: 8–19 kg/vine). Higher grape yields were found in plots with no tillage, compared to conventional tillage, in one of six comparisons (in 2010, in plots that were cover cropped with oats and legumes: 13 vs 9 kg/vine). Heavier clusters of grapes were found in plots that were cover cropped with oats only, compared to oats and legumes, in one of three years (2010: 70 vs 65 g/cluster), but lighter clusters were found in one of three years (2009: 110 vs 125). Heavier clusters were also found in plots with no tillage, compared to conventional tillage, in one of six comparisons (in 2010, in plots that were cover cropped with oats and legumes: 85 vs 70 g/cluster). Lighter-weight clusters of grapes were found in plots with cover crops, compared to resident vegetation, in one of three years (2010: 65–70 vs 80 g/cluster). **Methods:** Either seeded cover crops or resident vegetation was grown between the vine rows on 16 plots each (two vine rows/plot, 190 vines/row). The cover crops were either oats or oats and legumes, on eight plots each, seeded in November. The plots were mown in spring, before tillage. No tillage was used on half of the plots, and conventional tillage was used on the other half. A disk plough (15–20 cm depth) was used for conventional tillage, in spring, summer (three times), and autumn. Herbicide was used to control weeds in the vine rows (50 cm width).

A replicated, randomized, controlled study in 2005–2010 in an irrigated vineyard in Sardinia, Italy (11), found similar grape yields and similarly-sized grapes, of similar quality, in plots with ground cover (without tillage), compared to conventional tillage (without ground cover), between the vine rows. **Crop yield:** Similar crop yields were found in all plots (3.5–5.6 kg, 8.5–13.5 grape clusters/vine, 351–537 g/cluster). **Crop quality:** Similarly-sized grapes (1.8–3 g/grape), with similar compositions (sugar content: 19–22.5 ^{o}Brix; titratable acidity: 3.9–5.9 g/L; see publication for other measurements), were found in all plots. **Methods:** There were four plots (3 vine rows/plot) for each of four ground-cover treatments (all without tillage, with vegetation in the interrows: resident vegetation, complex grass-legume cover crop, simple grass-legume cover crop, or summer-dormant-grass cover crop), and there were four control plots (conventionally tilled interrow: 2–3 passes/year, 15 cm depth). Cover crops were sown in the interrows in October 2005. In the vine rows, weeds were controlled with herbicide. All vine rows were drip irrigated and fertilized. Grape yield and quality were measured in 2006–2010 (yield and size: 10 clusters/plot, 10 grapes/cluster; quality: 400 grapes every two weeks, from the beginning of ripening to harvest in 2007–2010; at harvest in 2006). It was not clear whether these results were a direct effect of ground cover or tillage.

A replicated, randomized, controlled study in 2009–2011 in a rainfed vineyard in northern Spain (12) found similar grape yields but differences in grape quality in plots with cover crops, compared to conventional tillage, between the vine rows. **Crop yield:** Similar grape yields were found in plots with cover crops or conventional tillage (4.2–6.2 vs 5.1–5.9 kg/vine; 14.1–16.8 vs 13.8–16.6 clusters/vine). **Crop quality:** Less yeast-assimilable nitrogen (which is needed for wine fermentation) was found in grapes from plots with cover crops, compared to conventional tillage, in one of six comparisons (with barley, in 2011: 48 vs 70 mg YAN/kg grape extract). Significant differences in amino acid content were found between plots with cover crops or conventional tillage (20 amino acids: see publication for details). Similar grape weight was found in plots with cover crops or conventional tillage (250–290 g/100 grapes). **Implementation options:** Less yeast-available nitrogen was found in grapes from plots that were cover cropped with barley, compared to clover (48 vs 77 mg YAN/kg grape extract). **Methods:** There were three plots (four vine rows/plot, 20 vines/row) for each of two cover crops (*Hordeum vulgare* barley or *Trifolium resupinatum* Persian clover between vine rows, sown in February 2009 and 2011), and there were three control plots (conventional tillage between vine rows: disk plough, 0–15 cm depth, every 4–6 weeks in February–August). No plots were fertilized. Herbicides were used under vine rows. Vine prunings were retained between rows. Grape yield and quality were measured in 2009–2011 (20 vines/plot, 500 grapes/plot).

A replicated, randomized, controlled study in 2008 in an irrigated vineyard in southern California, USA (13), found larger grapes in plots with cover crops, compared to bare fallows, but found similar grape yields and sugar contents. **Crop yield:** Similar grape yields were found in plots with cover crops or bare fallows (75–80 vs 55 g/cluster). **Crop quality:** Similar amounts of sugar were found in grapes from plots with cover crops or bare fallows (24 ^{o}Brix/cluster). Larger grapes were found in plots with cover crops, compared to bare fallows, in two of four comparisons (11 vs 10 mm diameter). **Methods:** Cover crops (*Fagopyrum esculentum* buckwheat) were sown between the vine rows in four plots, in summer 2008, and the cover crops were irrigated throughout the summer (sprinklers: 10 sprinklers/plot, 45 litre/hour, two hours after sowing and six hours every 7–10 days; tree sprayer: 60.5 litres/plot, thrice/week). This irrigation system was also used on three plots that did not have cover crops. Conventional management was used on six plots (bare fallows were maintained between the vine rows through cultivation and no irrigation). The plots had two vine rows each (28.7 x 6 m plots). Grapes were harvested in September 2008 (10 clusters from 3 m in the centre of each plot).

A replicated, randomized, controlled study in 2008–2010 in an irrigated vineyard in the San Joaquin Valley, California, USA (14) (same study as (10)), found lower titratable acidity in grapes from plots with seeded cover crops between the vine rows, compared to resident vegetation. **Implementation options:** Grapes of similar quality were found in plots with cover crops or resident vegetation between the vine rows (23–25 ^{o}Brix; pH 3.3–3.6; 107–135 g/100 grapes; 25–33 g sugar/100 grapes), except that lower titratable acidity was found in grapes from plots with cover crops, in one of three years (2008: 5.7–5.9 vs 6.8 mg/L). **Methods:** Cover crops (2.5 m width) were grown in the alleys between the vine rows (3.1 m width) on 16 plots (two alleys/plot, 190 vines/row), and resident vegetation was allowed to grow on 8 plots, over the winter. There were two combinations of cover crops (oats only, or oats and legumes, seeded in November, on 8 plots each). All plots were mown in spring and tilled (15–20 cm depth) in spring, summer, and autumn. Herbicide was used to control weeds in the vine rows (50 cm width), but not in the alleys. Vines were drip-irrigated (60–70% of evapotranspiration).

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2.8. Use crop rotations: Crop production (9 studies)

- **Crop yield (8 studies):** Four replicated, controlled studies (three randomized) from Italy[7], Spain[4,5], and Turkey[6] found higher crop yields in plots with rotations, compared to monocultures, in some comparisons. Four replicated, randomized, controlled studies from Australia[8,9], Portugal[3], and Spain[1] found similar crop yields in plots with or without rotations.
- **Crop quality (1 study)**: One replicated, controlled study from Italy[7] found more protein in wheat that was grown in rotation, compared to continuously-grown wheat.
- **Implementation options (2 studies)**: One study from the USA[2] found higher tomato yields in four-year rotations, compared to two-year rotations. One study from Italy[7] found higher wheat yields in rotations with beans, compared to clover.

A replicated, randomized, controlled study in 1983–1996 in a rainfed wheat field in the Henares river valley, Spain (1), found similar wheat yields in plots with or without crop rotations. **Crop yield:** Similar wheat yields were found in plots with or without crop rotations (2.5–2.7 vs 2.5–2.8 Mg/ha). **Methods:** Wheat was grown in continuous monoculture or in rotation with vetch (12 plots each, 20 x 30 m plots). Fertilizer and post–emergence herbicide were used on all plots. Wheat was harvested at maturity (July 1996), and yield was measured in two strips/subplot (1.4 x 30 m strips).

A replicated, randomized, controlled study in 1994–1998 on an irrigated, arable farm near Davis, California, USA (2), found higher tomato yields in plots with four-year crop rotations, compared to two-year rotations. **Implementation options:** Higher tomato yields were found in plots with four-year rotations, in one of five years (in 1994: 92 vs 85 mg/kg). **Methods:** A four-year rotation (tomato, safflower, corn and wheat, beans) was used on 16 plots (four plots for each phase, each year), and a two-year rotation (tomato, wheat) was used on eight plots (four plots for each phase, each year). Each plot was 68 x 18 m. Fertilizer and pesticide were used on all plots.

A replicated, randomized, controlled study in 2004–2006 in an occasionally irrigated oat field in Portugal (3), found similar oat yields in plots with a lupin-oat sequence, compared to an oat-oat sequence. **Crop yield:** Similar oat yields were found in all plots (4.2 t dry matter/ha). **Methods:** Oats or white lupins *Lupinus albus* were grown in six plots each in 2003–2004 (year 1). Oats were grown in all plots in 2004–2005 (year 2). Each plot was 5 x 10 m. Half were tilled (15 cm depth), and half were not (crop residues were retained). All plots were fertilized with phosphorus (60 kg/ha), and oats were also fertilized with nitrogen (100 kg/ha). The seeds were sown in September and the oats were harvested in May.

A replicated, randomized, controlled study in 1993–1997 in a rainfed barley field near Madrid, Spain (4), found higher barley yields in plots with vetch-barley or fallow-barley rotations, compared to plots with continuous barley. **Crop yield**: Higher barley yields were found in plots with rotations (4,107–4,395 vs 2,465 kg/ha). **Methods:** Barley was grown continuously (one plot), or in rotation with vetch *Vicia sativa* or fallow (one plot/phase), in each of three tillage treatments (conventional, reduced, or no tillage), in each of four blocks. Plots were 10 x 25 m. The barley phases were fertilized (8-24-8 NPK: 200 kg/ha; ammonium nitrate: 200 kg/ha). Before the experiment, barley was grown in these plots for over 10 years. Barley was harvested in June.

A replicated, randomized, controlled study in 1999–2005 in a rainfed cereal field in northeast Spain (5) found higher barley yields in plots with rotations, compared to continuous barley. **Crop yield:** Higher barley yields were found in plots with rotations, compared to continuous barley, in one of two comparisons (2,716 vs 2,192 kg/ha). Similar wheat yields were found in plots with or without rotations (1,981–2,125 vs 2,272 kg/ha). Similar aboveground biomass was found in cereal plots with or without rotations (6–9 vs 7–8 t/ha). **Methods:** Continuous wheat (one plot), continuous barley (one plot), a wheat-barley-rapeseed *Brassica napus* rotation (one plot/phase), or a wheat-barley-vetch *Vicia sativa* rotation (one plot/phase) were grown in each of three blocks. Each plot was 50 x 8 m. Wheat and barley were sown in early November (450 seeds/m^2). Vetch and rapeseed were sown in late September to early October (150 and 80 seeds seeds/m^2, respectively). Fertilizer was used on all plots (except vetch phases) in January and February. Herbicide was used in all plots.

A replicated, randomized, controlled study in 2003–2005 in a rainfed winter wheat field in Central Anatolia, Turkey (6), found higher wheat yields in plots with rotations, compared to continuous wheat. **Crop yield:** Wheat yields were higher in plots with rotations (1,320–2,243 vs 543 kg grain/ha). **Methods:** Wheat was grown continuously (three plots) or in rotation with one of five other phases (three plots each: winter lentil, chickpea, sunflower, spring lentil, or fallow). Each plot was 5 x 15 m. All plots were fertilized. Before the experiment, these rotations had been used for 21 years in this field. The wheat was harvested in July.

A replicated, controlled study in 1991–2009 in a rainfed durum wheat field in Sicily, Italy (7), found higher wheat yields, and higher protein content in wheat, in plots with rotations, compared to continuous wheat. **Crop yield:** Wheat yields were higher in plots with rotations (4.2–4.7 vs 3.2 mg grain/ha). **Crop quality:** Wheat protein content was higher in plots with rotations (141–143 vs 136 g protein/kg grain). **Implementation options:** Wheat yields were higher in rotations with faba beans, compared to rotations with berseem clover (4.7 vs 4.2 mg/ha). **Methods:** Continuous durum wheat *Triticum durum*, or durum wheat in rotation with faba bean *Vicia faba* or berseem clover *Trifolium alexandrinum*, was grown in three subplots each (in plots with conventional, reduced, or no tillage), in each of two blocks (one phase of each rotation in each block, each year). Each subplot was 18.5 x 20 m. The seeds were sown in December, and the wheat was harvested in May. All plots were fertilized (wheat: 69 kg/ha P_2O_5 before planting and 120 kg N/ha after; beans or clover: 46 kg/ha P_2O_5 before planting and 80 kg N/ha after). Herbicide was used in all plots. Wheat straw was removed from all plots, but bean and clover straw was not. Yield was measured in three samples areas/plot/year (8.6 x 8.6 m areas).

A replicated, randomized, controlled study in 2009–2010 in a rainfed wheat field in the Wongan Hills, Western Australia (8), found similar wheat yields in plots preceded by lupins or wheat. **Crop yield:** In 2010, wheat yields were similar in plots preceded by lupins or wheat (1.4 t/ha). **Methods:** Wheat or lupin *Lupinus angustifolius* was planted on six 150 m^2 plots each, in June 2009. In June 2010, wheat was planted on all plots. Lime was added to half of the plots (3.5 t/ha). Different fertilizers were used on each crop (e.g., no nitrogen was used on lupin). No plots were tilled.

A replicated, randomized, controlled study in 2010–2011 in a rainfed field in Western Australia (9), found similar wheat yields in plots preceded by canola or wheat. **Crop yield:** Similar wheat yields were found in plots preceded by canola or wheat (2,500 vs 2,600 kg/ha). **Methods:** Wheat or canola was grown on three plots each, in 2010, and wheat was grown on all plots in 2011. Each plot was 1.4 x 40 m. Fertilizer (150 kg/ha/year) and herbicide were used on all plots. Yield was measured in 2011.

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2.9. Use no tillage in arable fields: Crop production (23 studies)

- **Crop yield (23 studies)**
  - Crops (22 studies): Eight replicated, controlled studies (seven randomized) from Italy[14,18] and Spain[11-13,20-22] found higher crop yields in plots with no tillage, compared to conventional tillage, in some comparisons[11,12,18,22] or all comparisons[13,14,20,21]. Seven replicated, controlled studies (six randomized) from Italy[3], Lebanon[8], Spain[5,7,19], and the USA[1,6] found lower crop yields in plots with no tillage, compared to conventional tillage, in some comparisons[3,6-8,19] or all comparisons[1,5]. Four replicated, randomized controlled studies from Italy[17,23] and Spain[4,10] found inconsistent differences in crop yields (sometimes higher with no tillage, sometimes lower). Three replicated, controlled studies (two randomized) from Italy[16], Portugal[9], and Spain[2] found similar crop yields in plots with or without tillage.
  - Crop residues (5 studies): Two replicated, randomized, controlled studies from Lebanon[8] and Spain[15] found higher straw yields in plots with no tillage, compared to conventional tillage, in some comparisons. One replicated, randomized, controlled study from Spain[11] found inconsistent straw yields (sometimes higher with no tillage, sometimes lower). Two replicated, controlled studies (one randomized) from Italy[14] and Spain[22] found similar straw yields in plots with or without tillage.
- **Crop quality (6 studies):** One replicated, controlled study from Italy[16] found less protein in wheat grains from plots with no tillage, compared to conventional tillage. One replicated, randomized, controlled study from Spain[20] found heavier cereal grains in plots with no tillage, compared to conventional tillage. Two replicated, randomized, controlled studies from Spain[19,22] found other differences in crop quality, but two replicated, controlled studies from Italy[14] and the USA[1] did not.

A replicated, controlled study in 1996–1998 in an irrigated tomato field in the San Joaquin Valley, California, USA (1), found lower tomato yields in plots with no tillage (and winter cover crops), compared to tillage (and winter fallows). **Crop yield:** Lower tomato yields were found in plots with no tillage, compared to tillage, in four of 16 comparisons (27–36 vs 39–42 tons/acre). **Crop quality:** Similar amounts of soluble solids were found in tomatoes in the treatment and control plots (data not reported). **Methods:** There were 12 plots (4.5 x 27.5 m plots) for each of four treatments (two grass-legume mixtures, or two legumes without grasses, as winter cover crops, sown in October 1996–1997, killed and retained as mulch, with no tillage, in March 1997–1998) and each of two controls (bare-soil fallows in winter, with or without herbicide, and conventional tillage in spring). Tomato seedlings were transplanted in April 1997–1998 and harvested in August 1997 and September 1998. The tomatoes were irrigated (two inches/week) and fertilized (0, 100, or 200 lb N/acre). It was not clear whether these results were a direct effect of cover crops or tillage.

A replicated, randomized, controlled study in 1983–1996 in a rainfed wheat field in the Henares river valley, Spain (2), found similar crop yields in plots with no tillage or conventional tillage. **Crop yield:** Similar wheat yields were found in plots with no tillage or conventional tillage (2.7 vs 2.5 Mg/ha). **Methods:** No tillage or conventional tillage was used on four plots each. Each plot had two subplots (20 x 30 m, with or without crop rotation). A mouldboard plough (30 cm depth, in autumn) and a tine cultivator (10–15 cm depth, two passes, in spring) were used for conventional tillage. A seed drill and pre-emergence herbicide were used for no tillage. Fertilizer and post-emergence herbicide were used on all plots. Wheat was harvested at maturity (July 1996), and yield was measured in two strips/subplot (1.4 x 30 m strips).

A replicated, randomized, controlled study in 1993–2001 in a rainfed cereal field in central Italy (3) found lower crop yields in plots with no tillage, compared to conventional tillage. **Crop yield:** Lower grain yields were found in plots with no tillage, compared to conventional tillage, in five of seven years (data not reported). **Methods:** Conventional tillage or no tillage was used on 48 plots each (21 x 11 m sub-sub-plots, in a split-split-plot experimental design), from 1994–2000. A mouldboard plough (30 cm depth, in spring) and a standard precision seed drill were used for conventional tillage. A direct seed drill was used for no tillage. Herbicide and fertilizer were used on all plots. Winter cover crops were grown on three of four plots, and cereal crop residues were retained over winter on one of four plots.

A replicated, randomized, controlled study in 1996–1999 in three rainfed barley fields in the Ebro river valley, Spain (4) (same study as (11-13,15)), found that tillage had inconsistent effects on crop yield. **Crop yield:** Higher grain yields were found in plots with no tillage, compared to conventional tillage, in two of nine comparisons (3,645–5,420 vs 1,557–4,229 kg/ha), but lower grain yields were found in two of nine comparisons (770–1,247 vs 1,672–1,888 kg/ha). **Methods:** No tillage or conventional tillage was used on 27 plots each (50 x 6 m plots). A mouldboard plough (25–30 cm depth) and a cultivator (15 cm depth, 1–2 passes) were used for conventional tillage, in August–September. Herbicide was used for no tillage. Two-thirds of the plots were fertilized (50–75 or 100–150 kg N/ha). Barley was sown, with a seed drill, in October–November.

A replicated, randomized, controlled study in 1993–1997 in a rainfed barley field near Madrid, Spain (5), found lower crop yields in plots with no tillage, compared to conventional tillage. **Crop yield:** Lower barley yields were found in plots with no tillage, compared to conventional tillage (1995–1997: 3,593 vs 4,312 kg/ha). **Methods:** No tillage or conventional tillage was used on four plots each (five 10 x 25 m subplots/plot, with barley monocultures or barley rotations). A mouldboard plough (30 cm depth) and a cultivator (10–15 cm depth, when needed for weed control) were used for conventional tillage. Pre-emergence herbicide was used for no tillage. The barley was fertilized (NPK: 200 kg/ha; ammonium nitrate: 200 kg/ha).

A replicated, randomized, controlled study in 2003–2004 in an irrigated field in Davis, California, USA (6), found lower crop yields in plots with no tillage, compared to conventional tillage. **Crop yield:** Lower chickpea yields were found in plots with no tillage, compared to conventional tillage, in one of two comparisons (with continuous cropping: 25 vs 193 g dry weight/m^2). **Methods:** No tillage or conventional tillage was used on six plots each (67 x 4.7 m plots, three beds/plot). All plots had *Cicer arietinum* chickpeas (garbanzo beans) in rotation with other crops. Crop residues were incorporated to 20 cm depth, and the beds were shaped, on plots with conventional tillage (disk, lister, and ring roller). Crop residues were flail mown and spread on the plots with no tillage. All plots were fertilized in 2003, but not thereafter (112 kg P/ha phosphorous, 50 kg NPK/ha, and 67 kg N/ha). Cultivation was used to control weeds on plots with conventional tillage. Hand weeding was used on plots with no tillage. Herbicide was used on all plots. Some plots were irrigated. Chickpeas were harvested on 28 June 2004.

A replicated, randomized, controlled study in 2002–2005 on three rainfed farms in the Ebro river valley, Spain (7), found lower crop yields in plots with no tillage, compared to conventional tillage. **Crop yield:** Lower barley yields were found in plots with no tillage, compared to conventional tillage, in four of 10 comparisons (730–3,083 vs 1,314–3,514 kg/ha). **Methods:** No tillage or conventional tillage was used on ten plots each (Peñaflor: three plots each, 33 x 10 m plots; Agramunt: four plots each, 9 x 50 m plots; Selvanera: three plots each, 7 x 50 m plots). In Peñaflor, a mouldboard plough (30–40 cm depth) and a cultivator (10–15 cm depth) were used for conventional tillage. In Agramunt, a mouldboard plough (25–30 cm depth) and a cultivator (15 cm depth) were used for conventional tillage. In Selvanera, a subsoil plough (40 cm depth) and a cultivator (15 cm depth) were used for conventional tillage. Herbicide and a seed drill were used for no tillage.

A replicated, randomized, controlled study in 2005–2007 in a rainfed field in the central Bekaa Valley, Lebanon (8), found lower seed yields, but higher straw yields, in plots with no tillage, compared to conventional tillage. **Crop yield:** Lower seed yields were found in plots with no tillage, compared to conventional tillage, in one of three crops (barley seeds: 3,550 vs 4,550 kg/ha), but higher straw yields were found in one of three crops (safflower straw: 9,950 vs 9,050). **Methods:** No tillage or conventional tillage was used on four plots each (14 x 6 m), in October. Conventional plots were ploughed (25–30 cm depth) and then shallowly disk-cultivated. Barley, chickpeas, and safflower were planted in November. Barley and safflower were fertilized (60–100 kg N/ha). Mature crops were collected in three quadrats/plot (0.25 m^2 quadrats).

A replicated, randomized, controlled study in 2003–2005 in an occasionally irrigated oat field in Portugal (9) found similar crop yields in plots with or without tillage. **Crop yield:** Similar oat yields were found in plots with or without tillage (4.2 t/ha). **Methods:** Tillage or no tillage was used on four plots each (400 m^2 plots). A disk plough was used for tillage (two passes, 15 cm depth). The plots were intercropped with oats and *Lupinus albus* lupins in 2003–2004 (residues were retained, and incorporated into the soil in the plots with tillage) and oats were grown in monoculture in 2004–2005. The plots were fertilized in 2003–2004 (60 kg P/ha; 100 kg N/ha), but not in 2004–2005.

A replicated, randomized, controlled study in 1986–2008 in a rainfed wheat field in southern Spain (10) found that tillage had inconsistent effects on crop yields. **Crop yield:** Higher wheat yields were found in plots with no tillage, compared to conventional tillage, in two of five comparisons (3,482–4,698 vs 2,463–3,926 kg/ha), but lower yields were found in one of five comparisons (4,571 vs 5,216 kg/ha). **Methods:** No tillage or conventional tillage was used on three plots each (five subplots/plot, 10 x 5 m subplots, with different wheat rotations). Mouldboard ploughing, disk harrowing, and/or vibrating tine cultivation was used for conventional tillage (depth not reported). Pre-emergence herbicide was used for no tillage. The wheat phase was fertilized with nitrogen in some sub-subplots (0–150 kg N/ha/year) and phosphorus in all plots (65 kg P/ha/year). Crop residues were retained. Wheat yields were measured in 2008.

A replicated, randomized, controlled study in 1996–2009 in a rainfed barley field in the Ebro river valley, Spain (11) (same study as (4,12,13,15)), found that tillage had inconsistent effects on the yield of barley straw. **Crop yield:** More barley straw was found in plots with no tillage, compared to conventional tillage, in one of six comparisons (511 vs 242 g/m^2), but less barley straw was found in one of six comparisons (332 vs 541). In one of three years, the barley crop failed with conventional tillage, but not with no tillage. **Methods:** No tillage or conventional tillage was used on nine plots each (50 x 6 m plots). A mouldboard plough was used for conventional tillage (25–30 cm depth, 100% incorporation of crop residues). A seed drill and herbicide were used for no tillage. Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Mature barley was harvested in June 2006–2009 (three samples/plot, 50 cm of one row/sample).

A replicated, randomized, controlled study in 1996–2009 in a rainfed barley field in the Ebro river valley, Spain (12) (same study as (4,11,13,15)), found higher crop yields in plots with no tillage, compared to conventional tillage. **Crop yield:** Higher barley yields were found in plots with no tillage, compared to conventional tillage, in six of nine comparisons (1,350–2,500 vs 300–700 kg/ha). **Methods:** No tillage or conventional tillage was used on nine plots each (50 x 6 m plots). A mouldboard plough was used for conventional tillage (25–30 cm depth, 100% incorporation of crop residues), in October or November. A seed drill and herbicide were used for no tillage. Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Mature barley was harvested in June 2006–2009.

A replicated, randomized, controlled study in 1996–2009 in a rainfed barley field in the Ebro river valley, Spain (13) (same study as (4,11,12,15)), found higher barley yields in plots with no tillage, compared to conventional tillage. **Crop yield:** Higher barley yields were found in plots with no tillage, compared to conventional tillage (2,062 vs 1,155 kg/ha). **Methods:** No tillage or conventional tillage was used on nine plots each (50 x 6 m plots). A mouldboard plough was used for conventional tillage (25–30 cm depth, 100% incorporation of crop residues), in October or November. A seed drill and herbicide were used for no tillage. Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Mature barley was harvested in June 2006–2009.

A replicated, controlled study in 1991–2009 in a rainfed faba bean field in Sicily, Italy (14), found higher crop yields, but no differences in crop quality, in plots with no tillage, compared to conventional tillage. **Crop yield:** Higher faba bean yields were found in plots with no tillage, compared to conventional tillage (2.36 vs 1.80 Mg grain/ha), but no differences in straw yields were found (3.93 vs 3.86 Mg straw/ha). **Crop quality:** No differences were found in faba bean seed weight (99 vs 98 g/100 seeds), or the number of seeds/pod (2.7 vs 2.6), in plots with no tillage, compared to conventional tillage. **Methods:** No tillage or conventional tillage was used on two plots each (18.5 x 20 m plots). A mouldboard plough (30 cm depth; in summer) and a harrow (depth not reported; before sowing) were used for conventional tillage. Herbicide (before sowing) and a seed drill were used for no tillage. In all plots, a hoe was used to control weeds (depth not reported; 1–2 times/year). Faba beans were grown in rotation with durum wheat. During durum wheat growth, herbicide was used in all plots. All plots were fertilized (46 kg P_2O_5/ha). Faba beans were sown in December and harvested at maturity (month not reported). Yield and quality were measured in three samples/plot (four rows/sample, 3 m rows).

A replicated, randomized, controlled study in 1996–2008 in a rainfed barley field in the Ebro river Valley, Spain (15) (same study as (4,11-13)), found more barley straw in plots with no tillage, compared to conventional tillage, in two of three comparisons. **Crop yield:** More barley straw was found in plots with no tillage, compared to conventional tillage, in two of three comparisons (2,083–2,265 vs 1,571–1,748 kg/ha). **Methods:** There were nine plots (50 x 6 m) for each of two tillage treatments (no tillage: pre-emergence herbicide; conventional tillage: mouldboard plough, 25–30 cm depth). Plots were tilled in October or November. Two-thirds of the plots were fertilized (60 or 120 kg N/ha/year). Barley was harvested in June.

A replicated, controlled study in 1991–2009 in a rainfed wheat field in Sicily, Italy (16), found less protein in wheat that was grown on plots with no tillage, compared to conventional tillage. **Crop yield:** Similar wheat yields were found in plots with no tillage or conventional tillage (4 Mg/ha). **Crop quality:** Less protein was found in wheat that was grown in plots with no tillage, compared to conventional tillage (135 vs 144 g/kg). **Methods:** No tillage or conventional tillage was used on six plots each (19 x 20 m subplots). Conventional tillage was mouldboard ploughing in summer (30 cm depth) and harrowing before planting (two passes). No tillage was direct drilling and pre-emergence herbicide. The plots had either faba bean-wheat, clover-wheat, or wheat-wheat rotations. Fertilizer and post-emergence herbicide were used on all plots. Yield was measured in three samples/plot/year (8.6 x 8.6 m), in 1996–2009.

A replicated, randomized, controlled study in 2009–2011 in two irrigated pepper fields in central Italy (17) found that tillage had inconsistent effects on crop yields. **Crop yield:** Higher pepper yields were found in plots with no tillage, compared to conventional tillage, in five of eight comparisons (14–38 vs 6–20 t/ha, fresh weight), but lower yields were found in one of eight comparisons (21 vs 26). **Methods:** A mouldboard plough (30 cm depth) was used on all plots in autumn, before winter cover crops were planted. Cover crops were mown or chopped in spring, before tillage. No tillage or conventional tillage was used on 12 plots each (6 x 12 m plots), in May 2010–2011. A mouldboard plough (30 cm depth) and a disk (two passes) were used for conventional tillage (which incorporated the cover crop residues into the soil). Cover crop residues were mulched and herbicide was used for no tillage. Pepper seedlings were transplanted into the plots in May, and fruits were harvested twice/year in August–October 2010–2011. All plots were fertilized before the cover crops, but not after. All plots were irrigated.

A replicated, randomized, controlled study in 2009–2012 in two irrigated vegetable fields in central Italy (18) found higher crop yields in plots with no tillage, compared to conventional tillage. **Crop yield:** Higher crop yields were found in plots with no tillage, compared to conventional tillage, in two of six comparisons (in plots with hairy vetch as a winter cover crop: 23 vs 17 t/ha endive; 23 vs 15 t/ha savoy cabbage; fresh weights). **Methods:** No tillage or conventional tillage was used on nine plots each (6 x 4 m plots). Each plot had a winter cover crop (hairy vetch, oats, or oilseed rape). Cover crops were sown in September 2009–2010 and suppressed in May 2010–2011. A mouldboard plough and a disk harrow (two passes) were used for conventional tillage (incorporating the cover crop residues to 30 cm depth). The cover crop residues were gathered into strips of mulch (50 cm wide, along crop rows) in plots with no tillage. Pepper seedlings were transplanted into these plots in May 2010–2011 and were last harvested in October 2010 and September 2011. After the pepper harvest, endive and savoy cabbage seedlings were transplanted into these plots, and they were harvested in December 2010 and November 2011 (endive) or March 2011 and February 2012 (cabbage). No fertilizer was added while the crops were growing, but the plots were irrigated. It was not clear whether these results were a direct effect of tillage or mulch.

A replicated, randomized, controlled study in 2008–2013 in a rainfed wheat-sunflower-pea field near Seville, Spain (19), found lower crop yields, and differences in crop quality, in plots with no tillage, compared to conventional tillage. **Crop yield:** Lower crop yields were found in plots with no tillage, compared to conventional tillage, in two of five comparisons (sunflower seeds in 2013: 105 vs 3,520 kg/ha; wheat grain in 2012: 2,940 vs 3,860 kg/ha). **Crop quality:** Less oil, less of nine nutrients, more saturated and monounsaturated fatty acid, and less polyunsaturated fatty acid were found in sunflower seeds in plots with no tillage, compared to conventional tillage (34% vs 48% oil; see publication for other results). **Methods:** No tillage or conventional tillage was used on three plots each (6 x 33.5 m plots). A mouldboard plough (25–30 cm depth), a chisel plough (25 cm depth, twice/year), and a disk harrow (12 cm depth) were used for conventional tillage. A seed drill and herbicide were used for no tillage. Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. Sunflowers were sown in May 2013 (three months later than usual) and harvested in September. Yield and quality were measured in 16 sunflower heads/plot.

A replicated, randomized, controlled study in 1987–2010 in rainfed cereal fields in the Ebro river valley, Spain (20), found higher crop yields in plots with no tillage, compared to conventional tillage. **Crop yield:** Higher grain yields were found in plots with no tillage, compared to conventional tillage (4,449 vs 4,210 kg/ha). **Crop quality:** Heavier grains were found in plots with no tillage, compared to conventional tillage (35 vs 32 mg/grain). **Methods:** No tillage or conventional tillage was used on ten plot each (Peñalba: three plots each, 34 x 175 m plots, established in 2005; Agramunt: four plots each, 9 x 50 m plots, established in 1990; Selvanera: three plots each, 7 x 50 m plots, established in 1987). In Peñalba, a disk plough (20 cm depth) and a cultivator (10 cm depth) were used for conventional tillage. In Agramunt, a mouldboard plough (25 cm depth) and a cultivator (15 cm depth) were used for conventional tillage. In Selvanera, a subsoil plough (40 cm depth) and a chisel plough (15 cm depth) were used for conventional tillage. Herbicide was used for no tillage. Barley (Peñalba) or wheat (Agramunt and Selvanera) was planted in November 2009 with a seed drill (2–4 cm depth) and harvested in June–July 2010.

A replicated, randomized, controlled study in 1996–2013 in two rainfed barley fields in northeast Spain (21) found higher crop yields in plots with no tillage, compared to conventional tillage. **Crop yield:** Higher barley yields were found in plots with no tillage, compared to conventional tillage (1,554–5,692 vs 246–2,263 kg/ha). **Methods:** No tillage or conventional tillage was used on three plots each, in each of two fields (from 2010–2013 in the short-term field, and from 1996–2013 in the long-term field; plots size not clearly reported). A mouldboard plough (25 cm depth) and a cultivator (15 cm depth) were used for conventional tillage in the long-term field, and a chisel plough was used in the short-term field (depth not reported), in September–October. For no tillage, the residues were chopped and spread, and pre-emergence herbicide was used. Some plots were fertilized (0–150 kg N/ha). Crop yield was measured in 2011 (short-term field) and 2011–2013 (long-term field; the reported yield was the sum of three years).

A replicated, randomized, controlled study in 1994–2009 in a pea field near Madrid, Spain (22), found higher pea yields and different crop qualities in plots with no tillage, compared to conventional tillage. **Crop yield:** Higher pea yields were found in plots with no tillage, compared to conventional tillage, in one of four comparisons (0.6 vs 0.3 t/ha), but no differences in straw yields were found (2.6–3.5 vs 2.3–3.3 t/ha). **Crop quality:** Smaller peas were found in plots with no tillage, compared to conventional tillage, in one of four comparisons (238 vs 267 g/1,000 peas). Longer pea pods were found in plots with no tillage, compared to conventional tillage, in one of four comparisons (7.0 vs 6.5 cm), but shorter pods, with fewer peas, were found in one of four comparisons (5.9 vs 6.6 cm pods, 5.4 vs 6.4 peas/pod). **Methods:** No tillage or conventional tillage was used on four plots each (each with three 10 x 25 m sub-plots, with different pea-cereal rotations), in October or November. A mouldboard plough was used for conventional tillage (30 cm depth). A seed drill and herbicide were used for no tillage. Peas were planted in November 2005–2008 and harvested in June 2006–2009. The peas were not fertilized.

A replicated, randomized, controlled study in 2009–2011 in an irrigated eggplant field in central Italy (23) found that tillage had inconsistent effects on crop yield. **Crop yield:** Higher eggplant yields were found in plots with no tillage, compared to conventional tillage, in two of four comparisons (18–38 vs 14–32 Mg/ha fresh weight), but lower yields were found in one of four comparisons (11 vs 18). **Methods:** A mouldboard plough (30 cm depth) was used on all plots in autumn, before the winter cover crops were planted. The cover crops were mown or chopped in spring, before tillage. No tillage or conventional tillage was used on 12 plots each (6 x 4 m plots). A mouldboard plough (30 cm depth) and a disk (two passes) were used for conventional tillage (which incorporated the cover crop residues into the soil). Cover crop residues were mulched and herbicide was used for no tillage. Eggplant seedlings were transplanted into the plots in May, and fruits were harvested four times/year in July–September 2010–2011. All plots were fertilized before the cover crops were grown, but not after. All plots were irrigated.

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2.10. Use no tillage instead of reduced tillage: Crop production (15 studies)

- **Crop yield (15 studies)**
  - Cereals (7 studies): Three replicated, randomized, controlled studies from Spain[2,4,13] found higher cereal yields in plots with no tillage, compared to reduced tillage. One of these studies[2] also found lower cereal yields in some comparisons. One replicated, randomized, controlled study from Spain[11] found lower cereal yields in plots with no tillage, compared to reduced tillage, in some comparisons. Three replicated, randomized, controlled studies from Australia[12], Lebanon[3], and Spain[1] found similar cereal yields in plots with no tillage or reduced tillage, in all comparisons.
  - Fruits and vegetables (3 studies): Three replicated, randomized, controlled studies from Italy[9,10,15] found lower fruit or vegetable yields in plots with no tillage, compared to reduced tillage, in some comparisons. Two of these studies[9,15] also found higher yields, in some comparisons.
  - Legumes (3 studies): Two replicated, controlled studies from Italy[7] and Spain[14] found higher legume yields in plots with no tillage, compared to reduced tillage, in some

comparisons[14] or all comparisons[7]. One replicated, controlled study from Lebanon[3] found similar legume yields in plots with no tillage, compared to reduced tillage, in all comparisons.

  - Oilseeds (1 study): One replicated, randomized, controlled study from Spain[11] found lower sunflower seed yields in plots with no tillage, compared to reduced tillage, in some comparisons.
  - Crop residues (6 studies): Three replicated, controlled studies from Lebanon[3] and Spain[8,14] found higher straw yields in plots with no tillage, compared to reduced tillage, in some comparisons[8,14] or all comparisons[3]. One replicated, randomized, controlled study from Spain[5] found lower straw yields in plots with no tillage, compared to reduced tillage. Two replicated, controlled studies from Italy[7] and Spain[6] found similar straw yields in plots with no tillage or reduced tillage, in all comparisons.

- **Crop quality (3 studies):** One replicated, randomized, controlled study from Spain[14] found larger peas, and more peas in a pod, in plots with no tillage, compared to reduced tillage, in one of four comparisons. One replicated, controlled study from Italy[7] found similarly sized faba beans, and similar numbers of beans in a pod, in plots with no tillage, compared to reduced tillage. One replicated, randomized, controlled study from Spain[11] found differences in the nutritional values of sunflower seeds in plots with no tillage, compared to reduced tillage.

A replicated, randomized, controlled study in 1983–1996 in a rainfed wheat field in the Henares river valley, Spain (1), found similar crop yields in plots with no tillage or reduced tillage. **Crop yield:** Similar wheat yields were found in plots with no tillage or reduced tillage (2.7 vs 2.6 Mg/ha). **Methods:** No tillage or reduced tillage was used on four plots each. Each plot had two subplots (20 x 30 m, with or without crop rotations). A chisel plough (20 cm depth, in autumn) and a tine cultivator (10–15 cm depth, two passes, in spring) were used for reduced tillage. A seed drill and pre-emergence herbicide were used for no tillage. Fertilizer and post-emergence herbicide were used on all plots. Wheat was harvested at maturity (July 1996), and yield was measured in two strips/subplot (1.4 x 30 m strips).

A replicated, randomized, controlled study in 1996–1999 in three rainfed barley fields in the Ebro river valley, Spain (2), found that tillage had inconsistent effects on crop yields. **Crop yield:** Higher grain yields were found in plots with no tillage, compared to reduced tillage, in one of nine comparisons (3,645 vs 2,507 kg/ha), but lower grain yields were found in two of nine comparisons (770–1,247 vs 1,043–1,749 kg/ha). **Methods:** No tillage or reduced tillage was used on 27 plots each (50 x 6 m plots). A cultivator (10–15 cm depth, 1–2 passes) was used for reduced tillage, in September. Herbicide was used for no tillage. Two-thirds of the plots were fertilized (50–75 or 100–150 kg N/ha). Barley was sown, with a seed drill, in October–November (month of harvest not reported).

A replicated, randomized, controlled study in 2005–2007 in a rainfed field in the central Bekaa Valley, Lebanon (3), found higher seed and straw yields in plots with no tillage, compared to reduced tillage. **Crop yield:** Higher seed and straw yields were found in plots with no tillage, compared to reduced tillage, in one of three crops (safflower seed: 2,600 vs 1,900 kg/ha; safflower straw: 9,950 vs 7,450). **Methods:** No tillage or reduced tillage (shallow disc cultivation, 10 cm depth) was used in four plots each (14 x 6 m), in October. Barley, chickpeas, and safflower were planted in November. Barley and safflower were fertilized (60–100 kg N/ha). Mature crops were collected in three quadrats/plot (0.25 m^2 quadrats).

A replicated, randomized, controlled study in 1996–2009 in a rainfed barley field in the Ebro river valley, Spain (4) (same study as (5,6)), found higher barley yields in plots with no tillage, compared to reduced tillage. **Crop yield:** Higher barley yields were found in plots with no tillage, compared to reduced tillage (2,062 vs 1,792 kg/ha). **Methods:** No tillage or reduced tillage was used on nine plots each (50 x 6 m plots). A cultivator was used for reduced tillage (10–15 cm depth, 50% incorporation of crop residues), in October or November. A seed drill and herbicide were used for no tillage. Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Mature barley was harvested in June 2006–2009.

A replicated, randomized, controlled study in 1996–2009 in a rainfed barley field in the Ebro river valley, Spain (5) (same study as (4,6)), found similar crop yields in plots with no tillage or reduced tillage. **Crop yield:** Similar barley yields were found in plots with no tillage, compared to reduced tillage (1,350–4,400 vs 1,050–4,100 kg/ha). **Methods:** No tillage or reduced tillage was used on nine plots each (50 x 6 m plots). A cultivator was used for reduced tillage (10–15 cm depth, 50% incorporation of crop residues), in October or November. A seed drill and herbicide were used for no tillage. Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Mature barley was harvested in June 2006–2009.

A replicated, randomized, controlled study in 1996–2009 in a rainfed barley field in the Ebro river valley, Spain (6) (same study as (4,5)), found less barley straw in plots with no tillage, compared to reduced tillage, in one of nine comparisons. **Crop yield:** Less barley straw was found in plots with no tillage, compared to reduced tillage, in one of nine comparisons (321 vs 456 g/m^2). **Methods:** No tillage or reduced tillage was used on nine plots each (50 x 6 m plots). A cultivator was used for reduced tillage (10–15 cm depth, 50% incorporation of crop residues). A seed drill and herbicide were used for no tillage. Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Mature barley was harvested in June 2006–2009 (three samples/plot, 50 cm of one row/sample).

A replicated, controlled study in 1991–2009 in a rainfed faba bean field in Sicily, Italy (7), found higher crop yields, and no differences in crop quality, in plots with no tillage, compared to reduced tillage. **Crop yield:** Higher faba bean yields were found in plots with no tillage, compared to reduced tillage (2.36 vs 1.91 Mg grain/ha), but no differences in straw yields were found (3.93 vs 3.80 Mg straw/ha). **Crop quality:** No differences were found in faba bean seed weight (99 g/100 seeds), or number of seeds/pod (2.7 vs 2.6), in plots with no tillage, compared to reduced tillage. **Methods:** No tillage or reduced tillage was used on two plots each (18.5 x 20 m plots). A chisel plough (40 cm depth), a mouldboard plough (15 cm depth, in 1991–1998), and a harrow (depth not reported; before sowing) were used for reduced tillage. Herbicide (before sowing) and a seed drill were used for no tillage. In all plots, a hoe was used to control weeds (depth not reported; 1–2 times/year). Faba beans were grown in rotation with durum wheat. During durum wheat growth, herbicide was used in all plots. All plots were fertilized (46 kg P_2O_5/ha). Faba beans were sown in December and harvested at maturity (month not reported). Yield and quality were measured in three samples/plot (four rows/sample, 3 m rows).

A replicated, randomized, controlled study in 1996–2008 in a rainfed barley field in the Ebro river Valley, Spain (8), found more barley straw in plots with no tillage, compared to reduced tillage, in two of three comparisons. **Crop yield:** More barley straw was found in plots with no tillage, compared to reduced tillage, in two of three comparisons (2,083–2,265 vs 1,612–1,679 kg/ha). **Methods:** There were nine plots (50 x 6 m) for each of two tillage treatments (no tillage: pre-emergence herbicide and seed drill; reduced tillage: cultivator, 10–15 cm depth). Plots were tilled in October or

November. Two-thirds of the plots were fertilized (60 or 120 kg N/ha/year). Barley was harvested in June.

A replicated, randomized, controlled study in 2009–2011 in two irrigated pepper fields in central Italy (9) found that tillage had inconsistent effects on crop yields. **Crop yield:** Higher pepper yields were found in plots with no tillage, compared to reduced tillage, in four of eight comparisons (18–38 vs 7–18 t/ha, fresh weight), but lower yields were found in one of eight comparisons (10 vs 15). **Methods:** A mouldboard plough (30 cm depth) was used on all plots in autumn, before winter cover crops were planted. Cover crops were mown or chopped in spring, before tillage. No tillage or reduced tillage was used on 12 plots each (6 x 12 m plots), in May 2010–2011. A rotary hoe (10 cm depth) was used for reduced tillage (which incorporated the cover crop residues into the soil). Cover crop residues were mulched and herbicide was used for no tillage. Pepper seedlings were transplanted into the plots in May, and fruits were harvested twice/year in August–October 2010–2011. All plots were fertilized before the cover crops, but not after. All plots were irrigated.

A replicated, randomized, controlled study in 2009–2012 in two irrigated vegetable fields in central Italy (10) found lower crop yields in plots with no tillage, compared to reduced tillage. **Crop yield:** Lower crop yields were found in plots with no tillage, compared to reduced tillage, in one of six comparisons (in plots with oilseed rape as the winter cover crop: 5 vs 11 t/ha endive, fresh weight). **Methods:** Reduced tillage or no tillage was used on nine plots each (6 x 4 m plots). Each plot had a winter cover crop (hairy vetch, oats, or oilseed rape). Cover crops were sown in September 2009–2010 and suppressed in May 2010–2011. A rotary hoe was used for reduced tillage (incorporating the cover crop residues to 10 cm depth). The cover crop residues were gathered into strips of mulch (50 cm wide, along crop rows) in plots with no tillage. Pepper seedlings were transplanted into these plots in May 2010–2011 and were last harvested in October 2010 and September 2011. After the pepper harvest, endive and savoy cabbage seedlings were transplanted into these plots, and they were harvested in December 2010 and November 2011 (endive) or March 2011 and February 2012 (cabbage). No fertilizer was added while the crops were growing, but the plots were irrigated. It was not clear whether these results were a direct effect of tillage or mulch.

A replicated, randomized, controlled study in 2008–2013 in a rainfed wheat-sunflower-pea field near Seville, Spain (11), found lower crop yields and differences in crop quality in plots with no tillage, compared to reduced tillage, in some comparisons. **Crop yield:** Lower crop yields were found in plots with no tillage, compared to reduced tillage, in two of five comparisons (sunflower seeds in 2013: 105 vs 3,839 kg/ha; wheat grain in 2012: 2,940 vs 3,985 kg/ha). **Crop quality:** Less oil, more zinc, more saturated and polyunsaturated fatty acid, and less monounsaturated fatty acid were found in sunflower seeds in plots with no tillage, compared to reduced tillage (34% vs 50% oil; see publication for other results). **Methods:** No tillage or reduced tillage was used on three plots each (6 x 33.5 m plots). A chisel plough (25 cm depth), a disc harrow (5 cm depth), and herbicide were used for reduced tillage. A seed drill and herbicide were used for no tillage. Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. Sunflowers were sown in May 2013 (three months later than usual) and harvested in September. Yield and quality were measured in 16 sunflower heads/plot.

A replicated, randomized, controlled study in 2010–2011 in a rainfed wheat field in Australia (12) found similar crop yields in plots with no tillage or reduced tillage. **Crop yield:** Similar wheat yields were found in plots with no tillage or reduced tillage (2,600 kg/ha). **Methods:** No tillage or reduced tillage was used on three plots each (1.4 x 40 m plots) in 2010, when the plots were fallow. A rotary hoe (12 cm depth) was used for reduced tillage. Herbicide was used for no tillage. Wheat was grown on all plots in 2011. Fertilizer (150 kg/ha) and herbicides were used on all plots in 2011.

A replicated, randomized, controlled study in 1987–2010 in rainfed cereal fields in the Ebro river valley, Spain (13), found higher crop yields in plots with no tillage, compared to reduced tillage. **Crop yield:** Higher grain yields were found in plots with no tillage, compared to reduced tillage (4,449 vs 3,923 kg/ha). **Methods:** No tillage or reduced tillage was used on ten plot each (Peñalba: three plots each, 34 x 175 m plots, established in 2005; Agramunt: four plots each, 9 x 50 m plots, established in 1990; Selvanera: three plots each, 7 x 50 m plots, established in 1987). A cultivator (Peñalba: 10 cm depth; Agramunt: 15 cm) or a chisel plough (Selvanera: 15 cm) was used for reduced tillage. Herbicide was used for no tillage. Barley (Peñalba) or wheat (Agramunt and Selvanera) was planted in November 2009 with a seed drill (2–4 cm depth) and harvested in June–July 2010.

A replicated, randomized, controlled study in 1994–2009 in a rainfed pea-cereal field near Madrid, Spain (14), found higher pea yields, larger peas, and/or more peas/pod in plots with no tillage, compared to reduced tillage. **Crop yield:** Higher grain and straw yields were found in plots with no tillage, compared to reduced tillage, in one of four comparisons (peas, grain: 0.6 vs 0.08 t/ha; straw: 2.9 vs 1.5 t/ha). **Crop quality:** Larger peas and more peas/pod were found in plots with no tillage, compared to reduced tillage, in one of four comparisons (154 vs 80 g/1,000 peas; 5.4 vs 4.8 peas/pod), but no difference in the length of pea pods was found (5.9–7.0 vs 5.7–7.0 cm). **Methods:** No tillage or reduced tillage was used on four plots each (each with three 10 x 25 m sub-plots, with different pea-cereal rotations), in October or November. A chisel plough was used for reduced tillage (10 cm depth). A seed drill and herbicide were used for no tillage. Peas were planted in November 2005–2008 and harvested in June 2006–2009. The peas were not fertilized.

A replicated, randomized, controlled study in 2009–2011 in an irrigated eggplant field in central Italy (15) found that tillage had inconsistent effects on crop yield. **Crop yield:** Higher eggplant yields were found in plots with no tillage, compared to reduced tillage, in one of four comparisons (18 vs 7 Mg/ha fresh weight), but lower yields were found in two of four comparisons (11–18 vs 21–25). **Methods:** A mouldboard plough (30 cm depth) was used on all plots in autumn, before winter cover crops were planted. Cover crops were mown or chopped in spring, before tillage. No tillage or reduced tillage was used on 12 plots each (6 x 4 m plots). A rotary hoe (10 cm depth) was used for reduced tillage (which incorporated some of the cover crop residues into the soil). Cover crop residues were mulched and herbicide was used for no tillage. Eggplant seedlings were transplanted into the plots in May, and fruits were harvested four times/year in July–September 2010–2011. All plots were fertilized before the cover crops were grown, but not after. All plots were irrigated.

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2.11. Use reduced tillage in arable fields: Crop production (26 studies)

- **Crop yield (25 studies)**
  - Cereals (16 studies): Nine replicated, controlled studies from Egypt, France, Spain, and Turkey[3-5,7,11-14,25] found higher cereal yields in plots with reduced tillage, compared to conventional tillage, in some comparisons[3,5,11,13,14,25] or all comparisons[4,12]. Three of these studies[3,7,25] also found lower cereal yields in plots with reduced tillage, compared to conventional tillage, in some comparisons. Three replicated, randomized, controlled studies from Lebanon and Spain[6,10,22] found lower cereal yields in plots with reduced tillage, compared to conventional tillage. Four replicated, controlled studies from Italy, Spain, and the USA[1,9,18,21] found similar cereal yields in plots with reduced tillage or conventional tillage, in all comparisons. One replicated, randomized, controlled study

from Spain[14] found that crops failed in plots with conventional tillage, but not in plots with reduced tillage, in one of three comparisons.

- Fruits and vegetables (7 studies): Five replicated, randomized, controlled studies from Italy and the USA[2,8,20,24,26] found higher fruit or vegetable yields in plots with reduced tillage, compared to conventional tillage, in some comparisons. Two of these studies[2,26] also found lower fruit or vegetable yields in plots with reduced tillage, compared to conventional tillage, in some comparisons. Two replicated, controlled studies from Italy and the USA[16,19] found similar fruit yields in plots with reduced tillage or conventional tillage, in all comparisons. All fruit or vegetable plots were irrigated, in contrast to most cereal or legume plots.
- Legumes (3 studies): One replicated, randomized, controlled study from Spain[23] found lower legume yields in plots with reduced tillage, compared to conventional tillage, in one of four comparisons. Two replicated, controlled studies from Italy and Lebanon[10,15] found similar legume yields in plots with reduced tillage or conventional tillage, in all comparisons. No studies found higher legume yields in plots with reduced tillage, compared to conventional tillage.
- Oilseeds (1 study): One replicated, randomized, controlled study from Spain[7] found higher rapeseed yields in plots with reduced tillage, compared to conventional tillage.
- Crop residues (6 studies): Two replicated, randomized, controlled studies from Lebanon and Spain[10,23] found lower straw yields in plots with reduced tillage, compared to conventional tillage, in some comparisons. One replicated, randomized, controlled study from Spain[14] found higher straw yields in plots with reduced tillage, compared to conventional tillage, in some comparisons. Two replicated, controlled studies from Italy and Spain[15,17] found similar straw yields in plots with reduced tillage or conventional tillage, in all comparisons. One replicated, randomized, controlled study from the USA[24] found higher cover crop biomass in plots with reduced tillage, compared to conventional tillage.

- **Crop quality (7 studies):** One replicated, randomized, controlled study from Spain[21] found that sunflower seeds had more oil, more monounsaturated fatty acid, and less polyunsaturated fatty acid in plots with reduced tillage, compared to conventional tillage. One replicated, controlled study from Italy[18] found that wheat had a lower protein content in plots with reduced tillage, compared to conventional tillage. Two replicated, controlled studies from Italy and Turkey[4,15] found similar seed weights in plots with reduced tillage, compared to conventional tillage. One replicated, randomized, controlled study from the USA[2] found that lettuce or broccoli plants were larger in plots with reduced tillage, compared to conventional tillage, in some comparisons, but they were smaller in other comparisons.
- **Implementation options (2 studies):** One replicated, randomized, controlled study from Egypt[25] found higher wheat yields in plots that were tilled at slower speeds. One replicated, randomized, controlled study from Turkey[4] found higher wheat yields, but lower vetch yields, in plots with one type of reduced tillage (rototilling and disking), compared to another type (double disking).

A replicated, randomized, controlled study in 1983–1996 in a rainfed wheat field in the Henares river valley, Spain (1), found similar crop yields in plots with reduced tillage or conventional tillage. **Crop yield:** Similar wheat yields were found in plots with reduced tillage or conventional tillage (2.6 vs 2.5 Mg/ha). **Methods:** Conventional tillage or reduced tillage was used on four plots each. Each plot had two subplots (20 x 30 m, with or without crop rotations). A mouldboard plough (30 cm depth) was used for conventional tillage, in autumn. A chisel plough (20 cm depth) was used for reduced tillage, in autumn. A tine cultivator (10–15 cm depth, two passes) was used for both conventional and reduced tillage, in spring. Fertilizer and post-emergence herbicide were used on all plots. Wheat was harvested at maturity (July 1996), and yield was measured in two strips/subplot (1.4 x 30 m strips).

A replicated, randomized, controlled study in 1998–2000 in an irrigated vegetable field in the Salinas Valley, California, USA (2), found that tillage had inconsistent effects on crop yield and quality. **Crop yield:** Lower broccoli yields were found in plots with reduced tillage, compared to conventional tillage (610–620 vs 630–640 g dry weight/m^2). Higher lettuce yields were found in plots with reduced tillage, compared to conventional tillage, in two of six comparisons (310–410 vs 300–390 g dry weight/m^2), but lower lettuce yields were found in two of six comparisons (280–390 vs 300–430). **Crop quality:** Smaller lettuce or broccoli plants were found in plots with reduced tillage, compared to conventional tillage, in five of eight comparisons (lettuce: 750–1,080 vs 830–1,150 g fresh weight/plant; broccoli: 240 vs 270), but larger plants were found in two of eight comparisons (lettuce: 1,090 vs 1,050; broccoli: 230 vs 210). **Methods:** There were four plots (0.52 ha), for each of four treatments (reduced tillage or conventional tillage, with or without added organic matter). In plots with added organic matter, compost was added two times/year, and a cover crop (Merced rye) was grown every autumn or winter. Lettuce or broccoli crops were grown in raised beds. Sprinklers and drip irrigation were used in all plots. Soils were disturbed to different depths (conventional tillage: disking to 50 cm depth, cultivating, sub-soiling, bed re-making, and bed-shaping; reduced tillage: cultivating to 20 cm depth, rolling, and bed-shaping). Crops were collected in two 2 m^2 areas/plot.

A replicated, randomized, controlled study in 1996–1999 in three rainfed barley fields in the Ebro river valley, Spain (3) (same study as (12-14,17)), found that tillage had inconsistent effects on crop yields. **Crop yield:** Higher barley yields were found in plots with reduced tillage, compared to conventional tillage, in one of nine comparisons (2,507 vs 1,557 kg grain/ha), but lower barley yields were found in one of nine comparisons (1,043 vs 1,672 kg grain/ha). **Methods:** Reduced tillage or conventional tillage was used on 27 plots each (50 x 6 m plots). A mouldboard plough (25–30 cm depth) and a cultivator (15 cm depth, 1–2 passes) were used for conventional tillage, in August–September. A cultivator (10–15 cm depth, 1–2 passes) was used for reduced tillage, in September. Two-thirds of the plots were fertilized (50–75 or 100–150 kg N/ha). Barley was sown, with a seed drill, in October–November.

A replicated, randomized, controlled study in 2001–2004 in a rainfed wheat-vetch field in the Marmara region, Turkey (4) (same study as (5)), found higher wheat yields in plots with reduced tillage, compared to conventional tillage. Different types of reduced tillage had different effects on wheat and vetch yields. **Crop yield:** Higher wheat yields were found in plots with reduced tillage, compared to conventional tillage (4,821–5,057 vs 4,683 kg/ha), but similar vetch yields were found (2,462–3,764 vs 3,593 kg/ha). **Crop quality:** Similar seed weights were found in plots with reduced tillage or conventional tillage (35.8–38.9 vs 37.8 g/1,000 seeds). **Implementation options:** Higher wheat yields, but lower vetch yields, were found in plots that were rototilled and disked, compared to plots that were double disked (wheat: 5,057 vs 4,821 kg/ha; vetch: 2,462 vs 3,764), and similar seed weights were found (38.9 vs 35.8 g/1,000 seeds). **Methods:** Conventional tillage with a mouldboard plough (20–22 cm depth) and a double disc (two passes, 8–10 cm depth), reduced tillage with a rototiller (20–22 cm depth) and a double disc (one pass, 8–10 cm), or reduced tillage with a double disc (two passes, 8–10 cm) was used on three plots each (15 x 75 m plots). Fertilizer and herbicide were used on all plots. Wheat was sown in December 2001, October 2002, and November 2003. Vetch was sown in December 2001, November 2002, and December 2003. Wheat and vetch were harvested in June 2002–2004 (3 m^2 samples, three/plot).

A replicated, randomized, controlled study in 2001–2003 in a rainfed wheat field in northwest Turkey (5) (same study as (4)) found higher crop yields in plots with reduced tillage, compared to conventional tillage, in one of four comparisons. **Crop yield:** Higher wheat yields were found in plots with reduced tillage, compared to conventional tillage, in one of four comparisons (rototiller in 2002: 4,055 vs 3,540 kg/ha). **Methods:** Conventional tillage with a mouldboard plough, reduced tillage with a rototiller, or reduced tillage with a disc was used on three plots each (75 x 15 m plots). Fertilizer and herbicide were used on all plots. Winter wheat was planted in December 2001 and October 2002 and harvested in June 2002 and 2003. Crop yields were measured in three sections/plot (3 m^2 sections).

A replicated, randomized, controlled study in 1993-2000 in a rainfed field near Madrid, Spain (6), found lower crop yields in plots with reduced tillage, compared to conventional tillage. **Crop yield:** Lower barley yields were found in plots with reduced tillage, compared to conventional tillage (3,061 vs 4,312 kg/ha). **Methods:** Conventional tillage or reduced tillage was used on 20 subplots each (10 x 25 m subplots). Barley-barley, barley-vetch, or barley-fallow rotations were used on the subplots. A mouldboard plough (30 cm depth) was used for conventional tillage. A chisel plough (20 cm depth) was used for reduced tillage. Barley was fertilized, but vetch and fallows were not. Herbicide was used when needed. Barley was sown in October and harvested in June. Soil samples were collected after harvest (0–90 cm depth; nitrogen was measured at 0–30 cm depth; phosphorus and potassium at 0–80 cm depth).

A replicated, randomized, controlled study in 2002–2005 on three rainfed farms in the Ebro river valley, Spain (7), found that tillage had inconsistent effects on crop yield. **Crop yield:** Lower crop yields were found in plots with reduced tillage, compared to conventional tillage, in three of 10 comparisons (barley: 2,273–3,071 vs 2,493–3,514 kg/ha; wheat: 1,830 vs 2,703), but higher yields were found in two of 10 comparisons (rapeseed: 1,783 vs 1,261 kg/ha; wheat: 911 vs 798). **Methods:** Reduced tillage or conventional tillage was used on ten plots each (Peñaflor: three plots each, 33 x 10 m plots; Agramunt: four plots each, 9 x 50 m plots; Selvanera: three plots each, 7 x 50 m plots). In Peñaflor, a mouldboard plough (30–40 cm depth) and a cultivator (10–15 cm depth) were used for conventional tillage. In Agramunt, a mouldboard plough (25–30 cm depth) and a cultivator (15 cm depth) were used for conventional tillage. In Selvanera, a subsoil plough (40 cm depth) and a cultivator (15 cm depth) were used for conventional tillage. A cultivator (Agramunt and Selvanera: 15 cm depth) or chisel plough (Peñaflor: 25–30 cm depth) was used for reduced tillage.

A replicated, randomized, controlled study in 1999–2003 in an irrigated tomato-cotton field in the San Joaquin Valley, California, USA (8) (same study as (24)), found higher tomato yields in plots with reduced tillage, compared to conventional tillage. **Crop yield:** Higher tomato yields were found in plots with reduced tillage, compared to conventional tillage, in one of two comparisons (without winter cover crops: 58 vs 50 t/ha). **Methods:** Reduced tillage or conventional tillage was used on eight tomato plots each, in 1999–2003. The plots (9 x 82 m) had six raised beds each. Winter cover crops (triticale, rye, and vetch) were planted on half of the plots, in October 1999–2002, and crop residues were chopped in March. Different numbers of tillage practices were used for conventional tillage (19–23 tractor passes, including disc and chisel ploughing) and reduced tillage (11–12 tractor passes, not including disc and chisel ploughing). Tomato seedlings were transplanted in April 2000–2003. Fertilizer and herbicide were used in all plots. Tomatoes were grown in rotation with cotton.

A replicated, randomized, controlled study in 2003–2004 in three irrigated maize-tomato fields near Davis, California, USA (9), found similar crop yields in plots with reduced tillage or conventional tillage. **Crop yield:** Similar maize yields were found in plots with reduced tillage or conventional tillage (6.7–9.3 vs 4.1–13.6 Mg grain/ha). **Methods:** Reduced tillage or conventional tillage was used on nine plots each (1.5 x 1.0 m plots). Nine tillage practices, in 12–15 tractor passes, were used for conventional tillage. Five tillage practices, in 5–10 tractor passes, were used for reduced tillage. Maize seeds were sown with a seed drill in early May or mid-March. All plots were irrigated and fertilized with organic and/or inorganic fertilizer. Maize was harvested in September.

A replicated, randomized, controlled study in 2005–2007 in a rainfed field in the central Bekaa Valley, Lebanon (10), found lower seed and straw yields in plots with reduced tillage, compared to conventional tillage, in some crops. **Crop yield:** Lower seed yields were found in plots with reduced tillage, compared to conventional tillage, in two of three crops (barley: 3,250 vs 4,550 kg/ha; safflower: 1,900 vs 2,400), and lower straw yields were found in one of three crops (safflower: 7,450 vs 9,050). **Methods:** Reduced tillage or conventional tillage was used in four plots each (14 x 6 m), in October. Conventional plots were ploughed (25–30 cm depth) and then shallowly disc cultivated. Reduced plots were shallowly disc cultivated (10 cm depth). Barley, chickpeas, and safflower were planted in November. Barley and safflower were fertilized (60–100 kg N/ha). Mature crops were collected in three quadrats/plot (0.25 m^2 quadrats).

A replicated, controlled study in 2004–2008 in an irrigated maize field in the Garonne River corridor, southern France (11), found higher crop yields in plots with reduced tillage, compared to conventional tillage. **Crop yield:** Higher maize yields were found in plots with reduced tillage, compared to conventional tillage, in three of eight comparisons (11–12 vs 10–11 t/ha). **Methods:** Conventional tillage or reduced tillage was used on six plots each (20 x 50 m plots). Three of these plots had winter cover crops (white mustard or oats), and three had bare soil. A mouldboard plough (28–30 cm depth) and a cultivator (8 cm depth, 1–2 passes) were used for conventional tillage, in April–May. A cultivator (7–9 cm depth) and a disc harrow (8–12 cm depth) were used for reduced tillage, in March–April. Maize was sown in April–May 2005–2008 and harvested in October 2005–2008. A centre-pivot sprinkler was used for irrigation (857–943 mm water/year, irrigation plus rainfall).

A replicated, randomized, controlled study in 1996–2009 in a rainfed barley field in the Ebro river valley, Spain (12) (same study as (3,12-14,17)), found higher crop yields in plots with reduced tillage, compared to conventional tillage. **Crop yield:** Higher barley yields were found in plots with reduced tillage, compared to conventional tillage, in six of nine comparisons (1,050–1,950 vs 300–700 kg/ha). **Methods:** Reduced tillage or conventional tillage was used on nine plots each (50 x 6 m plots) in October or November. A mouldboard plough was used for conventional tillage (25–30 cm depth, 100% incorporation of crop residues). A cultivator was used for reduced tillage (10–15 cm depth, 50% incorporation of crop residues). Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Mature barley was harvested in June 2006–2009.

A replicated, randomized, controlled study in 1996–2009 in a rainfed barley field in the Ebro river valley, Spain (13) (same study as (3,12,14,17)), found more barley straw in plots with reduced tillage, compared to conventional tillage. **Crop yield:** More barley straw was found in plots with reduced tillage, compared to conventional tillage, in two of six comparisons (456–484 vs 210–242 g/m²). In one of three years, the barley crop failed with conventional tillage, but not with reduced tillage. **Methods:** Reduced tillage or conventional tillage was used on nine plots each (50 x 6 m plots). A mouldboard plough was used for conventional tillage (25–30 cm depth, 100% incorporation of crop residues). A cultivator was used for reduced tillage (10–15 cm depth, 50% incorporation of crop residues). Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Mature barley was harvested in June 2006–2009 (three samples/plot, 50 cm of one row/sample).

A replicated, randomized, controlled study in 1996–2009 in a rainfed barley field in the Ebro river valley, Spain (14) (same study as (3,12,13,17)), found higher crop yields in plots with reduced tillage, compared to conventional tillage. **Crop yield:** Higher barley yields were found in plots with reduced tillage, compared to conventional tillage (1,792 vs 1,155 kg/ha). **Methods:** Reduced tillage or conventional tillage was used on nine plots each (50 x 6 m plots) in October or November. A mouldboard plough was used for conventional tillage (25–30 cm depth, 100% incorporation of crop residues). A cultivator was used for reduced tillage (10–15 cm depth, 50% incorporation of crop residues). Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Mature barley was harvested in June 2006–2009.

A replicated, controlled study in 1991–2009 in a rainfed faba bean field in Sicily, Italy (15), found no differences in crop yield or crop quality in plots with reduced tillage, compared to conventional tillage. **Crop yield:** No differences in faba bean yields were found in plots with reduced tillage, compared to conventional tillage (1.91 vs 1.80 Mg grain/ha; 3.80 vs 3.86 Mg straw/ha). **Crop quality:** No differences in faba bean seed weight (99 vs 98 g/100 seeds), or numbers of seeds/pod (2.6 seeds/pod), were found in plots with reduced tillage, compared to conventional tillage. **Methods:** Reduced tillage or conventional tillage was used on two plots each (18.5 x 20 m plots). A mouldboard plough (30 cm depth; in summer) and a harrow (depth not reported; before sowing) were used for conventional tillage. A chisel plough (40 cm depth), a mouldboard plough (15 cm depth, in 1991–1998), and a harrow (depth not reported; before sowing) were used for reduced tillage. In all plots, a hoe was used to control weeds (depth not reported; 1–2 times/year). Faba beans were grown in rotation with durum wheat. During durum wheat growth, herbicide was used in all plots. All plots were fertilized (46 kg P_2O_5/ha). Faba beans were sown in December and harvested at maturity (month not reported). Yield and quality were measured in three samples/plot (four rows/sample, 3 m rows).

A replicated, controlled study in 2007–2009 in an irrigated tomato field in Davis, California, USA (16), found similar crop yields in plots with reduced tillage or conventional tillage. **Crop yield:** Similar tomato yields were found in plots with reduced tillage or conventional tillage (24–34 vs 26–33 marketable t/acre). **Methods:** Conventional tillage or reduced tillage was used on four plots each (90 x 220 feet). Broadcast disking, subsoiling, land planing, and rebedding were used for conventional tillage. A Wilcox Performer was used for reduced tillage (two passes; beds were conserved). Sprinklers, furrow irrigation, and drip-tape (in furrows) were used to irrigate the tomatoes. Winter cover crops (triticale) were grown on half of each plot, and the other half was fallow in winter. All plots were fertilized.

A replicated, randomized, controlled study in 1996–2008 in a rainfed barley field in the Ebro river valley, Spain (17) (same study as (3,12-14)), found similar crop yields in plots with reduced tillage or conventional tillage. **Crop yield:** Similar amounts of barley straw were found in plots with reduced tillage or conventional tillage (1,190–1,679 vs 1,351–1,748 kg/ha). **Methods:** There were nine plots (50 x 6 m) for each of two tillage treatments (reduced tillage: cultivator, 10–15 cm depth; conventional tillage:

mouldboard plough, 25–30 cm depth). Plots were tilled in October or November. Two-thirds of the plots were fertilized (60 or 120 kg N/ha/year). Barley was harvested in June.

A replicated, controlled study in 1991–2009 in a rainfed wheat field in Sicily, Italy (18), found similar crop yields, but lower crop quality, in plots with reduced tillage, compared to conventional tillage. **Crop yield:** Similar wheat yields were found in plots with reduced tillage or conventional tillage (4 Mg/ha). **Crop quality:** Wheat grains had less protein in plots with reduced tillage, compared to conventional tillage (141 vs 144 g/kg). **Methods:** Reduced tillage or conventional tillage was used on six plots each (18.5 x 20 m plots). Mouldboard ploughing (30 cm depth, in summer) and harrowing (1–2 passes) were used for conventional tillage. Chisel ploughing (40 cm depth, in summer) and mouldboard ploughing (15 cm, in autumn) were used for reduced tillage. A seed drill and pre-emergence herbicide were used for no tillage. All plots were fertilized (before planting wheat: 69 kg/ha P_2O_5; before planting bean and berseem: 46 kg/ha P_2O_5; wheat mono crop: 120 kg N/ha; rotational crops: 80 kg N/ha). Weeds were controlled with post-emergence herbicide. Yield was measured in three areas (8.6 x 8.6 m) in each plot, in each year.

A replicated, randomized, controlled study in 2009–2011 in two irrigated pepper fields in central Italy (19) found no difference in crop yields between plots with reduced tillage or conventional tillage. **Crop yield:** No difference in pepper yields was found between plots with reduced tillage or conventional tillage (3.7–41.4 vs 2.2–40.2 t/ha, fresh weight). **Methods:** A mouldboard plough (30 cm depth) was used on all plots in autumn, before winter cover crops were planted. Cover crops were mown or chopped in spring, before tillage. Conventional tillage or reduced tillage was used on 12 plots each (6 x 12 m plots), in May 2010–2011. A mouldboard plough and a disc (two passes) were used for conventional tillage (which incorporated the cover crop residues into the soil to a depth of 30 cm). A rotary hoe was used for reduced tillage (which incorporated the cover crop residues into the soil to a depth of 10 cm). Pepper seedlings were transplanted into the plots in May, and fruits were harvested twice/year in August–October 2010–2011. All plots were fertilized before the cover crops, but not after. All plots were irrigated.

A replicated, randomized, controlled study in 2009–2012 in two irrigated vegetable fields in central Italy (20) found higher crop yields in plots with reduced tillage, compared to conventional tillage. **Crop yield:** Higher crop yields were found in plots with reduced tillage, compared to conventional tillage, in one of six comparisons (in plots with hairy vetch as the winter cover crop: 21 vs 17 t/ha endive, fresh weight). **Methods:** Reduced tillage or conventional tillage was used on nine plots each (6 x 4 m plots). Each plot had a winter cover crop (hairy vetch, oats, or oilseed rape). Cover crops were sown in September 2009–2010 and suppressed in May 2010–2011. A mouldboard plough and a disk harrow (two passes) were used for conventional tillage (incorporating the cover crop residues to 30 cm depth). A rotary hoe was used for reduced tillage (incorporating the cover crop residues to 10 cm depth). Pepper seedlings were transplanted into these plots in May 2010–2011 and were last harvested in October 2010 and September 2011. After the pepper harvest, endive and savoy cabbage seedlings were transplanted into these plots, and they were harvested in December 2010 and November 2011 (endive) or March 2011 and February 2012 (cabbage). No fertilizer was added while the crops were growing, but the plots were irrigated.

A replicated, randomized, controlled study in 2008–2013 in a rainfed wheat-sunflower-pea field near Seville, Spain (21), found similar crop yields, but differences in crop quality, in plots with reduced tillage, compared to conventional tillage. **Crop yield:**

Similar crop yields were found in plots with reduced tillage or conventional tillage (data reported for multiple crops and years). **Crop quality:** More oil, more of five nutrients, more monounsaturated fatty acid, and less polyunsaturated fatty acid were found in sunflower seeds in plots with reduced tillage, compared to conventional tillage (49.6 vs 48.0% oil). **Methods:** Reduced tillage or conventional tillage was used on three plots each (6 x 33.5 m plots). A mouldboard plough (25–30 cm depth), a chisel plough (25 cm depth, twice/year), and a disc harrow (12 cm depth) were used for conventional tillage. A chisel plough (25 cm depth, once/year), a disc harrow (5 cm depth), and herbicide were used for reduced tillage. Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. Sunflowers were sown in May 2013 (three months later than usual) and harvested in September. Yield and quality were measured in 16 sunflower heads/plot.

A replicated, randomized, controlled study in 1987–2010 in rainfed cereal fields in the Ebro river valley, Spain (22), found lower crop yields in plots with reduced tillage, compared to conventional tillage. **Crop yield:** Lower grain yields were found in plots with reduced tillage, compared to conventional tillage (3,923 vs 4,210 kg/ha). **Crop quality:** No difference in grain weight was found between plots with reduced tillage or conventional tillage (34 vs 32 mg/grain). **Methods:** Reduced tillage or conventional tillage was used on ten plot each (Peñalba: three plots each, 34 x 175 m plots, established in 2005; Agramunt: four plots each, 9 x 50 m plots, established in 1990; Selvanera: three plots each, 7 x 50 m plots, established in 1987). In Peñalba, a disk plough (20 cm depth) and a cultivator (10 cm depth) were used for conventional tillage. In Agramunt, a mouldboard plough (25 cm depth) and a cultivator (15 cm depth) were used for conventional tillage. In Selvanera, a subsoil plough (40 cm depth) and a chisel plough (15 cm depth) were used for conventional tillage. A cultivator (Peñalba: 10 cm depth; Agramunt: 15 cm) or a chisel plough (Selvanera: 15 cm) was used for reduced tillage. Barley (Peñalba) or wheat (Agramunt and Selvanera) was planted in November 2009 with a seed drill (2–4 cm depth) and harvested in June–July 2010.

A replicated, randomized, controlled study in 1994–2009 in a rainfed pea-cereal field near Madrid, Spain (23), found lower pea yields and differences in crop quality in plots with reduced tillage, compared to conventional tillage. **Crop yield:** Lower grain yields were found in plots with reduced tillage, compared to conventional tillage, in one of four comparisons (peas: 0.08 vs 0.3 t/ha), and lower straw yields were found in two of four comparisons (1.5–2.4 vs 2.3–2.8 t/ha). **Crop quality:** Smaller peas, shorter pods, and fewer peas/pod were found in plots with reduced tillage, compared to conventional tillage, in one of four comparisons (80 vs 156 g/1,000 seeds; 5.7 vs 6.6 cm/pod; 4.8 vs 6.4 seeds/pod), but longer pods were found in one of four comparisons (7.0 vs 6.5 cm/pod). **Methods:** Reduced tillage or conventional tillage was used on four plots each (with three 10 x 25 m sub-plots each, with different pea-cereal rotations), in October or November. A mouldboard plough was used for conventional tillage (30 cm depth). A chisel plough was used for reduced tillage (10 cm depth). Peas were planted in November 2005–2008 and harvested in June 2006–2009. The peas were not fertilized.

A replicated, randomized, controlled study in 1999–2009 in an irrigated tomato-cotton field in the San Joaquin Valley, California, USA (24) (same study as (8)), found higher tomato yields in plots with reduced tillage, compared to conventional tillage. **Crop yield:** Higher tomato yields were found in plots with reduced tillage, compared to conventional tillage, in four of 10 years (102–120 vs 62–100 t/ha). Higher cover crop biomass was found in plots with reduced tillage, compared to conventional tillage (4,098 vs 3,609 t/ha). **Methods:** Reduced tillage or conventional tillage was used on eight tomato plots each, in 1999–2009. The plots (9 x 82 m) had six raised beds each. Winter cover crops (triticale, rye, and vetch) were planted on half of the plots, in October 1999–2008, and crop residues were chopped in March. Different numbers of tillage practices were used for conventional tillage (19–23 tractor passes, including disc and chisel ploughing) and reduced tillage (11–12 tractor passes, not including disc and chisel ploughing). Tomato seedlings were transplanted in April 2000–2009. Fertilizer and herbicide were used in all plots. Tomatoes were grown in rotation with cotton.

A replicated, randomized, controlled study in 2012–2013 in a rainfed wheat field in Wadi Madwar, northwestern Egypt (25), found higher crop yields in plots with less frequent tillage, compared to more frequent, lower crop yields in plots with shallower tillage, compared to deeper, and higher crop yields in plots that were tilled at slower speeds, compared to faster. **Crop yield:** Higher wheat yields were found in plots with reduced tillage, compared to conventional tillage (1,324 vs 1,238 kg grain/ha). Lower wheat yields were found in plots that were tilled to 15 cm depth, compared to 20–25 cm depth (1,392 vs 1,516–1,518 kg/ha). **Implementation options:** Higher wheat yields were found in plots that were tilled at slower tractor speeds (0.69–1.25 m/s: 1,454–1,528 kg/ha), compared to the fastest speed (1.53 m/s: 1,397 kg/ha). **Methods:** Reduced tillage or conventional tillage was used on three plots each (0.45 ha plots). A chisel plough was used for both reduced tillage (one pass) and conventional tillage (two passes). Each plot had three subplots (0.15 ha subplots, tilled to 15, 20, or 25 cm depth). Each subplot had four sub-subplots (size not reported; tilled at 0.69, 1, 1.25, or 1.53 m/s). Wheat was planted in December 2012, fertilized, and harvested in May 2013.

A replicated, randomized, controlled study in 2009–2011 in an irrigated eggplant field in central Italy (26) found that tillage had inconsistent effects on crop yield. **Crop yield:** Higher eggplant yields were found in plots with reduced tillage, compared to conventional tillage, in three of four comparisons (21–36 vs 18–32 Mg/ha fresh weight), but lower yields were found in one of four comparisons (7 vs 14). **Methods:** A mouldboard plough (30 cm depth) was used on all plots in autumn, before winter cover crops were planted. Cover crops were mown or chopped in spring, before tillage. Reduced tillage or conventional tillage was used on 12 plots each (6 x 4 m plots). A mouldboard plough (30 cm depth) and a disc (two passes) were used for conventional tillage (which incorporated the cover crop residues into the soil). A rotary hoe (10 cm depth) was used for reduced tillage (which incorporated some of the cover crop residues into the soil). Eggplant seedlings were transplanted into the plots in May, and fruits were harvested four times/year in July–September 2010–2011. All plots were fertilized before the cover crops were grown, but not after. All plots were irrigated.

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Habitat management: Effects on crop production

2.12. Plant flowers: Crop production (3 studies)

- **Crop yield (2 studies):** One replicated, controlled study from Spain[2] found higher crop yields in coriander plants next to planted flower strips, compared to coriander plants next to unplanted field margins. One replicated, randomized, controlled study from Italy[3] found higher crop yields in tomatoes next to planted flower strips, compared to tomatoes next to bare ground, in some comparisons.
- Crop quality (0 studies)
- **Implementation options (3 studies):** One replicated, randomized, controlled study from the USA[1] found smaller lettuces in fields planted with flowers, in five out of six configurations. One replicated, controlled study from Spain[2] found higher coriander yields next to field margins planted with more flower species, compared to fewer flower species. One replicated, randomized, controlled study from Italy[3] found lower crop yields in tomatoes next to field margins planted with more flower species, compared to fewer flower species, in some comparisons.

A replicated, randomized, controlled study in 2008–2009 in a lettuce field in Salinas, California, USA (1), found smaller lettuces in fields with planted flower strips, compared to fields without planted flower strips. **Implementation options:** When lettuce plants were removed to make space for sweet alyssum *Lobularia maritima* flower strips, and alyssum was planted perpendicular rather than parallel to lettuce rows, lettuces were not significantly smaller than lettuces in monocultures without flower strips (50 g/head). In five other configurations, lettuces were smaller than in monoculture (38–44 vs 50 g/head). **Methods:** Eight plots (1 x 10 m) in each of four blocks were planted with a lettuce monoculture (control) or a combination of lettuce and alyssum (replacement or addition, in different configurations).

A replicated, controlled study in 2013 in coriander plots near Madrid, Spain (2), found higher seed set and seed weight in coriander next to planted flower strips, compared to coriander next to unplanted field margins. **Crop yield:** Seed set and seed weight were higher in coriander next to flower strips, compared to coriander next to unplanted margins (28–29% vs 18% seed set/umbel; 2.1–2.5 vs 1.0 g seed/plant). **Implementation options:** Similar seed set and seed weight were found in coriander next to flower strips with one flower species, compared to six flower species (28% vs 29% seed set/umbel; 2.1 vs 2.5 g seed/plant). **Methods:** Potted coriander plants were transplanted into the field on 1 May 2013, one month before flowering. Fifteen pots were buried 1.5 m from three field margins with one flower species (*Diplotaxis tenuifolia*), three margins with six flower species, or three unplanted margins (135 pots total). All margins were 1.5 x 15 m. Flowers were planted in autumn 2012.

A replicated, randomized, controlled study in 2011–2012 in an organic tomato field near Pisa, Italy (3), found more and bigger tomatoes on plants grown next to some combinations of planted flower species, compared to other combinations, or compared to bare ground. **Crop yield and Implementation options:** The most and biggest fruits were found in 2011 on Roma tomato plants grown next to flower strips with three species (140 fruits/plant; 195 g dry biomass/fruit), which had more and bigger fruits than those grown next to bare ground (55 fruits/plant; 50 g dry biomass/fruit) or next to flower strips with either six or nine species (40–65 fruits/plant; 35–40 g dry biomass/fruit). The number of fruits/plant varied with the number of flower species/strip (three/strip: 35–140 fruits/plant; six/strip: 40–95; nine/strip: 35–50; bare ground: 30–55), as did fruit biomass (three/strip: 35–195 g dry biomass/fruit; six/strip: 35–70; nine/strip: 40–65; bare ground: 35–50), but not all differences were significant in both years (2011–2012), or both tomato varieties (Roma and Perfect Peel). **Methods:** Four treatments were compared: three flower species/strip (Apiaceae species), six species/strip (three Apiaceae and three Fabaceae), nine species/strip (three Apiaceae, three Fabaceae, and three others), and a control strip with no flowers. Three strips/treatment were sown with flower seeds (2011: 6 and 21 June; 2012: 13 and 17 June). Each flower strip (2 x 4 m) was positioned between two tomato plots (4 x 10 m/plot; one Roma plot and one Perfect Peel plot). Number of fruits/plant was assessed for five plants/plot and dry biomass was assessed for four fruits/plant.

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2.13. Plant hedgerows: Crop production (1 study)

- **Crop yield (1 study):** One replicated, paired site comparison from the USA[1] found similar crop yields in fields with hedgerows and fields with bare/weedy edges.
- Crop quality (0 studies)

A replicated, paired site comparison in 2012–2013 in sunflower fields in the Central Valley, California, USA (1), found similar crop yields in fields with hedgerows and fields with bare/weedy edges. **Crop yield:** Similar numbers of sunflower seeds were found in fields with hedgerows and fields with bare/weedy edges (650 seeds/head). **Methods:** Seeds from three sunflower heads were counted at each of four locations/transect (10, 50, 100, and 200 m from field edges), on two transects/field (2012: 10 fields; 2013: 8 fields). Half of the fields had bare/weedy edges (managed by burning, scraping, or herbicides). Half had hedgerows (3–6 x 250–300 m, 5–12 years old).

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Livestock management: Effects on crop production

Our search found no studies of the effects of livestock management on crop production.

3. Soil

Crop and soil management: Effects on soil

3.1. Add compost to the soil: Soil (24 studies)

- **Organic matter (12 studies):** Twelve replicated, controlled studies (ten randomized) from Italy[11,12,17,23], Spain[3,19,20], Syria[14], Turkey[4], and the USA[5,16,24] found more organic matter in soils with added compost, compared to soils without added compost, in some comparisons[4,11,12,14,16,19,20,23], or in all comparisons[3,5,17,24].
- **Nutrients (10 studies):** Six replicated, controlled studies (five randomized) from Italy[12,23], Portugal[15], Spain[7,19], and Syria[14] found more nutrients in soils with added compost, compared to soils without added compost, in some comparisons[12,15,19,23] or all comparisons[7,14]. Three replicated, randomized, controlled studies from Italy[17,23] and the USA[5] found inconsistent differences in nitrogen between soils with or without added compost. One replicated, randomized, controlled study from the USA[22] found no differences in phosphorus between soils with or without added compost. Three replicated, randomized, controlled studies from Italy[12,17] and Spain[19] found similar pH levels in soils with or without added compost.
- **Soil organisms (10 studies):** Six replicated, controlled studies (five randomized) from Italy[12], Spain[3,8,10,18], and the USA[5] found more microbial biomass in soils with added compost, compared to soils without added compost, in some comparisons[5,8,10,12] or all comparisons[3,18]. Two replicated, controlled studies from Italy[17] and the USA[22] found similar amounts of microbial biomass in soils with or without added compost. One replicated, randomized, controlled study from Italy[21] found inconsistent differences in bacterial abundance between plots with or without added compost. Two replicated, randomized, controlled studies from Italy[21] and Spain[19] found differences in bacteria communities, in some comparisons.
- **Soil erosion and aggregation (5 studies):** Two replicated, controlled studies (one randomized) from Spain[2,9] found less erosion of soils with added compost, compared to soils without added compost, in some comparisons[9], or in all comparisons[2]. Four replicated, randomized, controlled studies from Spain and Turkey[4,8,9,20] found that soils with added compost were more stable than soils without added compost, in some comparisons[4,8,9], or in all comparisons[20].
- **Greenhouse gases (10 studies):** Six replicated, controlled studies (five randomized) from Italy[11], Spain[3,8,19,20], and the USA[16] found more greenhouse gas in soils with added compost, compared to soils without added compost, in some comparisons[11,16,19], or in all comparisons[3,8,20]. Four replicated, randomized, controlled studies from Spain[1,6,13,18] found no differences in greenhouse gas between soils with or without added compost.
- **Implementation options (2 studies):** One replicated, randomized, controlled study from Syria[14] found more nitrogen in soils with compost added every two years, compared to soils with compost added every four years. One replicated, randomized, controlled study from Italy[21] found inconsistent differences in bacteria abundance between soils with different amounts of added compost.

A replicated, randomized, controlled, study in 1995 in a broccoli field in the Salinas Valley, California, USA (1), found similar amounts of nitrate, pH levels, and carbon dioxide emissions in soils with or without added compost. **Nutrients:** Similar amounts of nitrate, and similar pH levels, were found in soils with or without added compost (3–10 vs 2 kg NO_3-N/ha; pH 8.1–8.3 vs 8.1). **Greenhouse gases:** Similar carbon dioxide emissions were found in soils with or without added compost (soil respiration: 17–32 vs 63 kg CO_2-C/ha/day). **Methods:** There were four plots for each of three compost treatments (0, 22, or 44 Mg/ha). Fertilizer (165 kg ammonium nitrate/ha) was added to half (6.1 x 7.7 m) of each plot. The compost was made from green wastes (>30%), cow manure (>20%), spoiled hay (>15%), clay soil (>5%), and crop processing residues. Soil samples were collected on 11 October 1995 (0–7.6 cm depth).

A replicated, controlled study (year not reported) on a slope in Murcia, Spain (2), found less soil erosion in plots with added compost, compared to plots without added compost. **Soil erosion and aggregation:** Less soil was lost in runoff from plots with added compost, compared to plots without added compost, after rainfall events (eight initial events: 17 vs 299 g soil/m^2; later events: 5 vs 62). **Methods:** Composted municipal waste was added to three treatment plots, but not three control plots (10 x 3 m plots, 15% slope). Soil loss was measured in runoff water, collected from the lower edge of each plot, after each rainfall event. Enough compost was added to the soil to increase its organic carbon content by 2%. The soil was rotovated to a depth of 20 cm, to incorporate the compost.

A replicated, controlled study in 1997–1998 in farmland in Murcia, Spain (3), found more organic matter, soil organisms, and greenhouse gas in soils with added municipal waste compost, compared to soils without compost. **Organic matter:** More organic carbon was found in soils with added compost, compared to soils without added compost (14–33 vs 2–4 g C/kg soil). **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with added compost, compared to soils without added compost (360–760 vs 130–320 µg C/g soil). **Greenhouse gases:** More carbon dioxide was found in soils with added compost, compared to soils without added compost (40–150 vs 5–15 mg CO_2/kg soil/day). **Methods:** Municipal waste compost was added to three treatment plots (25–30 kg compost/m^2), but not three control plots (no compost). The plots were 5 x 3 m. Soil samples were collected 0–24 months after adding the compost (eight time points, four samples/plot, 0–15 cm depth).

A replicated, randomized, controlled study in 1995–1999 in farmland in southern Turkey (4) found more organic matter and greater soil stability in soils with added compost, compared to soils without added compost, at some depths. **Organic matter:** More organic matter was found in soils with added compost, compared to soils without added compost, at one of two depths (0–15 cm: 1.8% vs 1.6%). **Soil erosion and aggregation:** Larger soil particles were found in plots with added compost, compared to plots without added compost, at one of two depths (15–30 cm: 0.31 vs 0.18 mm mean weight diameter). **Methods:** Compost (25 t/ha) was added to three treatment plots (10 x 20 m), but not three control plots. The compost was made of grass, stubble, and leaves. Wheat, sweet peppers, maize, and wheat were grown in rotation. Soils were sampled in 1999, after harvesting the last wheat crop (0–30 cm depth). Wet sieving was used to determine mean weight diameter.

A replicated, randomized, controlled study in 1998–2000 in an irrigated vegetable field in the Salinas Valley, California, USA (5), found more organic matter, and sometimes found more microbial biomass, in soils with added compost, compared to soils without added compost. Adding compost had inconsistent effects on nutrients. **Organic matter:**

More carbon was found in soils with added compost, compared to soils without added compost (15 vs 14 g total C/kg soil, 0–15 cm depth). **Nutrients:** More nitrogen was found in soils with added compost, compared to soils without added compost (1.6 vs 1.5 g total N/kg soil, 0–15 cm depth). At depths of 0–90 cm, less nitrate was found in soils with added compost, compared to soils without added compost, in 13 of 14 comparisons (4–54 vs 5–64 g NO_3-N/g soil), but more nitrate was found in one of 14 comparisons (34 vs 24). At depths of 0–15 cm, less nitrate was found in soils with added compost, compared to soils without added compost, in six of 16 comparisons (2–17 vs 3–64 μg NO_3-N/g soil), but more nitrate was found in one of 16 comparisons (31 vs 12). At depths of 0–15 cm, less ammonium was found in soils with added compost, compared to soils without added compost, in eight of 16 comparisons (1–6 vs 5–9 μg NH_4-N/g soil), but more ammonium was found in two of 16 comparisons (4–7 vs 1–4). **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with added compost, compared to soils without added compost, nine of 16 comparisons (120–220 vs 80–130 μg C/g soil). More microbial biomass (measured as nitrogen) was found in soils with added compost, compared to soils without added compost, in 10 of 16 comparisons (14–26 vs 5–17 μg N/g soil). **Methods:** There were four plots (0.52 ha), for each of four treatments (minimum tillage or conventional tillage, with or without added organic matter). In plots with added organic matter, compost was added two times/year, and a cover crop (Merced rye) was grown every autumn or winter. The compost was made from municipal yard waste, salad packing plant waste, horse manure, clay, straw, and other compost. Lettuce or broccoli crops were grown in raised beds. Sprinklers and drip irrigation were used in all plots. Soils were disturbed to different depths (conventional tillage: 50 cm with disking, cultivating with a liliston, sub-soiling, bed re-making, and bed-shaping; minimum tillage: 20 cm with a liliston, rollers, and bed-shaping). Soils were collected, along the planting line, with 6 cm soil cores. It was not clear whether these results were a direct effect of adding compost or growing cover crops.

A replicated, randomized, controlled study in 2004 in a maize field in the Jarama river basin, Spain (6), found no difference in greenhouse-gas emissions between soils with or without added compost. **Greenhouse gases:** No difference in nitrous oxide emissions was found between soils with or without added compost (composted pig slurry: 9.3 vs 8.6 kg N/ha; composted municipal solid waste 7.1 vs 8.6). **Methods:** There were three plots (40 m^2) for each of two treatments (composted solid fraction of pig slurry or composted municipal solid waste, both with urea) and one control (urea only). Urea was applied at a rate of 50 kg N/ha. Both composts were applied at a rate of 175 kg available N/ha. Soils were cultivated to a depth of 5 cm to incorporate the fertilizers. Nitrous oxide was measured in closed chambers (two chambers/plot, one within a maize row, one between rows, 35 cm diameter, 23 cm height, one sample/week, April–September).

A replicated, controlled study in 2001–2003 in a degraded wood pasture in Catalonia, Spain (7), found more nitrate in soils with added compost, compared to soils without it. **Nutrients:** More nitrate was found in soils with added compost, compared to soils without it (24 vs 3 kg N-NO_3/ha). **Methods:** Composted sewage sludge was added to five treatment plots (10 t dry matter/ha), but not five control plots (no compost). Each plot was 20 x 5 m. To restore the wood pasture, shrubs and small trees were crushed and scattered on the soil, and grass seeds were sown. Soil was collected in soil cores (10 cores/plot, 0–20 cm depth).

A replicated, randomized, controlled study in 2001–2005 in the Guadalquivir Valley, Andalusia, Spain (8), found more soil organisms, more carbon dioxide, and greater stability in soils with four years of added compost, compared to soils without added compost. **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with added compost, after 3–4 years of adding it, compared to soils without it, in five of six comparisons (351–501 vs 118–120 µg C/g dry soil), but no differences were found after 1–2 years of adding compost (171–317 vs 119–128). **Greenhouse gases:** More carbon dioxide was found in soils with added compost, after four years of adding it, compared to soils without added compost (1,596–2,004 vs 859 mg/kg soil). **Soil erosion and aggregation:** More stable soils were found in plots with added compost, after 3–4 years of adding it, compared to plots without it (data reported as log instability index), and more stable soils were also found after two years of adding compost, in two of three comparisons, but no differences were found after one year of adding it. **Methods:** There were three plots (10 x 7 m) for each of three treatments (5, 7.5, or 10 t/ha of organic matter, added as composted beet vinasse and crushed cotton gin waste) and one control (no compost). The compost was added in October 2001–2004. Soil samples were collected one day before the compost was added (four subsamples/plot, 0–25 cm depth).

A replicated, randomized, controlled study in 2001–2005 in the Guadalquivir Valley, Andalusia, Spain (9), found greater stability and less erosion in soils with added compost, compared to soils without added compost. **Soil erosion and aggregation:** More stable soils were found in plots with added compost, compared to plots without added compost, in two of four years (data reported as log instability index). Less soil was lost from plots with added compost, compared to plots without added compost, after rainfall (60 mm rainfall/hour, in two of four years: 171–182 vs 210–211 kg/ha; 140 mm rainfall/hour, in three of four years: 366–430 vs 508–520). **Methods:** There were four plots (9 x 9 m) for each of two treatments (10 or 20 t compost/ha) and one control (no compost). The compost was added in October 2001–2004, and soils were ploughed to a depth of 25 cm. Soil samples were collected one day before the compost was added, in 2002–2004, and also in October 2005 (gauge augers, 30 mm diameter, 25 cm depth). Soils were watered to simulate rainfall in October 2002–2005 (60 or 140 mm rainfall/hour), and soil loss was measured in plots (1 x 1 m) that overlapped the borders of the treatment and control plots by 0.5 m.

A replicated, randomized, controlled study in 2002–2005 in a barley field in Toledo, Spain (10), found more soil organisms in plots with added compost, compared to plots without added compost, in two of four comparisons. **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with low amounts of added compost, compared to plots without added compost (one application: 157 vs 76 mg C/ha; one application/year: 265 vs 76), but significant differences were not found between plots with high amounts of added compost and plots without added compost (one application: 95 vs 76; one application/year: 136 vs 76). **Methods:** The compost was made from sewage sludge. There were four plots (10 x 3 m) for each of four fertilizer treatments (20 or 80 t compost/ha, applied once in three years or once/year) and one control (no fertilizer). Plots were fertilized in mid-September and planted in mid-October.

A replicated, randomized, controlled study in 2003–2005 in farmland in the Sele river plain, Italy (11), found more organic matter and more carbon dioxide in soils with added compost, compared to soils without added compost. **Organic matter:** More organic carbon was found in soils with added compost, compared to soils without added compost, in eight of 18 comparisons (greenhouse: 28–32 vs 23–25 mg organic C/kg soil [dry weight]; open field: 10–12 vs 8). **Greenhouse gases:** More carbon dioxide was found in soils with added compost, in five of six comparisons (greenhouse: 0.9–1.2 vs 0.7 µg CO_2/g soil [dry weight]/hour; open field: 1.2–1.4 vs 0.6). **Methods:** The compost was made from municipal food waste and yard trimmings. At each of two sites (unheated tunnel greenhouse with 24 m^2 plots, or open field with 70 m^2 plots), there were three replicates for each of three treatments (15, 30, or 45 t compost/ha, in March–April each year) and one control (no compost). Crops were grown in rotation (greenhouse: tomatoes, beans, lettuce; open field: tomatoes or eggplants, endive and/or broccoli sprouts). Soil samples (five/plot, 0–20 cm depth) were collected three times/year before the crops were harvested (greenhouse: spring, autumn, winter; open field: summer, autumn, winter). Organic carbon was measured in winter samples (residual carbon). Carbon dioxide (soil respiration) was measured in all samples.

A replicated, randomized, controlled study in 2001–2009 in an irrigated nectarine orchard in Italy (12) found more organic matter, nutrients, and soil organisms in plots with added compost, compared to plots without added compost. **Organic matter:** More organic matter was found in plots with added compost, in 11 of 24 comparisons (2–5% vs 1.5%). **Nutrients:** More nitrogen was found in soils with added compost (ammonium, in four of 21 comparisons: 7–15 vs 4–6 mg/kg dry soil; nitrate, in at least eight of 84 comparisons: results not clearly reported). More phosphorus and potassium were found in plots with added compost (phosphorus, in one of three comparisons in 2006: 24 vs 13 mg P/kg dry soil; potassium, in two of three comparisons: 299–350 vs 227 mg K/kg dry soil). Similar pH levels were found in plots with or without added compost (pH 7.8 vs 7.7). **Soil organisms:** More microbial biomass (measured as carbon) was found in plots with added compost, in 14 of 60 comparisons (5–22 vs 4–10 mg C/g dry soil). **Soil erosion and aggregation:** Similar water-stability was found in soils with or without added compost (13% vs 14–17% of soil aggregates were water-stable). **Methods:** There were four plots for each of three compost treatments (5 t/ha in May, 5 t/ha split into two applications, in May and September, or 10 t/ha split into two), and there were four control plots (no fertilizer; plot size not reported). The compost was made from domestic organic waste and urban pruning material (50% each). Compost was tilled into the soil (25 cm depth). Soil samples were collected in September (3–40 cm depth for organic matter in 2001–2008 and phosphorus in 2006; 5–40 cm depth for aggregate stability in 2008) and four times in spring and summer in 2008–2009 (0–80 cm depth for nitrogen, and 4–20 cm depth for microbial biomass).

A replicated, randomized, controlled study in 2006 in a barley field in the Henares river basin, Spain (13), found no difference in greenhouse-gas emissions between soils with or without added municipal waste compost. **Greenhouse gases:** No difference in greenhouse-gas emissions was found between soils with or without added compost (carbon dioxide: 466 vs 411 kg C/ha; methane: –231 vs –294 mg C/m^2). **Methods:** Composted municipal solid waste (125 kg available N/ha) was added to three treatment plots, but not three control plots, in January. Plots were 30 m^2. Plots were cultivated (0–5 cm depth) to incorporate the compost. Barley was planted in January and harvested in June. Greenhouse-gas emissions were measured with closed chambers (35 cm diameter, 25 cm height, 1–4 measurements/plot/week, 23 January–28 November).

A replicated, randomized, controlled study in 1996–2008 in farmland near Aleppo, Syria (14), found more nitrogen, and sometimes found more organic matter, in soils with added compost, compared to soils without added compost. **Organic matter:** More organic matter was found in soils with added compost, compared to soils without added compost, in two of eight comparisons (2003, compost added every two years: 13–17 vs 10–12 g/kg soil). **Nutrients:** More nitrogen was found in soils with added compost, compared to soils without added compost (0.75–0.93 vs 0.71 g/kg soil). **Implementation options:** More nitrogen was found in soils with compost added every two years, compared to every four years (0.93 vs 0.75 g/kg soil). **Methods:** There were two plots (25 x 25 m) for each of eight treatments (10 Mg/ha dry weight of compost added every two or four years, with shallow or conventional tillage, and two-course or four-course crop rotations) and four controls (no compost, with shallow or conventional tillage, and two-course or four-course crop rotations). The compost was 75% plant residues, 20% sheep manure, and 5% soil. The crop rotations were vetch-barley (two-course) or vetch-barley-vetch-wheat (four-course). Soils were tilled with a mouldboard plough to a depth of 30 cm after cereal crops (conventional tillage) and/or with a cultivator to a depth of 12 cm after vetch (conventional and shallow tillage). Soils were sampled in 2003 (0–30 cm depth) and 2008 (0–20 cm depth).

A replicated, randomized, controlled study in 2006–2008 in a cereal field in the Castelo Branco region, Portugal (15), found similar amounts of nitrate in soils with and without added compost. **Nutrients:** Similar amounts of nitrate were found in plots with and without added compost, in 30 of 32 comparisons (1–50 vs 1–10 mg NO_3-N/L water). In two of 32 comparisons, more nitrate was found in plots with added compost, compared to plots without (33 days after single application: 16 vs 7 mg NO_3-N/L water; 130 days after split application: 12 vs 1 mg). **Methods:** Water in the soil was collected in porous ceramic suction cup samplers (four/plot, 0.6–0.7 m depth, 50 kPa for 24 hours), whenever drainage occurred (October–November and April–May, 16 samples in total). There were three plots (5.6 x 8 m) for each of two treatments (single application of compost in spring, or split application in spring and autumn) and one control (no compost). The compost was made from municipal waste. Maize was grown in spring–summer, and oats were grown in autumn–winter.

A replicated, randomized, controlled, paired study in 2008–2011 in grazed annual grasslands in California, USA (16), found more organic matter and carbon dioxide in soils with added compost, compared to soils without added compost. **Organic matter:** More organic carbon was found in soils with added compost, compared to soils without added compost, in three of seven comparisons (350–1,000 more g C/m^2). **Greenhouse gases:** More carbon dioxide was found in soils with added compost, compared to soils without added compost, in four of six comparisons (150–250 more g CO_2-C/m^2/year), but no differences were found in other greenhouse gases (methane: –1.4 to –2.5 g CH_4-C/ha/day; nitrous oxide: 0.1–1.0 g N_2O-N/ha/day). **Methods:** Composted organic green waste was added to three treatment plots (129 g total N/m^2), but not to six control plots, at each of two sites (coastal grassland in Nicasio and valley grassland in Browns Valley). The plots were 25 x 60 m. Greenhouse gases were measured in flux chambers, every 1–4 weeks for three years. Organic carbon was measured in soil samples that were collected at the end of the growing seasons (May or June, nine soil cores/plot, 7 cm diameter, 10 cm depth).

A replicated, randomized, controlled study in 2009–2011 on two farms in the Salerno district, Italy (17), found more organic matter, and sometimes found more ammonium, but found no difference in soil organisms or pH, in soils with added compost, compared to soils without added compost. Adding compost had inconsistent effects on nitrate. **Organic matter:** More organic carbon was found in soils with added compost, compared to soils without added compost (5–110% more). **Nutrients:** More nitrate was found in soils with added compost, compared to soils without added compost, in 10 of 18 samples (20–125% more), but less nitrate was found in the first two samples (25–70% less). More ammonium was found in soils with added compost, compared to soils without added compost, on one of two farms (amounts of ammonium not reported). No difference in pH was found between soils with and without added compost (pH levels not reported). **Soil organisms:** No difference in microbial biomass was found between soils with and without added compost (amounts of biomass not reported). **Methods:** On each of two farms, there were three plots (7 x 5 m) for each of four treatments (30 or 60 Mg organic matter/ha/year, with a carbon-to-nitrogen ratio of 15:1 or 25:1) and one control (no organic matter). Organic matter was added in February 2009, February 2010, and June 2011. It was made from the composted organic fraction of municipal solid waste, and it was mixed with wood scraps to control the carbon-to-nitrogen ratio. It was not clear whether these results were a direct effect of adding composted municipal waste or wood scraps.

A replicated, randomized, controlled study in 2013 in greenhouses in southeast Spain (18) found more soil organisms, but similar amounts of carbon dioxide, in soils with added compost, compared to soils without added compost. **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with added compost, compared to soils without added compost (280–330 vs 130–160 mg C/kg soil). **Greenhouse gases:** Similar amounts of carbon dioxide were found in soils with and without added compost (8–19 vs 7–15 mg CO_2-C/kg soil/day). There were four replicates for each of four treatments (50.5 t/ha of compost R1 or 40 t/ha of compost R2, with low or medium doses of mineral fertilizer) and two controls (low or medium doses of mineral fertilizer). Mineral fertilizer (Hoagland's solution) was added in two of three waterings (medium dose) or one of five waterings (low dose). Compost R1 was made from sheep and goat manure. Compost R2 was made from alperujo, manure, and olive prunings.

A replicated, randomized, controlled study in 1996–2011 in a vineyard in Navarra, Spain (19), found more organic matter, nutrients, and greenhouse-gas emissions in soils with some types of added compost, compared to soils without added compost. **Organic matter:** A higher percentage of organic matter was found in plots with added compost, compared to plots without added compost, for one of three types of compost (SMC: 1.8 vs 1.2% organic matter). **Nutrients:** More nitrogen, phosphorus, and/or potassium were found in plots with some types of added compost, compared to plots without added compost. The largest differences were between plots with added sheep-manure compost and plots without added compost (nitrogen: 0.10% vs 0.06%; phosphorus: 81 vs 30 mg/kg; potassium oxide: 474 vs 232 mg/kg). Similar pH was found in all plots (7.34–7.41). **Soil organisms:** Similar bacteria communities were found in all plots, for 11 of 12 bacteria genera. However, in plots with added compost, a higher percentage of RNA sequences came from *Rhizobium* species, for two types of compost (SMC: 0.3%; OF-MSW: 0.5%), but not for one type (PEL: 0.2%), compared to plots without added compost (0.1%). **Greenhouse gases:** Higher greenhouse-gas emissions were found in plots with added compost, for one type of compost (OF-MSW: 1,745 kg CO_2 equivalent/ha; cumulative over 115 days after adding compost or fertilizer), but not for two types (SMC: 1,591 kg; PEL: 1,598 kg), compared to plots without added compost (1,104 kg). Higher nitrous oxide emissions were found in plots with added compost, compared to plots without added compost (1.8–5.1 vs 1.7 g N_2O–N/ha/day; 15 days after compost). **Methods:** Three types of compost were compared: pelletized organic compost (PEL), compost from the organic fraction of municipal solid waste (OF-MSW), and sheep-manure compost (SMC). Each of three compost treatments and one control was assigned to a plot (15 vines), and there were three blocks (the size of plots within blocks was not clearly reported). The vines were planted in 1996. Compost was added in February 1998–2011 (PEL: 3,700 kg fresh weight/ha/year; OF-MSW: 4,075 kg; SMC: 4,630 kg). For N, P, K, and pH measurements, soil samples were taken at the end 2011 (four/plot, 0–30 cm depth). For greenhouse-gas measurements, ambient air samples (20 ml, 10/plot, closed chamber technique) were taken over 115 days after adding compost. For partial prokaryotic 16S rRNA sequencing, soil samples (four/plot, 5–30 cm depth) were taken 15 days after adding compost.

A replicated, randomized, controlled study in 2010–2011 in the Jarama river basin, Spain (20), found more carbon dioxide and higher soil stability, but rarely found more organic matter, in soils with added compost, compared to soils without added compost. **Organic matter:** Higher percentages of organic carbon were found in soils with added compost, compared to soils without added compost, in one of five comparisons (spring 2010, immediately after adding compost: 72% vs 85% unhydrolyzed carbon), but not in four of five comparisons (summer 2010–spring 2011: 63–72% vs 55–72%). **Soil erosion and aggregation:** Larger soil aggregates were found in plots with added compost, compared to plots without added compost (3.0–3.4 vs 0.7–1.3 mm mean weight diameter). **Greenhouse gases:** More carbon dioxide was found in soils with added compost, compared to soils without added compost (amounts of carbon dioxide not reported). Three plots (10 x 15 m) were fertilized with municipal solid waste compost in spring 2010, and three plots were not fertilized. Carbon dioxide was measured once every two weeks (three open chambers/plot, 20 cm diameter, 5 cm deep in the soil). Soil cores were collected (three 100 cm^2 soil cores/plot) for other measurements.

A replicated, randomized, controlled study in 2015 in a sorghum field in southern Italy (21) found inconsistent differences in bacteria abundance between soils with or without added compost, but found higher bacteria diversity in soils with added compost. **Soil organisms:** Higher bacteria abundance was found in soils with added compost, in three of 32 comparisons (*Actinobacteria* and one other group: 111–2,017 vs 32–1,746 phylotype 16S rRNA sequences), but lower bacteria abundance was found in three of 32 comparisons (*Gemmatimonadetes* and *Proteobacteria*: 80–1,658 vs 141–1,810 sequences). Higher bacteria diversity was found in soils with added compost, compared to soils without added compost, in one of many comparisons (with double compost application: data reported as Chao 1 index). **Implementation options:** Higher bacteria abundance was found in plots with a double application of compost, compared to single application, in one of 16 comparisons (*Proteobacteria*: 1,658 vs 1,469 sequences), but lower bacteria abundance was found in one of 16 comparisons (another group: 34 vs 111 sequences). **Methods**: Compost was added to eight treatment plots (single application: 130 kg N/ha; double application: 260 kg N/ha), but not four control plots (5 x 8 m plots). After three years of compost addition, plants were dug up (three plants/plot) and soil that was clinging to plant roots was collected for sampling bacteria (through RNA sequencing).

A replicated, randomized, controlled study in 2003–2011 in farmland the Salinas Valley, California, USA (22), found no difference in nutrients or soil organisms between soils with or without added compost. **Nutrients:** No difference in phosphorus was found between soils with or without added compost (497 vs 456 mg total phosphorus/kg soil). **Soil organisms:** No difference in microbial biomass (measured as phosphorus) was found between soils with or without added compost (2.0 vs 1.7 mg chloroform-extractable phosphorus/kg soil). **Methods:** Composted yard waste (15 Mg/ha/year) was added to four treatment plots (240 m^2), but not four control plots. Lettuce and broccoli were grown in rotation (two crops/year). Soil samples were collected in soil cores (20 cores/plot, 0–30 cm depth) in 2011.

A replicated, randomized, controlled study in 2009–2011 in farmland in the Salerno district, Italy (23), found more organic matter and more nutrients in soils with added compost, compared to soils without added compost, in some comparisons, but less nitrate was found in some comparisons. **Organic matter:** More organic matter was found in soils with added compost, compared to soils without added compost, in some comparisons (farm 1: 30–100% more organic carbon, in 19 of 28 comparisons; farm 2: up to 70% more; number of significant comparisons not reported). **Nutrients:** More nitrate was found in soils with added compost, compared to soils without added compost, in some comparisons (Farm 1: 55–185% higher nitrate concentration, in eight of 16 reported comparisons; Farm 2: 45–70% higher, in four of 16 reported comparisons), but less nitrate was found in some comparisons (Farm 1: 45–55% less, in two of sixteen reported comparisons). More nitrogen and/or phosphorus were found in soils with added compost, compared to soils without added compost, in some comparisons (up to 50% more nitrogen; number of significant comparisons not reported; percentage increase in phosphorus not reported). **Methods:** There were three plots (approximately 30 m^2) for each of eight treatments (30 or 60 t/ha of added organic matter, with carbon-to-nitrogen ratios of 15:1 or 2:1, with or without mineral fertilizer) and two controls (no organic matter, with or without mineral fertilizer), on two farms. Composted municipal solid waste was mixed with poplar tree prunings to control carbon-to-nitrogen ratios in the organic matter. Crops were grown in unheated glasshouses (farm 1: lettuce and melon; farm 2: kohlrabi). Organic matter was added in early 2009 and 2010. Soil samples were collected at seven time points in two years (five subsamples/plot, 0–20 cm depth). It was not clear whether these results were a direct effect of adding compost or adding poplar prunings.

A replicated, controlled study in 2014 in 29 organic vegetable fields on the Central Coast, California, USA (24), found more organic matter, phosphorus, and potassium in soils with added compost, compared to soils without added compost. **Organic matter:** More organic matter was found in soils with added compost, compared to soils without added compost (data reported as model coefficients). **Nutrients:** More phosphorus and potassium, but similar amounts of nitrate and similar pH levels, were found in soils with added compost, compared to soils without added compost (data reported as model coefficients). **Methods:** In each of 29 vegetable fields, compost was added to one plot, but not to one adjacent plot (5 x 5 m plots), 1–2 months before lettuces were planted (25 t compost/ha, made from cow, chicken, and green manures). Lettuces were planted in spring (5–28 March) and summer (30 May–5 July). Lettuce weights were measured at maturity in one 1 x 1 m quadrat/plot. Soil samples were collected in spring (1.25 cm diameter, 0–10 cm depth).

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3.2. Add manure to the soil: Soil (11 studies)

- **Organic matter (8 studies):** Five replicated, controlled studies (two randomized) from Italy[8,9], Tunisia[5], Turkey[2], and the USA[1] found more organic matter in soils with added manure, compared to soils without it. Three replicated, randomized, controlled studies from Italy[6], Spain[11], and Greece[3] found similar amounts of organic matter in plots with or without added manure.
- **Nutrients (5 studies)**
    - Nitrogen (5 studies): Three replicated, controlled, studies (one randomized) from Italy[8,9] and Tunisia[5] found more nitrogen in soils with added manure, compared to soils without it, in some comparisons. Two replicated, randomized, controlled studies from Greece[3] and Italy[6] found similar amounts of nitrogen in soils with or without added manure.
    - Phosphorus (3 studies): One replicated, randomized, controlled study from Greece[3] found more phosphorus in soils with added manure, compared to soils without it. One replicated, randomized, controlled study from Italy[6] found similar amounts of phosphorus in soils with or without added manure. One replicated, controlled study from Italy[9] found inconsistent differences in phosphorus between soils with or without added manure.
    - Potassium (2 studies): Two replicated, randomized, controlled studies from Italy[6] and Greece[3] found more potassium in soils with added manure, compared to soils without it.
    - pH (3 studies): One replicated, randomized, controlled study from Tunisia[5] found lower pH levels in soils with added manure, compared to soils without it. One replicated, controlled study from Italy[8] found higher pH levels in soils with added manure. One replicated, randomized, controlled study from Italy[6] found similar pH level in soils with or without added manure.
- **Soil organisms (3 studies)**
    - Microbial biomass (2 studies): Two replicated, randomized, controlled studies from Italy[6] and Spain[11] found similar amounts of microbial biomass in soils with or without added manure.
    - Nematodes (1 study): One replicated, randomized, controlled study from Greece[10] found similar numbers of nematodes in soils with or without added manure.
- **Soil erosion and aggregation (4 studies):** One replicated, randomized, controlled study from Spain[4] found less erosion in plots with added manure, compared to plots without added manure. Three replicated, randomized, controlled studies from Spain[4,11] and Turkey[2] found higher soil stability in plots with added manure, compared to plots without added manure, in some or all comparisons. One replicated, controlled study from the USA[1] found similar soil stability in plots with or without added manure.
- **Greenhouse gases (2 studies):** One replicated, controlled study from the USA[1] found higher carbon dioxide emissions in plots with added manure, compared to plots without added manure. One replicated, randomized, controlled study from Spain[7] found higher nitrous oxide emissions in plots with added manure, compared to plots without added manure.
- **Implementation options (1 study):** One study from Tunisia[5] found no differences in organic matter or pH between soils with different amounts of added manure, but found less nitrate in soils with less added fertilizer.

A replicated, controlled study in 1997–1998 in irrigated fallow land in California, USA (1), found more organic matter and higher carbon dioxide emissions in plots with added manure, compared to plots without manure added. **Organic matter:** More organic matter was found in soils with added manure (16 vs 10 g/kg). **Soil erosion and aggregation:** Similar aggregate stability was found in soils with or without added manure (366 vs 300 g/kg). **Greenhouse gases:** Higher carbon dioxide emissions were found in plots with added manure (3 vs 1 carbon dioxide µg/g/day). **Methods:** Plots (2 x 2 m) had poultry manure (25 Mg/ha) or no added fertilizer (five plots each). Manure was added in April 1987, February 1988, and October 1988 and was immediately incorporated into the soil (15 cm depth). Plots were irrigated weekly (100 mm/day). Five soil samples (25–100 mm depth) were taken from each plot.

A replicated, randomized, controlled study in 1995–1999 in arable farmland in southern Turkey (2) found more organic matter and greater soil stability in soils with added manure, compared to soils without added manure. **Organic matter:** More organic matter was found in soils with added manure, compared to soils without added manure, in one of two comparisons (1.8% vs 1.6%). **Soil erosion and aggregation:** Larger soil particles were found in plots with added manure, compared to plots without added manure (0.38–0.43 vs 0.18–0.29 mm mean weight diameter). **Methods:** Cattle manure (25 t/ha) was added to three treatment plots (10 x 20 m), but not three control plots. Wheat, sweet peppers, and maize were grown in rotation. Soils were sampled in 1999, after harvesting the last wheat crop (0–30 cm depth). Wet sieving was used to determine mean weight diameter.

A replicated, randomized, controlled study in 2002–2005 in an irrigated maize field in Greece (3) found similar amounts of organic matter in soils with or without added manure. **Organic matter:** Similar amounts of carbon were found in soils with or without added manure (5.7 vs 5.3 g/kg). **Nutrients:** Similar amounts of nitrogen were found in soils with or without added manure (0.81 vs 0.72 g N/kg). More phosphorus and potassium was found in soils with added manure, compared to soils without added manure (15–21 vs 4–11 mg P/kg; 67–85 vs 46–75 mg K/kg). **Methods:** Plots (5.6 x 8 m) had liquid cow manure (80 Mg/ha/year) or no added fertilizer (six plots each). The manure was incorporated into soil with a disk harrow (12–15 cm depth) within two hours of application. Soil samples were collected at the end of the growing season in 2005 (three samples/plot, 0–30 cm depth).

A replicated, randomized, controlled study in 2001–2005 in the Guadalquivir Valley, Andalusia, Spain (4), found greater stability and less erosion in soils with added manure, compared to soils without added manure. **Soil erosion and aggregation:** More stable soils were found in plots with added manure, compared to plots without added manure, in two of four years (data reported as log instability index). Less soil was lost from plots with added manure, compared to plots without added manure, after rainfall (60 mm rainfall/hour, in two of four years: 175–192 vs 210–211 kg/ha; 140 mm rainfall/hour, in three of four years: 390–439 vs 508–520). **Methods:** There were four plots (9 x 9 m) for each of two treatments (5.8 or 11.6 t poultry manure/ha) and there wre four control plots (no manure). The manure was added in October 2001–2004, and soils were ploughed (25 cm depth). Soil samples were collected one day before the manure was added, in 2002–2004, and also in October 2005 (30 mm diameter gauge augers, 25 cm depth). Soils were watered to simulate rainfall in October 2002–2005 (60 or 140 mm rainfall/hour), and soil loss was measured in plots (1 x 1 m) that overlapped the borders of the treatment and control plots by 0.5 m.

A replicated, randomized, controlled study in 1999–2004 in bare plots in Tunisia (5) found more organic matter and nitrogen, but lower pH levels, in soils with added manure, compared to soils without added manure. **Organic matter:** More carbon was found in soils with added manure, in one of four comparisons (28 vs 9 g/kg). **Nutrients:** More nitrogen was found in soils with added manure (1.3–2 vs 1 g/kg). Lower pH levels were found in soils with added manure, in one of four comparisons (8 vs 8.3). **Implementation options:** Less carbon and nitrogen was found in plots with less fertilizer, compared to more fertilizer (carbon, in one of two comparisons: 12 vs 28 g/kg; nitrogen: 1 vs 2 g/kg). Similar pH levels were found in plots with different amounts of added manure (pH 8). **Methods:** Bare plots (1.5 x 1.5 m) had added manure (0, 40, or 120 t/ha) or no added manure (four plots for each). Manure was incorporated into the soil (10–15 cm depth). Soil samples (five samples/plot, 0–40 cm depth) were collected in September 2004.

A replicated, randomized, controlled study in 2001–2009 in an irrigated nectarine orchard in Italy (6) found more potassium in plots with added manure, compared to plots without added manure. **Organic matter:** Similar amount of organic matter were found in plots with or without added manure (2–3% vs 2%). **Nutrients:** Similar amounts of ammonium (1–6 vs 2–6 mg/kg) and phosphorus (20 vs 13 mg/kg), and similar pH levels (pH 7.8) were found in plots with or without added manure. More potassium was found in plots with added manure (312 vs 227 mg/kg). **Soil organisms:** Similar amounts of microbial biomass (measured as carbon) were found in plots with or without added manure (2–13 vs 4–10 mg/g). **Methods:** Four plots received 5–10 kg dry cow manure/ha, and four plots received no fertilizer. The manure was tilled into the soil (25 cm depth). Soil samples were collected in September (3–40 cm depth for organic matter in 2001–2008 and phosphorus in 2006) and four times in spring and summer in 2008–2009 (0–80 cm depth for nitrogen, and 4–20 cm depth for microbial biomass).

A replicated, randomized, controlled study in 2007–2009 in an irrigated onion field near Madrid, Spain (7), found higher nitrous oxide and methane emissions in plots with added manure, compared to plots without added manure. **Greenhouse gases:** Higher nitrous oxide and methane emissions were found in plots with added manure (nitrous oxide: 1 vs 0.4 kg/ha; methane: 0.08 vs –1.15 kg/ha). **Methods:** Plots (20 m^2) had manure (a mixture of hen and goat manure) or no fertilizer (three plots each), added in 2007 and 2008 (110 kg N/ha). The manure was immediately incorporated into the soil (10 cm depth), using a rotocultivator. Plots were irrigated 1–2 times/week (608–618 mm/year). Greenhouse-gas samples (closed chambers, 19 litre volume, 10 mL samples, 0, 30, and 60 minutes after closing) and soil samples (0–10 cm depth) were collected four times/week in the first two weeks after fertilizer was applied, twice/week during the first month, and once/week until the end of cropping season.

A replicated, controlled study in 2006 in an almond orchard in Italy (8) found more organic matter, nitrogen, and higher pH levels in plots with added manure, compared to plots without added manure. **Organic matter:** More carbon was found in plots with added manure, compared to plots without added manure, in four of six comparisons (8,173–9,420 vs 7,339–8,263 mg/kg). **Nutrients:** More nitrogen was found in plots with added manure (1,027–1,280 vs 727–827 mg/kg). Higher pH levels were found in plots with added manure, in one of six comparisons (8.57 vs 8.31). **Methods:** Plots (495 m^2) had manure pellets (1.5 t/ha) or no fertilizer (three plots for each). Plots were drip-irrigated (2,000 m^3/ha/year). Soil samples were collected in 2006 (five samples/plot, 0–15 cm depth).

A replicated, controlled study in 2006–2007 in an almond orchard in Italy (9) found more organic matter and nitrogen, but inconsistent difference in phosphorus, in soils with added manure, compared to soils without added manure. **Organic matter:** More carbon was found in soils with added manure, in five of six comparisons (0.81–0.91% vs 0.52–0.63%). **Nutrients:** More nitrogen was found in soils with added manure (0.10–0.17 vs 0.06–0.08%). Less phosphorus was found in soils with added manure, in five of six comparisons (1–6 vs 7–16 μg/g), but more was found in one of six comparisons. **Methods:** Plots (85 x 17.5 m) had added manure (commercial cow manure pellets: 1.5 t/h) or no added manure (three plots for each). Manure was incorporated into the soil (15 cm depth). Soil samples (five samples/plot, 0–15 cm depth) were collected in November 2006 and 2007.

A replicated, randomized, controlled study in 2009 in an abandoned wheat field in Greece (10) found similar numbers of nematodes in plots with or without added manure. **Soil organisms:** Similar numbers of nematodes were found in soils with or without added manure (368–559 vs 308–567 individuals/100 cm^3). **Methods:** Plots (1 x 1 m) had added manure (4 kg/m^2) or no added manure (four plots for each). Manure was added in January and incorporated into the soil with a mattock. Soil samples (three/plot, 3–20 cm depth) were collected in March and June.

A replicated, randomized, controlled study in 2008–2011 in a wheat-barley field in northeast Spain (11) found similar amounts of organic matter and microbial biomass, but greater soil stability, in soils with added manure, compared to soils without added manure. **Organic matter:** Similar amounts of organic carbon were found in soils with or without added manure (amounts not reported). **Soil organisms:** Similar amounts of microbial biomass (measured as carbon) were found in soils with or without added manure (579–1,230 vs 591–900 mg C/kg soil). **Soil erosion and aggregation:** More water-stable macroaggregates, and larger macroaggregates, were found in soils with added manure, compared to soils without added manure (0.43 vs 0.39 kg water-stable macroaggregates/kg soil; 3.23 vs 3.02 mm mean weight diameter). **Methods:** Poultry manure (100 kg N/ha) was added to three treatment plots, but not to three control plots (5 x 12 m plots). Soil samples were collected seven times, from March 2010 to July 2011, with a flat spade (0–5 cm depth, two samples/plot).

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3.3. Add sewage sludge to the soil: Soil (6 studies)

- **Organic matter (1 study):** One replicated, controlled study from the USA[1] found more organic matter in soils with added sewage sludge, compared to soils without it.
- **Nutrients (2 studies):** One replicated, controlled study from Spain[4] found more nitrate in soils with added sewage sludge, compared to soils without it. One replicated, randomized, controlled study from Portugal[6] found similar amounts of nitrate in soils with or without added sewage sludge.
- **Soil organisms (2 studies):** Two replicated, controlled studies (one randomized) from Spain[3,5] found similar amounts of microbial biomass in soils with or without added sewage sludge.
- **Soil erosion and aggregation (2 studies):** One replicated, controlled study from Spain[2] found less erosion in plots with added sewage sludge, compared to plots without it. One replicated, controlled study from the USA[1] found no difference in stability between soils with or without added sewage sludge.
- **Greenhouse gases (2 studies):** Two replicated, controlled studies from Spain[3] and the USA[1] found higher carbon dioxide emissions from soils with added sewage sludge, compared to soils without it.
- **Implementation options (1 study):** One replicated, controlled study from Spain[4] found more nitrate in soils with digested sewage sludge, compared to composted or thermally dried sewage sludge.

A replicated, controlled study in 1997–1998 in irrigated fallow land in California, USA (1), found more organic matter and carbon dioxide in soils with added sewage sludge, compared to soils without it. **Organic matter:** More organic matter was found in soils with added sewage sludge, compared to soils without it (19 vs 10 g/kg). **Soil erosion and aggregation:** Similar amounts of water-stable aggregates were found in soils with or without added sewage sludge (367 vs 300 g/kg). **Greenhouse gases:** Higher carbon dioxide emissions were found in plots with added sewage sludge compared to plots without it (4 vs 1 μg/g/day). **Methods:** Plots (2 x 2 m) had sewage sludge (25 Mg/ha) or no added fertilizer (five plots each). Sewage sludge was added in April 1987, February 1988, and October 1988, and immediately incorporated into the soil (15 cm depth). Plots were irrigated weekly (100 mm/day). Five soil samples (25–100 mm depth) were taken from each plot.

A replicated, controlled study (year not reported) on a slope in Murcia, Spain (2), found less soil erosion in plots with added sewage sludge, compared to plots without it. **Soil erosion and aggregation:** Less soil was lost in runoff water from plots with added sewage sludge, compared to plots without it, after rainfall events (eight initial events: 48

vs 299 g soil/m^2; later events: 25 vs 62). **Methods:** Sewage sludge was added to three treatment plots, but not three control plots (10 x 3 m plots, 15% slope). Soil loss was measured in runoff water, collected from the lower edge of each plot, after each rainfall event. Enough sewage sludge was added to the soil to increase its organic carbon content by 2%. The soil was rotovated to a (20 cm depth), to incorporate the sewage sludge.

A replicated, controlled study in 2004 in a barley field in Spain (3) found more carbon dioxide in soils with added sewage sludge, compared to soils without it. **Soil organisms:** Similar amounts of microbial biomass (measured as carbon) were found in soils with or without added sewage sludge (179–229 vs 174 mg/kg). **Greenhouse gases:** Higher rates of respiration (measured as carbon dioxide) were found in soils with added sewage sludge, compared to soils without it, in one of two comparisons (50 vs 15 µg CO_2/g/day). **Methods:** Sewage sludge (40 t/ha) was added to some plots, but not to others (plot size and number of replicates not reported). Soil samples (0–20 cm depth) were taken from each plot, nine and 36 months after adding the sewage sludge.

A replicated, controlled study in 2001–2003 in a degraded wood pasture in Catalonia, Spain (4), found more nitrate in soils with added sewage sludge, compared to soils without it. **Nutrients:** More nitrate was found in soils with added sewage sludge, compared to soils without it (24–47 vs 3 kg N-NO_3/ha). **Implementation options:** More nitrate was found in soils with added digested sewage sludge, compared to composted or thermally dried sewage sludge (47 vs 24–28 kg N-NO_3/ha). **Methods:** There were five plots (20 x 5 m) for each of three sewage-sludge treatments (10 t dry matter/ha of composted, digested, or thermally dried sewage sludge) and one control (no sewage sludge). To restore the wood pasture, shrubs and small trees were crushed and scattered on the soil, and grass seeds were sown. Soil was collected in soil cores (10 cores/plot, 0–20 cm depth).

A replicated, randomized, controlled study in 2002–2005 in a barley field in Toledo, Spain (5), found similar amounts of microbial biomass in soils with or without added sewage sludge. **Soil organisms:** Similar amounts of microbial biomass (measured as carbon) were found in soils with or without added sewage sludge (86–136 vs 76 mg C/ha). **Methods:** The sewage sludge was thermally dried at 75^{o}C. There were four plots (10 x 3 m) for each of four fertilizer treatments (20 or 80 t sewage sludge/ha, applied once in three years or once/year) and there were four control plots (no fertilizer). Plots were fertilized in mid-September and planted in mid-October.

A replicated, randomized, controlled study in 2006–2008 in a cereal field in the Castelo Branco region, Portugal (6), found similar amounts of nitrate in soils with or without added sewage sludge. **Nutrients:** Similar amounts of nitrate were found in soils with or without added sewage sludge (1–50 vs 1–10 mg NO_3-N/litre water). **Methods:** Water in the soil was collected in porous ceramic suction cup samplers (four/plot; 0.6–0.7 m depth; 50 kPa for 24 hours), whenever drainage occurred (October–November and April–May; 16 samples in total). There were three plots (5.6 x 8 m) for each of two treatments (single application or split application of sewage sludge) and one control (no sewage sludge). Maize was grown in spring–summer, and oats were grown in autumn–winter.

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(3) García-Gil, J.C., Plaza, C., Senesi, N., Brunetti, G. & Polo, A. (2004) Effects of sewage sludge amendment on humic acids and microbiological properties of a semiarid Mediterranean soil. *Biology and Fertility of Soils*, 39, 320-328.
(4) Tarrasón, D., Ortiz, O. & Alcañiz, J.M. (2007) A multi-criteria evaluation of organic amendments used to transform an unproductive shrubland into a Mediterranean dehesa. *Journal of Environmental Management*, 82, 446-456.
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(6) Carneiro, J.P., Coutinho, J. & Trindade, H. (2012) Nitrate leaching from a maize × oats double-cropping forage system fertilized with organic residues under Mediterranean conditions. *Agriculture, Ecosystems & Environment*, 160, 29-39.

3.4. Add slurry to the soil: Soil (14 studies)

- **Organic matter (4 studies):** Three studies (two replicated, randomized, controlled; one meta-analysis) from Spain[9,11] and multiple Mediterranean countries[8] found similar amounts of organic matter in soils with or without added slurry. One replicated, randomized, controlled study from Spain[10] found more organic matter in soils with added slurry, compared to soils without it, in some comparisons.
- **Nutrients (4 studies):** Two replicated, randomized, controlled studies from Spain[1,12] found more nitrate in soils with added slurry, compared to soils without it. Two replicated, randomized, controlled studies from Portugal[7] and Spain[13] found similar amounts of nitrate in soils with or without added slurry. One of these studies[13] also found more ammonium, but another one[12] did not.
- **Soil organisms (2 studies):** One replicated, randomized, controlled study from Spain[12] found more microbial biomass in soils with added slurry, compared to soils without it, but another one[9] did not.
- **Soil erosion and aggregation (1 study):** One replicated, randomized, controlled study from Spain[9] found more stable soils in plots with added slurry, compared to plots without it, in some comparisons.
- **Greenhouse gases (8 studies)**
    - Carbon dioxide (3 studies): Of three replicated, randomized, controlled studies from Spain[4,11,12], two studies[11,12] found higher carbon dioxide emissions in soils with added slurry, compared to soils without it, but one study[4] did not.
    - Methane (4 studies): One replicated, randomized, controlled study from Spain[5] found that less methane was absorbed by soils with added slurry, compared to soils without it. Three replicated, randomized, controlled studies from Spain[4,11,12] found similar methane fluxes in soils with or without added slurry.
    - Nitrous oxide (6 studies): Five replicated, randomized, controlled studies from Spain[2,3,5,6,13] found higher nitrous oxide emissions in soils with added slurry, compared to soils without it, in some or all comparisons. One replicated, randomized, controlled study from Spain[12] found similar nitrous oxide emissions in soils with or without added slurry.

- **Implementation options (3 studies):** One replicated, randomized, controlled study from Spain[11] found no differences in organic matter or greenhouse-gas emissions between plots with different amounts of slurry. One replicated, randomized, controlled study from Spain[14] found similar amounts of nitrogen in soils with or without added slurry. One replicated, randomized, controlled study from Spain[3] found similar nitrous oxide emissions in soils with digested or untreated pig slurry. One replicated, randomized, controlled study from Spain[4] found similar carbon dioxide and methane emissions in soils with digested or untreated slurry.

A replicated, controlled study in 1998–1999 in irrigated arable farmland in Spain (1) found more nitrate in soils with added slurry, compared to soils without it. **Nutrients:** More nitrate was found in soils with added slurry, compared to soils without it (40–90 vs 10–22 mg/kg). **Methods:** Plots (10 × 11 m) had added pig slurry (165 kg/ha) or no added fertilizer (three replicates each). Slurry was incorporated into the soil, five days after application, using a rotocultivator (0–5 cm depth). Soil samples were taken during the first 15 days after application and every 2 weeks thereafter.

A replicated, randomized, controlled study in 2002 in irrigated arable farmland in Spain (2) found higher nitrous oxide emissions in plots with added slurry, compared to plots without it. **Greenhouse gases:** Higher nitrous oxide emissions were found in plots with added slurry, compared to plots without it, in one of two comparisons (1.1 vs 0.5 g N/m^2). **Implementation options:** Similar nitrous oxide emissions were found in plots with surface application, compared to injection, of slurry (0.8 vs 1 g N/m^2). **Methods:** Plots (3 x 3 m) growing tall fescue *Festuca arundinacea* had pig slurry (surface application or injection, 200 kg N/ha) or no fertilizer (three plots each). Each plot had a lysimeter (1 x 1 m, 0.75 m depth) to measure leaching. Slurry was injected (5 L/m) or applied with a watering can. Water (5 L/plot) was added to the control plots. All plots were sprinkler-irrigated (June–August: daily; September: twice/week). Soil cores were taken from the centre of the plots (0–10 cm depth). Gas samples were taken (chambers, 30 cm diameter, 30 cm height) twice/day for 1–4 days after slurry application, every 2–3 days from 7 to 40 days after application, once/week in July and August, and every fortnight in September–December.

A replicated, randomized, controlled study in 2004 in a maize field in the Jarama river basin, Spain (3), found higher nitrous oxide emissions from soils fertilized with slurry, compared to unfertilized soils. **Greenhouse gases:** Higher nitrous oxide emissions were found in soils with slurry, compared to unfertilised soils (untreated pig slurry: 8.3 vs 6.0; digested pig slurry: 7.7 vs 6.0 kg N/ha). **Implementation options:** No difference in nitrous oxide emissions was found between soils fertilized with digested pig slurry or untreated pig slurry (7.7 vs 8.3 kg N/ha). **Methods:** There were three plots (40 m^2) for each of two treatments (untreated pig slurry or anaerobically digested thin fraction of pig slurry) and one control (no slurry). Both slurries were applied at a rate of 175 kg available N/ha. Nitrous oxide was measured in closed chambers (two chambers/plot, one within a maize row, one between rows; 35 cm diameter, 23 cm height; one sample/week, April-September).

A replicated, randomized, controlled study in 2006 in a barley field in the Henares river basin, Spain (4), found no difference in greenhouse-gas emissions between soils with or without added slurry. **Greenhouse gases:** No differences in greenhouse-gas emissions were found between soils with or without added slurry (digested slurry, carbon dioxide: 465 vs 411 kg C/ha; methane: –287 vs –294 mg C/m^2; untreated slurry, carbon dioxide: 447 vs 411; methane: –229 vs –294). **Implementation options:** No differences in greenhouse-gas emissions were found between soils fertilized with digested slurry, compared to untreated slurry (carbon dioxide: 465 vs 447 kg C/ha; methane: –287 vs –229 mg C/m^2). **Methods:** There were three plots (30 m^2) for each of two treatments (anaerobically digested thin fraction of pig slurry or untreated pig slurry) and three control plots (no slurry). Slurry was applied in January (125 kg available N/ha). Plots were cultivated (5 cm depth) to incorporate the slurry. Barley was planted in January and harvested in June. Greenhouse-gas emissions were measured with closed chambers (35 cm diameter, 25 cm height, 1–4 measurements/plot/week, 23 January–28 November).

A replicated, randomized, controlled study in 2007–2009 in an irrigated onion field near Madrid, Spain (5), found that more nitrous oxide was emitted from, and less methane was absorbed by, plots with added slurry, compared to plots without it. **Greenhouse gases:** More nitrous oxide was emitted from plots with slurry, compared to plots without it (1 vs 0.4 kg/ha), and less methane was absorbed by plots with slurry (–0.5 vs –1 kg/ha). **Methods:** Plots (20 m^2) had anaerobically digested pig slurry (110 kg N/ha) or no fertilizer in 2007 and 2008 (three plots for each). Slurry was immediately incorporated into the soil (10 cm depth), using a rotocultivator. Plots were irrigated 1–2 times/week (608–618 mm/year). Greenhouse-gas samples (closed chambers, 19 litre volume, 10 mL samples, 0, 30, and 60 minutes after closing) and soil samples (0–10 cm depth) were collected four times/week in the first two weeks after fertilizer was applied, twice/week during the first month, and once/week until the end of cropping season.

A replicated, randomized, controlled study in 2007 in an irrigated melon field in Spain (6) found lower nitrous oxide emissions from plots with added slurry, compared to plots without it. **Greenhouse gases:** Higher nitrous oxide emissions were found in plots with added slurry, compared to plots without it (1–3 vs 2–3 kg/ha). **Methods:** Plots (4 x 5 m) growing melon *Cucumis melo* (6,950 plants/ha) had digested pig slurry or no slurry, and were either drip or furrow irrigated (three plots for each). Slurry was applied using a hose pipe (175 kg N/ha). Additional fertilizers were added immediately after (phosphorous: 50 kg/ha; potassium: 150 kg/ha). Slurry and fertilizer were incorporated into the soil (15 cm) using a rotocultivator. For furrow irrigation (2 L/min), there were five furrows/plot (80 cm width, 15 cm depth, 100 cm apart). For drip irrigation (3 L/h), there were two lines/subplot (1.8 m apart). Irrigation was applied 20 times, on a weekly basis. Gas samples were taken weekly until irrigation, daily for the first week after fertilizer application, 2–3 days/week for the first month, and then weekly.

A replicated, randomized, controlled study in 2006–2008 in a cereal field in the Castelo Branco region, Portugal (7), found similar amounts of nitrate in soils with or without added slurry. **Nutrients:** Similar amounts of nitrate were found in plots with and without added slurry (1–22 vs 1–10 mg NO_3–N/L water). **Methods:** Water in the soil was collected in porous ceramic suction cup samplers (four/plot; 0.6–0.7 m depth; 50 kPa for 24 hours), whenever drainage occurred (October–November and April–May; 16 samples in total). Cattle slurry was added to three treatment plots (5.6 x 8 m), but not three control plots, in spring. Maize was grown in spring–summer, and oats were grown in autumn–winter.

A meta-analysis from 2013 of studies in Mediterranean climates (8) found similar percentages of organic carbon in soils with or without added slurry. **Organic matter:** There was no difference in organic carbon between soils with or without added slurry (2% higher in soils with slurry). **Methods:** Slurry included liquid pig and cattle manure, both raw and digested. The Web of Knowledge database was searched, using the keywords, “Mediterranean”, “soil”, and “conventional”, and 3 data sets from 3 studies of slurry amendment were found and meta-analysed. The most recent studies included in this meta-analysis were published in 2011.

A replicated, randomized, controlled study in 2008–2011 in a wheat-barley field in Catalonia, northeast Spain (9), found similar amounts of organic matter and soil organisms, but greater soil stability, in soils with added manure, compared to soils without it. **Organic matter:** Similar amounts of organic carbon were found in soils with or without added slurry (amounts not reported). **Soil organisms:** Similar amounts of microbial biomass (measured as carbon) were found in soils with or without added slurry (655–1,372 vs 591–900 mg C/kg soil). **Soil erosion and aggregation:** More water-stable macroaggregates, and larger macroaggregates, were found in soils with added slurry in (200 kg N/ha) compared to soils without it, in one of two comparisons (0.43–0.44 vs 0.39 kg water-stable macroaggregates/kg soil; 3.30 vs 3.02 mean weight diameter). **Methods:** There were three plots (5 x 12 m) for each of two treatments (pig slurry, added at 100 or 200 kg N/ha) and there were three control plots (no slurry). Crops were planted in October (with a seed drill) and harvested by the end of June. Soil samples were collected seven times, from March 2010 to July 2011, with a flat spade (0–5 cm depth, two samples/plot).

A replicated, randomized, controlled study in 2002–2012 in a rainfed cereal field in Spain (10) found more organic matter and nutrients in soils with added slurry, compared to soils without it. **Organic matter:** More organic matter was found in plots with slurry, in one of five comparisons (1.9% vs 1.6%). **Nutrients:** More nitrogen, phosphorus, and potassium was found in plots with added slurry (nitrogen, in one of five comparisons: 0.14% vs 0.12%; phosphorus, in three of five comparisons: 52–78 vs 31 mg/kg; potassium, in two of five comparisons: 408–528 vs 279 mg/kg). Similar pH levels were found in plots with or without added slurry (pH 8.3–8.4). **Soil organisms:** Similar numbers of oribatid mites were found in plots with or without added slurry (2,404–5,448 vs 4,304 individuals/m^2). **Methods:** Plots (11 x 12.5 m or 7 x 12.5 m) had slurry (pig: 30 or 55 t/ha/year; sow: 25, 55, or 80 t/ha/year) or no fertilizer (12 replicates of each, but three replicates with sow slurry at 25 t/ha/year). Plots had reduced tillage (disc-harrowing, 15 cm depth) or no tillage (with herbicide). Straw was removed from all plots. Soil samples were collected in October 2011, February 2012, and May 2012 from plots without fertilizer and plots with 25 t/ha/year (three cores/plot, 0–5 cm depth). The other plots were sampled in May 2012.

A replicated, randomized, controlled study in 2010–2013 in rainfed barley fields in Spain (11) (same study as (13)), found higher carbon dioxide emissions in plots with added slurry, compared to plots without it. **Organic matter:** Similar amounts of carbon were found in plots with or without added slurry (98–110 vs 83–96 Mg/ha). **Greenhouse gases:** Similar amounts of methane were absorbed by plots with or without added slurry (–1 vs –2 kg C/ha). Higher carbon dioxide emissions were found in plots with added slurry (4,294–4,586 vs 3,227 kg C/ha). **Implementation options:** Similar amounts of carbon were found in plots with less or more slurry (98–110 vs 100–107 Mg/ha). Similar amounts of methane were absorbed by plots with less or more slurry (–1 vs –2 kg C/ha). Similar carbon dioxide emissions were found in plots with less or more slurry (4,294 vs 4,586 kg C/ha). **Methods:** Plots (40 x 12 m) had pig slurry (75 or 150 kg N/ha) or no fertilizer (three plots for each). Plots had conventional tillage (mouldboard plough: 25 cm depth; cultivator: 15 cm depth) or no tillage. Soil samples were collected at the end of the experiment (two samples/plot; 0–75 cm depth).

A replicated, randomized, controlled study in 2010–2012 in a rainfed barley field in Spain (12) found more nitrate and higher carbon dioxide emissions in plots with added slurry, compared to plots without it. **Nutrients:** Similar amounts of ammonium were found in plots with or without slurry (2.6 vs 1.9 mg/kg). More nitrate was found in plots with slurry (89 vs 20 mg/kg). **Soil organisms:** Similar amounts of microbial biomass (measured as carbon) were found in plots with or without slurry (859 vs 893 mg/kg), but more microbial biomass (measured as nitrogen) was found in plots with slurry (338 vs 177 mg/kg). **Soil erosion and aggregation:** Similar amounts of water-stable aggregates were found in plots with or without slurry (0.2 vs 0.1–0.2 g). **Greenhouse gases:** Higher carbon dioxide emissions were found in plots with slurry (1,669 vs 1,218 μg/kg macroaggregates/hour). Similar amounts of methane were absorbed by plots with or without slurry (–0.1 vs –0.2 μg/kg macroaggregates/hour). Similar nitrous oxide emissions were found in plots with or without slurry (1 vs 0.6 μg/kg macroaggregates/hour). **Methods:** Plots had pig slurry (150 kg N/ha) or no fertilizer (three plots each; plot size not clearly reported). Plots had conventional tillage (20 cm depth) or no tillage. Soil samples (0–5 cm depth) and gas samples (15 mL) were collected in March 2012.

A replicated, randomized, controlled study in 2010–2013 in rainfed barley fields in Spain (13) (same study as (11)) found more ammonium and higher nitrous oxide emissions in plots with added slurry, compared to plots without it. **Nutrients:** Similar amounts of nitrate were found in plots with or without added slurry (59–107 vs 65 kg/ha). More ammonium was found in plots with added slurry (12–16 vs 3 kg/ha). **Greenhouse gases:** Higher nitrous oxide emissions were found in plots with added slurry, compared to plots without it, in one of two comparisons (0.2 vs 0.1 mg/m/d) **Methods:** Plots (40 x 12 m) had pig slurry (75 or 150 kg N/ha) or no fertilizer (three plots for each). Plots had conventional tillage (mouldboard plough: 25 cm depth; cultivator: 15 cm depth) or no tillage. Soil samples were collected at the end of the experiment (two samples/plot; 0–75 cm depth).

A replicated, randomized, controlled study in 2003–2004 in an irrigated maize field in Spain (14) found similar amounts of nitrogen in plots with different amounts of added slurry. **Implementation options:** Similar amounts of nitrogen were found in plots with different amounts of added slurry (21–80 kg N/ha). **Methods:** Plots (30 x 40 m) had pig slurry (30, 60, 90, or 120 Mg/ha) or no fertilizer (three plots for each). Slurry was immediately covered after application. Lysimeters (2.6 x 2 m; 1.5 m depth) were installed in each plot, five years before the study. Each lysimeter was drip-irrigated, simulating flood irrigation (May to mid-September, with 7–12 intervals). Soil samples were collected after harvest (0–120 cm depth).

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3.5. Use organic fertilizer instead of inorganic: Soil (26 studies)

- **Organic matter (13 studies):** Eight replicated studies (including one meta-analysis) from France[26], Italy[6,9,15], Spain[19,23], Turkey[1], and Mediterranean countries[16] found more organic matter in soils with organic fertilizer, compared to inorganic fertilizer, in some comparisons. Five replicated, randomized, controlled studies from Greece[3], Spain[2,11,20], and the USA[7] found similar amounts of organic matter in soils with organic or inorganic fertilizer.
- **Nutrients (14 studies)**
  - Nitrogen (9 studies): Four replicated studies (three controlled, two randomized; one site comparison) from France[26], Italy[15], and Spain[19,23] found more nitrogen in soils with organic fertilizers, compared to inorganic fertilizer, in some comparisons. Five replicated, randomized, controlled studies from Greece[3], Spain[11,12,25], and the USA[7] found similar amounts of nitrogen in soils with organic or inorganic fertilizer.
  - Ammonium (3 studies): Two replicated, randomized, controlled studies from Italy[9] and Spain[21] found more ammonium in soils with organic fertilizer, compared inorganic fertilizer, in some comparisons. One replicated, randomized, controlled study from Spain[22] found similar amounts of ammonium in soils with organic or inorganic fertilizer.
  - Nitrate (3 studies): One replicated, randomized, controlled study from Spain[21] found less nitrate in soils with organic fertilizer, compared to inorganic fertilizer, in some comparisons. Two replicated, randomized, controlled studies from Portugal[14] and Spain[22] found similar amounts of nitrate in soils with organic or inorganic fertilizer.

- Phosphorus (5 studies): Three replicated, randomized, controlled studies from Italy[9] and Spain[19,23] found more phosphorus in soils with organic fertilizer, compared to inorganic fertilizer, in some or all comparisons. One replicated site comparison from France[26] found less phosphorous in soils with organic fertilizer, in some comparisons. One replicated, randomized, controlled study from Spain[12] found similar amounts of phosphorous in soils with organic or inorganic fertilizer.
- Potassium (6 studies): Three replicated, randomized, controlled studies from Italy[9] and Spain[19,23] found more potassium in soils with organic fertilizer, compared to inorganic fertilizer, in some comparisons. Three replicated studies (two controlled, one site comparison) from France[26] and Spain[11,12] found similar amounts of potassium in soils with organic or inorganic fertilizer.
- pH (6 studies): Four replicated studies (three randomized and controlled, one site comparison) from France[26], Italy[9], and Spain[11,23] found similar pH levels in soils with organic or inorganic fertilizer. One replicated, controlled study from Italy[15] found higher pH levels in soils with organic fertilizer, in some comparisons. One replicated, randomized, controlled study from Spain[2] found lower pH levels in soils with organic fertilizer, in some comparisons.

- **Soil organisms (7 studies)**
  - Microbial biomass (4 studies): Four replicated studies (three randomized and controlled, one site comparison) from France[26], Italy[9], and Spain[5,22] found more microbial biomass in soils with organic fertilizer, compared to inorganic fertilizer, in some comparisons.
  - Other soil organisms (4 studies): One replicated, randomized, controlled study from Spain[23] found fewer bacteria in soils with organic fertilizer, compared to inorganic fertilizer, in one comparison. One replicated site comparison from France[26] found fewer nematodes in plots with organic fertilizer, compared to inorganic fertilizer, in some comparisons. One replicated, randomized, controlled study from Spain[19] found fewer mites in plots with organic fertilizer, compared to inorganic fertilizer. One replicated, randomized, controlled study from Italy[24] found inconsistent differences in microbes between plots with organic or inorganic fertilizer.
- **Soil erosion and aggregation (5 studies):** Three replicated, randomized, controlled studies from Turkey[1] and Spain[18,22] found greater aggregation in soils with organic fertilizer, compared to inorganic fertilizer, in some or all comparisons. Two replicated, randomized, controlled studies from Spain[11] and the USA[7] found no difference in aggregation between soils with organic or inorganic fertilizer.
- **Greenhouse gases (11 studies)**
  - Carbon dioxide (5 studies): Four replicated, randomized, controlled studies from Italy[6] and Spain[20,22,23] found higher carbon dioxide emissions from plots with organic fertilizer, compared to inorganic fertilizer, in some comparisons. One replicated, randomized, controlled study from Spain[13] found similar carbon dioxide emissions from plots with organic or inorganic fertilizer.
  - Methane (4 studies): Two replicated, randomized, controlled studies from Spain[10,13] found that more methane was absorbed by soils with organic fertilizer, compared to inorganic fertilizer, in some comparisons. Two replicated, randomized, controlled studies from Spain[20,22] found that similar amounts of methane were absorbed by soils with organic or inorganic fertilizer.

- Nitrous oxide (8 studies): Five replicated, randomized, controlled studies from Spain[4,8,13,22,23] found similar nitrous oxide emissions from plots with organic or inorganic fertilizer. Three studies (including one meta-analysis and two replicated, randomized, controlled studies) from Spain[21], the USA[7], and Mediterranean countries[17] found lower nitrous oxide emissions from plots with organic fertilizer, compared to inorganic fertilizer, in some comparisons.

- **Implementation options (4 studies):** One study from Spain[13] found that plots with slurry absorbed methane, but plots with manure emitted methane. One study from Italy[9] found more organic matter, nutrients, and microbial biomass in plots fertilized with compost, compared to manure. One meta-analysis[17] found lower nitrous oxide emissions after adding solid organic fertilizer, but not liquid organic fertilizer, compared to inorganic fertilizer. One study[24] found inconsistent differences in soil bacteria with a single or double application of organic fertilizer.

A replicated, randomized, controlled study in 1995–1999 in arable farmland in southern Turkey (1) found more organic matter and greater stability in soils with organic fertilizer, compared to inorganic fertilizer. **Organic matter:** More organic matter was found in soils with compost, compared to mineral fertilizer, at one of two depths (0–15 cm: 1.8% vs 1.7%). Similar amounts of organic matter were found in soils with manure, compared to mineral fertilizer (1.6–1.8% vs 1.6%). **Soil erosion and aggregation:** Larger particles were found in soils with compost, compared to mineral fertilizer, at one of two depths (0–15 cm: 0.38 vs 0.27 mm mean weight diameter). Larger particles were found in soils with manure, compared to mineral fertilizer (0.38–0.43 vs 0.19–0.29 mm mean weight diameter). **Methods:** There were three plots (10 x 20 m) for each of three treatments: cattle manure (25 t/ha), compost (25 t/ha), or mineral fertilizer (160 kg N/ha, 26 kg P/ha, 83 kg P/ha). The compost was made of grass, stubble, and leaves. Wheat, sweet peppers, maize, and wheat were grown in rotation. Soils were sampled in 1999, after harvesting the last wheat crop (0–30 cm depth). Wet sieving was used to determine mean weight diameter.

A replicated, randomized, controlled study in 2003–2004 in a vegetable field in Murcia, Spain (2), found lower pH levels in plots with organic fertilizer, compared to inorganic fertilizer. **Organic matter:** Similar amounts of carbon were found in plots with organic or inorganic fertilizer (5–8 vs 3–5 g/kg). **Nutrients:** Lower pH was found in plots with organic fertilizer, compared to inorganic fertilizer, in one of four comparisons (pH 7.7 vs 8). **Methods:** Plots (6 m^2) growing Swiss chard *Beta vulgaris* followed by saltwort *Beta maritima* either had organic fertilizer (51 t/ha cow manure) or inorganic fertilizer (200 kg/ha). Soil was sampled four times, at sowing and sampling of each species (0–20 cm depth).

A replicated, randomized, controlled study in 2002–2005 in an irrigated maize field in Greece (3) found similar amounts of carbon and nitrogen in plots with organic or inorganic fertilizer. **Organic matter:** Similar amounts of organic carbon were found in soils with organic or inorganic fertilizer (5.7 vs 5.5 g C/kg). **Nutrients:** Similar amounts of nitrogen were found in soils with organic or inorganic fertilizer (0.81 vs 0.79 g Kjeldahl N/kg, 0–30 cm depth). **Methods:** Plots (5.6 x 8 m) had organic fertilizer (liquid cow manure 80 Mg/ha/year, before sowing) or inorganic fertilizer (260 kg N/ha/year and 57 kg P/ha/year, before sowing) (six plots each). Fertilizers were incorporated with a disk harrow (12–15 cm depth) within two hours of application. Soil samples were collected at the end of the growing season in 2005 (three samples/plot, 0–30 cm depth).

A replicated, randomized, controlled study in 2004 in a maize field in the Jarama river basin, Spain (4), found similar greenhouse-gas emissions in soils with organic or inorganic fertilizer. **Greenhouse gases:** No difference in nitrous oxide emissions was found in soils fertilized with pig slurry, compared to soils fertilized with urea (untreated pig slurry: 8.3 vs 8.6 kg N/ha; digested pig slurry: 7.7 vs 8.6). **Methods:** There were three plots (40 m^2) for each of two organic fertilizers (anaerobically digested thin fraction of pig slurry or untreated pig slurry) and one mineral fertilizer (urea, which was a mineral fertilizer in this study, but urea is also produced from animal waste). Slurries were applied at a rate of 175 kg available N/ha. Urea was applied at a rate of 50 kg N/ha. Soils were cultivated to a depth of 5 cm to incorporate the fertilizers. Nitrous oxide was measured in closed chambers (two chambers/plot, one within a maize row, one between rows; 35 cm diameter, 23 cm height; one sample/week, April–September).

A replicated, randomized, controlled study in 2002–2005 in a barley field in Toledo, Spain (5), found more microbial biomass in soils with organic fertilizer, compared to inorganic fertilizer. **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with organic fertilizer, compared to inorganic fertilizer, in two of eight comparisons (composted sewage sludge: 157–266 vs 83 mg C/ha). **Methods:** There were four plots (10 x 3 m) for each of eight organic fertilizers (20 or 80 t thermally dried sewage sludge/ha, applied once in three years or once/year; 20 or 80 t composted sewage sludge/ha, applied once in three years or once/year) and one mineral fertilizer (400 kg NPK/ha/year; 15-15-15 NPK). Plots were fertilized in mid-September and planted in mid-October.

A replicated, randomized, controlled study in 2003–2005 in farmland in the Sele river plain, Italy (6), found more organic matter and more carbon dioxide in organically fertilized soils, compared to inorganically fertilized soils. **Organic matter:** More organic matter was found in organically fertilized soils, compared to inorganically fertilized soils, in five of 18 comparisons (greenhouse, 45 t compost/ha: 30 vs 26 mg organic C/kg dry soil; open field, 30–45 t compost/ha: 10–12 vs 8). **Greenhouse gases:** More carbon dioxide was found in organically fertilized soils, compared to inorganically fertilized soils, in a greenhouse (0.9–1.2 vs 0.7 µg CO_2/g dry soil/hour), but there were no significant differences in an open field (0.8–1.4 vs 0.9). **Methods:** At each of two sites (unheated tunnel greenhouse with 24 m^2 plots, or open field with 70 m^2 plots), there were three replicates for each of four treatments (15, 30, or 45 t compost/ha, in March–April each year, or NPK fertilizer with 260–325 kg N/ha, 160–320 kg P_2O_5/ha, 140–310 kg K_2O/ha). The compost was made from municipal food waste and yard trimmings. Crops were grown in rotation (greenhouse: tomatoes, beans, lettuce; open field: tomatoes or eggplants, endive and/or broccoli sprouts). Soil samples (five/plot, 0–20 cm depth) were collected three times/year before the crops were harvested (greenhouse: spring, autumn, winter; open field: summer, autumn, winter). Organic carbon was measured in winter samples (residual carbon). Carbon dioxide (soil respiration) was measured in all samples.

A replicated, randomized, controlled study in 2003–2004 in three maize-tomato fields near Davis, California, USA (7), found lower greenhouse-gas emissions in soils with organic fertilizer, compared to inorganic fertilizer. **Organic matter:** Similar amounts of organic carbon were found in soils with organic or inorganic fertilizer (18 vs 19 Mg C/ha). **Nutrients:** Similar amounts of nitrogen were found in soils with organic or inorganic fertilizer (1.8–1.9 vs 2.0 Mg N/ha). **Soil erosion and aggregation:** Similar amounts of aggregation were found in soils with organic or inorganic fertilizer (1.2 vs 1.4 mm mean weight diameter). **Greenhouse gases:** Lower nitrous oxide emissions were found in soils with organic fertilizer, compared to inorganic fertilizer, in two of seven comparisons (emissions not reported for all comparisons; the highest emissions were found in plots with conventional tillage: 40 g N_2O–N/ha/day). **Methods:** Organic or inorganic fertilizer was used on six plots each (1.5 x 1.0 m plots). Urea was added to inorganically-fertilized plots (April: 60 kg N/ha; May: 200 kg N/ha). On organically-fertilized plots, inorganic fertilizer was replaced, every other year, with the residues of legume cover crops (100 kg N/ha). Soil samples were collected with soil cores (two cores/plot, 4 cm diameter, 0–15 cm depth), when the maize was harvested (September). Greenhouse-gas emissions were measured with closed chambers (March–September, every three week). Maize was sown at different times (organically-fertilized plots: March; inorganically-fertilized plots: May), and different amounts of nitrogen were applied. It was not clear whether these results were direct effects of differences in the type of fertilizer (organic or inorganic), the amount of fertilizer, or the planting date.

A replicated, randomized, controlled study in 2009 in a rainfed barley field in Spain (8) found similar nitrous oxide emissions in plots with organic or inorganic fertilizers. **Greenhouse gases:** Similar nitrous oxide emissions were found in plots with organic or inorganic fertilizers (266–373 vs 345 g/ha). Lower nitric oxide emissions were found from plots with organic fertilizer, compared to inorganic fertilizers, in three of four comparisons (29–45 vs 62 g/ha). **Methods:** Plots (30 m^2) had organic fertilizer (pig slurry, anaerobically-digested pig slurry, municipal solid waste, or composted crop residue with sludge) or inorganic fertilizer (urea), applied in January 2006 (125 kg N/ha; three plots for each fertilizer) and incorporated into the soil using a roto-cultivator (0–5 cm depth). Phosphate and potassium (75 and 40 kg/ha, respectively) were added to all plots. Greenhouse gases were measured in manual chambers (35 cm diameter, 20 cm height), four times in the first week after fertilizer application, 2–3 times/week in the first month, and once/week until the end of the cropping season or until emissions were close to zero.

A replicated, randomized, controlled study in 2001–2009 in an irrigated nectarine orchard in Italy (9) found more organic matter, nutrients, and microbial biomass in soils with organic fertilizer, compared to inorganic fertilizer. **Organic matter:** More organic matter was found in soils with organic fertilizer, compared to inorganic fertilizer, in 11 of 32 comparisons (2–5% vs 1–2%). **Nutrients:** More nitrogen (ammonium), phosphorus, and potassium was found in soils with organic fertilizer, compared to inorganic (ammonium, in two of 28 comparisons: 10–15 vs 6–7 mg/kg; phosphorus, in one of four comparisons: 24 vs 14 mg/kg; potassium, in three of four comparisons (299–350 vs 234 mg/kg). Similar pH levels were found in plots with organic or inorganic fertilizer (pH 7.7–7.8 vs 7.8). **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with organic fertilizer, compared to inorganic fertilizer, in 11 of 76 comparisons (5–22 vs 4–11 mg/g). **Implementation options:** More organic matter, nutrients, and microbial biomass was found in plots with compost, compared to manure (organic matter, in seven of 21 comparisons: 2–5% vs 2–3%; ammonium, in two of 21 comparisons: 10–14 vs 6 mg/kg; phosphorus, in one of three comparisons: 24 vs 20 mg/kg; potassium, in one of three comparisons: 350 vs 312 mg/kg; microbial biomass, in nine of 60 comparisons: 5–22 vs 2–13 mg/g). Similar pH levels were found in plots with compost or manure (pH 7.7 vs 7.8). **Methods:** There were four plots for each of four organic-fertilizer treatments (5 t compost/ha in May; 5 t/ha split into two applications, in May and September; 10 t/ha split into two; or 5–10 kg dry cow manure/ha), and there were four plots for inorganic fertilizer (70–130 kg N/ha, 100 kg P/ha, 200 kg K/ha; plot size not reported). The compost was made from domestic organic waste and urban pruning material (50% each). Fertilizers were tilled into the soil (25 cm depth). Soil samples were collected in September (3–40 cm depth for organic matter in 2001–2008 and phosphorus in 2006) and four times in spring and summer in 2008–2009 (0–80 cm depth for nitrogen, and 4–20 cm depth for microbial biomass).

A replicated, randomized, controlled study in 2006 in a barley field in the Henares river basin, Spain (10), found that more methane was absorbed by soils with organic fertilizer, compared to inorganic fertilizer. **Greenhouse gases:** More methane was absorbed by soils with organic fertilizer, compared to inorganic fertilizer, in one of four comparisons (digested slurry: –286 vs –115 mg C/m^2). No differences in carbon dioxide emissions were found between soils with organic fertilizers or urea (334–466 vs 458 kg C/ha). **Methods:** There were three plots (30 m^2) for each of four organic fertilizers (anaerobically digested thin fraction of pig slurry, untreated pig slurry, composted municipal solid waste, or sewage sludge and composted crop residues) and one mineral fertilizer (urea), applied in January (125 kg available N/ha). Plots were cultivated (0–5 cm depth) to incorporate the fertilizers. Barley was planted in January and harvested in June. Greenhouse-gas emissions were measured with closed chambers (35 cm diameter, 25 cm height, 1–4 measurements/plot/week, 23 January–28 November).

A replicated, randomized, controlled study in 2006 in a rainfed almond orchard near Granada, Spain (11), found no differences in organic matter, nutrients, or soil stability between plots with organic or inorganic fertilizer. **Organic matter:** Similar amounts of organic carbon were found in soils with organic or inorganic fertilizer (8.8 vs 8.6 g C/kg soil). **Nutrients:** Similar amounts of nitrogen (1.1 g N/kg soil), phosphorus (1.7 vs 2 mg P/kg soil), and potassium (156 vs 153 mg K/kg soil), and similar pH levels (pH 8.3), were found in soils with organic or inorganic fertilizer. **Soil erosion and aggregation:** Similar soil stability was found in plots with organic or inorganic fertilizer (62% of soil aggregates were water-stable; 16% vs 15% change in the mean weight diameter of soil aggregates after sieving). **Methods:** Organic fertilizer (1,500 kg compost/ha, made from sheep manure and turf) or mineral fertilizer (250 kg/ha, 4.6% N, 1.2% P, 1.5% K) was used on 18 plots each (588 m^2). Some organic fertilizer was used on all plots (30 t manure/ha), and one-third of the plots were grazed by sheep (7 kg organic C/ha from excrement). All plots had cover crops. Soil samples were collected on 18 July 2006 (0–20 cm depth). It was not clear whether these results were a direct effect of the type or amount of fertilizer.

A replicated, randomized, controlled in 2006–2008 in an irrigated alfalfa field in Spain (12) found no differences in nutrients between soils with organic or inorganic fertilizers. **Nutrients:** Similar amounts of nitrogen (3%), phosphorous (0.3%), and potassium (3%) were found in plots with organic or inorganic fertilizer. **Methods:** Lysimeters (5 m^2 and 1.5 m deep) had either organic fertilizer (pig slurry: 170 or 340 kg N/ha/year) or inorganic fertilizer (phosphorous-potassium: 200 kg/ha/year; phosphorus pentoxide and potassium oxide: 150 kg/ha/yr). Soil was sampled before sowing alfalfa (April 2006), at the start of the second growing season (February 2007), and at the end of the two growing seasons when the slurry was applied (November 2007 and 2008).

A replicated, randomized, controlled study in 2007–2009 in an irrigated onion field near Madrid, Spain (13), found similar nitrous oxide emissions in plots with organic or inorganic fertilizer, but more methane was absorbed by plots with organic fertilizer, in some comparisons. **Greenhouse gases:** Similar nitrous oxide emissions were found in plots with organic or inorganic fertilizer (1.1–1.2 vs 1.2 kg/ha). More methane was absorbed by plots with organic fertilizer, compared inorganic fertilizer, in one of two comparisons (–0.49 vs –0.02 kg/ha). **Implementation options:** Plots that were fertilized with slurry absorbed methane, but plots that were fertilized with manure emitted methane (–0.5 to –0.02 vs 0.08 kg/ha). **Methods:** Plots (20 m^2) had organic fertilizer (anaerobically digested pig slurry, or hen and goat manure) or inorganic fertilizer (urea) in 2007 and 2008 (110 kg N/ha; three plots for each). Fertilizers were immediately incorporated into the soil (10 cm depth), using a rotocultivator. Plots were irrigated 1–2 times/week (608–618 mm/year). Greenhouse-gas samples (closed chambers, 19 litre volume, 10 mL samples, 0, 30, and 60 minutes after closing) and soil samples (0–10 cm depth) were collected four times/week in the first two weeks after fertilizer was applied, twice/week during the first month, and once/week until the end of cropping season.

A replicated, randomized, controlled study in 2006–2008 in a cereal field in the Castelo Branco region, Portugal (14), found similar amounts of nitrate in soils with organic fertilizer, compared to inorganic fertilizer, in most comparisons. **Nutrients:** Similar amounts of nitrate were found in soils with organic fertilizer, compared to inorganic fertilizer, in 78 of 80 comparisons (1–50 vs 1–31 mg NO_3-N/litre water). In two of 16 comparisons, less nitrate was found in plots with cattle slurry, compared to mineral fertilizer (13 days after application: 11 vs 28 mg NO_3-N/litre water; 33 days after application: 6 vs 15 mg). **Methods:** Water in the soil was collected in porous ceramic suction cup samplers (four/plot, 0.6–0.7 m depth, 50 kPa for 24 hours), whenever drainage occurred (October–November and April–May: 16 samples in total). There were three plots (5.6 x 8 m) for each of five organic-fertilizer treatments (single application in spring, or split application in spring and autumn, of municipal waste compost or sewage sludge, or split application of cattle slurry) and one mineral-fertilizer treatment. Maize was grown in spring–summer, and oats were grown in autumn–winter.

A replicated, controlled study in 2006 in an almond orchard in Italy (15) found more carbon and nitrogen, and higher pH levels, in plots with organic fertilizer, compared to inorganic fertilizer. **Organic matter:** More carbon was found in soils with organic fertilizer, compared to inorganic fertilizer, in seven of 12 comparisons (8,173–9,420 vs 7,307–8,740 mg/kg). **Nutrients:** More nitrogen was found in soils with organic fertilizer, compared to inorganic fertilizer, in 10 of 12 comparisons (1,027–1,280 vs 760–1,037 mg/kg). **pH:** Higher pH levels were found in soils with organic fertilizer, compared to inorganic fertilizer, in six of 12 comparisons (pH 8.3–8.8 vs 7.5–8.0). **Methods:** Plots (495 m^2) had organic fertilizer (manure pellets: 1.5 t/ha) or inorganic fertilizer (300 kg/ha in summer; three unspecified doses in spring) (three plots for each fertilizer). Plots were drip-irrigated (2,000 m^3/ha/year). Soil samples were collected in 2006 (five samples/plot, 0–15 cm depth).

A meta-analysis from 2013 of studies in Mediterranean climates (16) found a higher percentage of organic carbon in soils with added organic matter, compared to conventionally fertilized soils. **Soil organic matter:** A higher percentage of soil organic carbon was found with than without added organic matter (24% higher). **Methods:** The Web of Knowledge database was searched, using the keywords, “Mediterranean”, “soil”, and “conventional”, and 37 data sets from 26 studies of organic amendment were found and meta–analysed. The most recent studies included in this meta–analysis were published in 2011.

A meta-analysis from 2013 of studies in Mediterranean climates (17) found that nitrous oxide emissions from soils were lower after adding organic fertilizer, compared to synthetic fertilizer. **Greenhouse gases:** Nitrous oxide emissions were 23% lower after adding organic fertilizer, compared to synthetic fertilizer. **Implementation options:** Nitrous oxide emissions were lower after adding solid organic fertilizer, but not liquid organic fertilizer, compared to synthetic fertilizer (solid: 28% lower; liquid: 8% lower).

Methods: Solid organic fertilizers included cover-crop residues, manure, composed manure, composted municipal solid waste, and composted thick fractions of digested pig slurries. Liquid organic fertilizers included raw or digested pig slurries. Synthetic fertilizers included ammonium nitrate, ammonium sulfate, urea, and NPK. Eight studies were included in the meta-analysis. These studies were found by searching the Web of Knowledge database, using the terms "nitrous oxide" or "N_2O" and "emission" and "Mediterranean" or the name of a country with a Mediterranean climate, and also by searching the references in the publications that were found.

A replicated, randomized, controlled study in 2000–2005 in an irrigated barley-maize field in Spain (18) found more water-stable aggregates in soils with organic fertilizer, compared to inorganic fertilizer. **Soil erosion and aggregation:** More water-stable aggregates were found in soils with organic fertilizer, compared to inorganic fertilizer (15–17% vs 6%). **Methods:** Plots (3.8 x 2.5 m) had inorganic fertilizer (barley: 150 kg N/ha/year; maize: 100 kg N/ha/year) or organic fertilizer (slurry: 30, 60, 90, or 120 Mg/ha/year) in 2000–2003 (three plots for each). Phosphorus (120 kg P_2O_5/ha) and potassium (180 kg KCl/ha) were added to all plots in 2003 and 2004. Barley was sown in December 2003 and harvested in June 2004. Maize was sown in July 2004 and harvested in December.

A replicated, randomized, controlled study in 2002–2012 in a rainfed cereal field in Spain (19) found more organic matter and nutrients, but fewer mites, in soils with organic fertilizer, compared to inorganic fertilizer. **Organic matter:** More organic matter was found in plots with organic fertilizer, compared to inorganic fertilizer, in one of 10 comparisons (1.9% vs 1.6%). **Nutrients:** More nitrogen (in two of 10 comparisons: 0.14% vs 0.10–0.12%), phosphorus (in 8 of 10 comparisons: 35–78 vs 24–40 mg/kg), and potassium (in six of ten comparisons: 268–528 vs 188–294 mg/kg) was found in soils with organic fertilizer, compared to inorganic fertilizer, but similar pH levels were found. **Soil organisms:** Fewer oribatid mites were found in plots with organic fertilizer, compared to inorganic fertilizer, in one of ten comparisons (2,404 vs 5,440 individuals/m^2). **Methods:** Plots (11 x 12.5 m or 7 x 12.5 m) had no fertilizer, slurry (pig: 30 or 55 t/ha/year; sow: 25, 55, or 80 t/ha/year), or mineral fertilizer (60 or 120 kg N/ha) (12 replicates of each, but three replicates with sow slurry at 25 t/ha/year). Plots had reduced tillage (disc-harrowing, 15 cm depth) or no tillage (with herbicide). Straw was removed from all plots. Soil samples were collected in October 2011, February 2012, and May 2012 from plots without fertilizer and plots with 25 t/ha/year (three cores/plot, 0–5 cm depth). The other plots were sampled in May 2012.

A replicated, randomized, controlled study in 2010–2013 in rainfed barley fields in Spain (20) (same study as (21)) found higher carbon dioxide emissions in plots with organic fertilizer, compared to inorganic fertilizer. **Organic matter:** Similar amounts of carbon were found in soils with organic and inorganic fertilizers (92–110 vs 87–101 Mg/ha). **Greenhouse gases:** Similar uptake of methane was found in plots with organic fertilizer compared to inorganic fertilizer (–3 to –1 vs –4 to –1 kg C/ha). Higher carbon dioxide emissions were found in plots with organic fertilizer, compared to inorganic fertilizer, in two of 12 comparisons (4,586 vs 3,575–3,802 kg C/ha). **Methods:** Plots (inorganic: 50 x 6 m or 40 x 6 m; organic: 40 x 12 m) had inorganic fertilizer (60, 75, 120, or 150 kg N/ha) or organic fertilizer (pig slurry: 75 or 150 kg N/ha) (three plots for each). Plots had conventional tillage (mouldboard plough: 25 cm depth; cultivator: 15 cm depth) or no tillage. Soil samples were collected at the end of the experiment (two samples/plot; 0–75 cm depth).

A replicated, randomized, controlled study in 2010–2013 in rainfed barley fields in Spain (21) (same study as (20)) found less nitrate and lower nitrous oxide emissions, but more ammonium, in plots with organic fertilizer, compared to inorganic fertilizer. **Nutrients:** Less nitrate was found in plots with organic fertilizer, compared to inorganic fertilizer, in two of four comparisons (59 vs 107–148 kg/ha). More ammonium was found in plots with organic fertilizer, compared to inorganic fertilizer, in one of four comparisons (16 vs 9 kg/ha). **Greenhouse gases:** Lower nitrous oxide emissions were found in plots with organic fertilizer, compared to inorganic fertilizer, in one of four comparisons (0.1 vs 0.3 mg/m/day). **Methods:** Plots (inorganic: 50 x 6 m or 40 x 6 m; organic: 40 x 12 m) had inorganic fertilizer (60, 75, 120, or 150 kg N/ha) or organic fertilizer (75 or 150 kg N/ha) (three plots for each). Plots had conventional tillage (mouldboard plough: 25 cm depth; cultivator: 15 cm depth) or no tillage. Soil samples (0–5 cm depth) and nitrous oxide samples (closed chambers, 15 mL samples, 0, 30, and 60 minutes after closing), were collected every 2–3 weeks in 2011–2013.

A replicated, randomized, controlled study in 2010–2012 in a rainfed barley field in Spain (22) found higher carbon dioxide emissions in plots with organic fertilizer, compared to inorganic fertilizer. **Nutrients:** Similar amounts of ammonium (3 vs 2 mg/kg) and nitrate (89 vs 85 mg/kg) were found in plots with organic or inorganic fertilizer. **Soil organisms:** Similar amounts of microbial biomass (measured as carbon) were found in plots with organic or inorganic fertilizer (859 vs 978 mg/kg), but more microbial biomass (measured as nitrogen) was found in plots with organic fertilizer (338 vs 183 mg/kg). **Soil erosion and aggregation:** More water-stable aggregates were found in plots with organic fertilizer, compared to inorganic fertilizer, in one of two comparisons (0.2 vs 0.1 g). **Greenhouse gases:** Higher carbon dioxide emissions were found in plots with organic fertilizer, compared to inorganic fertilizer (1,669 vs 1,199 μg/kg macroaggregates/hour). Similar methane fluxes were found in plots with organic or inorganic fertilizer (–0.1 vs 0.1 μg/kg macroaggregates/hour). Similar nitrous oxide emissions were found in plots with organic or inorganic fertilizer (1 vs 0.9 μg/kg macroaggregates/hour). **Methods:** Plots had organic or inorganic fertilizer (150 kg N/ha) (three plots each; plot size not clearly reported). Plots had conventional tillage (20 cm depth) or no tillage. Soil samples (0–5 cm depth) and gas samples (15 mL) were collected in March 2012.

A replicated, randomized, controlled study in 1996–2011 in a vineyard in Navarra, Spain (23), found more organic matter and nutrients, and higher greenhouse-gas emissions, in plots with organic fertilizer, compared to inorganic fertilizer. **Organic matter:** More organic matter was found in plots with organic fertilizer, compared to inorganic fertilizer, in one of three comparisons (SMC compost: 1.8% vs 1.1%). **Nutrients:** More nitrogen (in two of three comparisons: 0.1% vs 0.06%), phosphorus (65–81 vs 29 mg/kg), and potassium (potassium oxide, in one of three comparisons: 474 vs 253 mg/kg) were found in soils with organic fertilizer, compared to inorganic fertilizer. **Soil organisms:** Similar bacteria communities were found in all plots, for 11 of 12 bacteria genera. However, in plots fertilized with compost, a lower percentage of RNA sequences came from *Nitrosporia* or *Nitrosolobus* species (0.0–0.1%), compared to plots fertilized with inorganic fertilizer (0.2%). **Greenhouse gases:** Higher greenhouse-gas emissions were found in plots with organic fertilizer, compared to inorganic fertilizer (1,591–1,745 vs 1,053 kg CO_2 equivalent/ha, cumulative over 115 days after fertilizer). Similar nitrous oxide emissions were found in plots with organic or inorganic fertilizer (1.8–5.1 g N_2O-N/ha/day, 15 days after fertilizer). **Methods:** Three types of organic fertilizer (compost) were compared with one mineral fertilizer (MIN): pelletized organic compost (PEL), compost from the organic fraction of municipal solid waste (OF-MSW), and sheep-manure compost (SMC). Each treatment was assigned to a plot (15 vines), and there were three blocks (the size of plots within blocks was not clearly reported). Compost or fertilizer was added in February 1998–2011 (PEL: 3,700 kg fresh weight/ha/year; OF-MSW: 4,075 kg; SMC: 4,630 kg; MIN: 340 kg NPK/ha/year). For N, P, K, and pH measurements, soil samples were taken at the end of 2011 (four samples/plot, 0–30 cm depth). For greenhouse-gas measurements, air samples (20 ml, 10 samples/plot, closed chambers) were taken over 115 days after adding fertilizer. For partial prokaryotic 16S rRNA sequencing, soil samples (four/plot, 5–30 cm depth) were taken 15 days after adding fertilizer.

A replicated, randomized, controlled study in 2015 in a sorghum field in Italy (24) found inconsistent differences in bacteria between plots with organic or inorganic fertilizer. **Soil organisms:** More bacteria were found in plots with organic fertilizer, compared to inorganic fertilizer, in three of 32 comparisons (111–2,017 vs 20–1,690 phylotype 16S rRNA sequences), but fewer were found in three of 32 comparisons (60–1,658 vs 103–1,858 sequences). **Implementation options:** More bacteria were found in plots with a double application of organic fertilizer, compared to a single application, in one of 16 comparisons (1,658 vs 1,469 sequences), but less were found in one of 16 comparisons (34 vs 111 sequences). **Methods**: Plots (5 x 8 m) had inorganic fertilizer (130 kg urea/ha) or compost (single application: 130 kg N/ha; double application: 260 kg N/ha) (four plots for each). After three years of compost addition, plants were dug up (three plants/plot) and soil that was clinging to plant roots was collected for sampling bacteria (through RNA sequencing).

A replicated, randomized, controlled study in 2003–2004 in an irrigated maize field in Spain (25) found similar amounts of nitrogen in plots with organic or inorganic fertilizer. **Nutrients:** Similar amounts of nitrogen were found in plots with organic or inorganic fertilizer (21–80 vs 13–37 kg N/ha). **Methods:** Plots (30 x 40 m) had organic fertilizer (pig slurry: 30, 60, 90, or 120 Mg/ha) or inorganic fertilizer (0, 180, 240, or 300 kg N/ha) (three plots for each). Slurry was immediately covered after application. Lysimeters (2.6 x 2 m; 1.5 m depth) were installed in each plot, five years before the study. Each lysimeter was drip-irrigated, simulating flood irrigation (May to mid-September, with 7–12 intervals). Soil samples were collected after harvest (0–120 cm depth).

A replicated site comparison in 2009 in rainfed vineyards in southern France (26) found more organic matter, nitrogen, and microbial biomass, but less phosphorus and fewer nematodes, in soils with organic fertilizer, compared to inorganic fertilizer. **Organic matter:** More organic carbon was found in soils with organic fertilizer, compared to inorganic fertilizer, in one of three comparisons (11 vs 7 g C/kg soil). **Nutrients:** More nitrogen was found in soils with organic fertilizer, compared to inorganic fertilizer, in one of three comparisons (1.1 vs 0.7 g N/kg soil), but less phosphorus was found in one of three comparisons (6 vs 8 mg P/kg soil). Similar amounts of potassium and similar pH levels were found in soils with organic or inorganic fertilizer (data not reported). **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with organic fertilizer, compared to inorganic fertilizer, in one of three comparisons (49 vs 23 mg C/kg soil), and fewer nematodes were found in one of three comparisons (616 vs 860 total nematodes/100 g soil). **Methods:** In 146 plots of three soil types, inorganic fertilizer only (37–69% of plots in each soil type) or at least some organic fertilizer (31–63%) was used for at least five years before soil sampling. Soil samples were collected from the interrows in March–May 2009 (10 homogenized samples/plot, 0–15 cm depth).

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3.6. Grow cover crops in arable fields: Soil (29 studies)

- **Organic matter (12 studies):** One meta-analysis of studies from Mediterranean-type climates[20] and ten replicated, controlled studies (nine randomized, two before-and-after) from Italy[17,25], Spain[11], and the USA[5,6,9,10,12,14,27] found more organic matter (mostly measured as carbon) in soils with winter cover crops, compared to soils without them, in some comparisons[5,11,17,25] or all comparisons[5,6,9,10,12,14]. One replicated, randomized, controlled, before-and-after study from Italy[26] found inconsistent differences in organic matter in soils with or without winter cover crops (sometimes more, sometimes less).
- **Nutrients (22 studies)**
  - Nitrogen (21 studies): Ten replicated, randomized, controlled studies (two before-and-after) from Italy[17,22,26,29], Spain[11], and the USA[5,8,12,14,21] found more nitrogen in soils with winter cover crops, compared to soils without them, in some comparisons. One replicated, randomized, controlled study from the USA[1] found less nitrogen in soils with winter cover crops, compared to soils without them. Ten replicated, controlled studies (nine randomized, two before-and-after) from Italy[25], Spain[15,18], and the USA[2-4,7,9,10,16] found inconsistent differences in nitrogen (sometimes more, sometimes less) between soils with or without winter cover crops (but see the paragraphs, below, for distinctions between different forms of nitrogen).
  - Phosphorus (1 study): One replicated, randomized, controlled study from the USA[24] found similar amounts of phosphorus in soils with or without winter cover crops.
  - Potassium (1 study): One replicated, randomized, controlled, before-and-after study from the USA[10] found an increase in potassium in soils with winter cover crops, and no increase in soils without them.
- **Soil organisms (12 studies)**
  - Microbial biomass (6 studies): Five replicated, randomized, controlled studies from the USA[3,4,9,16,24] found more microbial biomass in soils with cover crops, compared to soils

without them, in some comparisons[3,4,9,16] or all comparisons[24]. One replicated, randomized, controlled, before-and-after study from Italy[26] found inconsistent differences in microbial biomass (sometimes more, sometimes less) between soils with or without winter cover crops.

  - Nematodes (2 studies): Two replicated, randomized, controlled studies from the USA[8,12] found more nematodes in soils with cover crops, compared to soils without them, in some comparisons. One of these studies[8] also found a higher ratio of bacteria-feeding nematodes to fungus-feeding nematodes in soils with cover crops, compared to soils without them.
  - Earthworms (2 studies): One replicated, controlled study from the USA[6] found more earthworms in soils with winter cover crops, compared to soils without them. One replicated site comparison from the USA[13] found similar numbers of earthworms in soils with or without winter cover crops.
  - Bacteria and fungi (2 studies): One replicated, randomized, controlled study from Spain[11] found more bacteria and fungi in soils with winter cover crops, compared to soils without them, in some comparisons. One replicated, controlled study from Italy[28] found more spores and species of beneficial fungi (mycorrhizae) in soils with winter cover crops, compared to soils without them, in some comparisons.

- **Soil erosion and aggregation (4 studies)**
  - Soil erosion (2 studies): Two controlled studies (one replicated and randomized) from Israel[23] and the USA[19] found less erosion of soils with cover crops, compared to soils with fallows or bare soils.
  - Soil aggregation (2 studies): Two replicated, randomized, controlled studies from Spain[11] and the USA[5] found more water-stable soil aggregates in plots with winter cover crops, compared to plots without them, in some comparisons[11] or all comparisons[5].
- **Greenhouse gases (5 studies)**
  - Carbon dioxide (5 studies): Three controlled studies (two replicated and randomized) from Italy[25] and the USA[8,19] found similar amounts of carbon dioxide in soils with or without cover crops. Two replicated, randomized, controlled studies from the USA[14,16] found more carbon dioxide in soils with cover crops, compared to soils without them, in some comparisons.
  - Carbon storage (1 study): One replicated, randomized, controlled study from Italy[25] found more carbon accumulation in soils with cover crops, compared to soils without them, in some comparisons.
  - Nitrous oxide (2 studies): One replicated, randomized, controlled study from the USA[14] found more nitrous oxide in soils with cover crops, compared to soils without them, in some comparisons. One controlled study from the USA[19] found similar amounts of nitrous oxide in soils with cover crops or fallows.
- **Implementation options (9 studies):** Five studies from Italy[17,22,29], Spain[18], and the USA[12] found more nitrogen in soils that were cover cropped with legumes, compared to non-legumes. One study from the USA[21] found inconsistent differences in nitrogen (sometimes more, sometimes less) between soils with different cover crops. One study from the USA[24] found no differences in phosphorus or microbial biomass between soils with different cover crops. One study from Italy[28] found differences in beneficial fungi (mycorrhizae) between plots with different

cover crops. One study from Spain[11] found higher soil quality in plots with long-term cover crops, compared to short-term.

A replicated, randomized, controlled study in 1986–1988 in an irrigated lettuce field in the Salinas Valley, California, USA (1), found less ammonium in plots with winter cover crops, compared to winter fallows. **Nutrients:** Less ammonium was found in soils with cover crops, compared to fallows, in at least one of eight comparisons (after harvesting the spring crop, in plots that were side-dressed with fertilizer: 4.4 vs 5.2 ppm NH_4-N). Similar amounts of nitrate were found in soils with or without cover crops (in March 1998: 11–27 vs 29 ppm NO_3-N). **Methods:** There were six plots (10.7 x 1.1 m raised beds) for each of two winter cover crops (broad beans or rye) and six control plots (bare fallow, maintained with herbicide). The cover crops were seeded in November 1986–1987, irrigated until emergence, and chopped, disked, and chisel ploughed in spring (25–30 cm depth). Lettuces were planted in May and July 1987 and March and August 1988, and they were harvested in July and October 1987 and June and October 1988. The lettuces were irrigated (1–2 cm every 2–3 days until emergence, then 2 cm/week), and some lettuce plots were fertilized (110–220 kg N/ha in total; up to 110 kg N/ha as side-dressing). Soil samples were collected in March, June, August, and September 1988 (0–22 cm depth, 6 cm diameter, four samples/plot).

A replicated, randomized, controlled before-and-after study in 1989–1991 in an irrigated lettuce field in Salinas, California, USA (2), found less nitrate, and nitrate depletion, in soils with winter cover crops, compared to bare fallows. **Nutrients:** At the beginning of spring, less nitrate was found in soils with cover crops, compared to bare fallows, in some comparisons (all cover crops in 1990: 2–6 vs 18–21 µg NO_3-N/g dry soil; one of two cover crops in 1991: 66–79 vs 85–112). After the first rainfall in spring, more nitrate was found in soils with winter cover crops, compared to bare fallows (amounts of nitrate not clearly reported). The inference was that more nitrate was depleted by cover crops over winter, and more nitrate was leached from bare fallows in spring. In early spring, more ammonium was found in soils with winter cover crops, compared to bare fallows (0–15 cm: 2–6 vs 0–1 µg NH_4-N/g soil), but similar amounts were found later in the spring (0–15 cm: 0.5 µg), in 1991. In the lettuce-growing season, similar amounts of nitrate, ammonium, and mineralizable nitrogen were found in plots with winter cover crops or bare fallows (0–60 cm: 9–60 µg NO_3-N/g dry soil; 0–15 cm: 0.2–0.8 µg NH_4-N/g dry soil; 0–15 cm: 3–6 µg mineralizable N/g dry soil). **Methods:** In 1989–1990, six winter cover crops (*Raphanus sativus* oilseed radish, *Brassica hirta* white senf mustard, *Brassica alba* white mustard, *Lolium multiflorum* annual ryegrass, *Secale cerale* Merced rye, and *Phacelia tanacetifolia*) were grown on three plots each (two 12 m rows/plot), and bare fallows were maintained (with herbicide and hand cultivation) on three plots. In 1990–1991, two winter cover crops (*Secale cerale* Merced rye and *Phacelia tanacetifolia*) were grown on six plots each (two 8 m rows/plot), and bare fallows were maintained on six plots. Cover crops were tilled into the soil (15–20 cm depth in March 1990, depth not reported in February 1991). Lettuce was sown in April 1990–1991. All plots were irrigated and fertilized (56–85 kg N/ha, before sowing lettuce). Soil samples were collected in November 1989–1990, January 1990–1991, February 1991, and March 1990 (0–60 cm depth, 4 cm diameter, two cores/plot), weekly from late March to the end of June 1990 (0–15 cm depth), and every 2–7 days from mid-February to the end of March 1991 (0–15 cm depth).

A replicated, randomized, controlled study in 1991–1992 in an irrigated lettuce field in the Salinas Valley, California, USA (3), found less nitrate, but more ammonium, mineralizable nitrogen, and microbial biomass, in soils with winter cover crops, compared to bare soils. **Nutrients:** Less nitrate, more ammonium, and more mineralizable nitrogen were found in soils with winter cover crops, compared to bare soils, before the cover crops were incorporated into the soil (4.3 vs 8.6 g NO_3-N/m^2, 0–60 cm depth; 1.8 vs 1.1 g NH_4-N/m^2, net mineralizable nitrogen, 0–30 cm depth; 0.26 vs 0.24 g NH_4-N/m^2, 0–60 cm depth), and also in some comparisons after the cover crops were incorporated (1–6 vs 3–24 µg NO_3-N/g dry soil, 0–15 cm depth; 3–38 vs 1–21 µg NH_4-N/g dry soil, net mineralizable nitrogen, 0–15 cm depth; 0.17–0.98 vs 0.10–0.68 µg NH_4-N/g dry soil; 1–15 cm depth; number of significantly different comparisons not clearly reported). **Soil organisms:** More microbial biomass (measured as nitrogen) was found in soils with winter cover crops, compared to bare soils, in some comparisons (14–29 vs 6–14 µg N/g dry soil). **Methods:** Three plots had winter cover crops (Merced rye *Secale cereale*, sown on 19 December 1991) and three plots had bare soils over winter. The plots (raised beds) were 8 x 4 m each. All plots were disked on 8 April (incorporating the cover crops). Soil samples were collected 6 days before the cover crops were incorporated, and on 7–9 days between cover-crop incorporation and lettuce harvesting. Lettuce was sown on 8 May and harvested on 8 July 1992.

A replicated, randomized, controlled study in 1992–1993 in an irrigated broccoli field in the Salinas Valley, California, USA (4), found more mineralizable nitrogen and more microbial biomass in soils with winter cover crops, compared to soils without winter cover crops, but found inconsistent effects on nitrate. **Nutrients:** More mineralizable nitrogen was found in soils with cover crops, compared to bare soils, in five of 14 comparisons (8.5–17 vs 3–9 µg NH_4-N/g dry soil, 0–15 cm depth), but there were similar amounts of ammonium in soils with or without cover crops (0.5–4.2 µg NH_4-N/g dry soil, 0–15 cm depth). Less nitrate was found in soils with cover crops, in three of nine comparisons at the end of the cover-cropping season (March–April: 0–7 vs 3–10 µg NO_3-N/g dry soil, 0–15 cm depth), but more was found in one of nine comparisons (4 vs 2 µg). **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with cover crops, compared to bare soils, in seven of 14 comparisons (150–500 vs 70–150 µg C/g dry soil, 0–15 cm depth), and more microbial biomass (measured as nitrogen) was found in two of 14 comparisons (11–30 vs 5–12 µg N/g dry soil). **Methods:** There were three plots for winter cover crops (half *Phacelia tanacetifolia* phacelia and half *Secale cereale* Merced rye, sown in November 1992 and mown in March 1993) and three control plots with bare soil in winter. All plots (252 x 24 m) were tilled in March 1993 (15 cm depth), and the cover crops were incorporated into the soil. Two broccoli crops were grown on raised beds (first crop: April–August 1993; second crop: August–November 1993). All plots were irrigated (440–450 mm/crop, subsurface drip irrigation) and fertilized (41–42 g N/m^2/crop). Soil samples were collected 16 times in November 1992–August 1993, including nine samples in March–April, when the cover crops were incorporated (0–75 cm depth, 6 cm diameter, four cores/plot).

A replicated, randomized, controlled study in 1991–1994 in an irrigated tomato field in the San Joaquin Valley, California, USA (5), found more organic matter and nitrogen, and higher soil stability, in soils with winter cover crops, compared to winter fallows. **Organic matter:** More organic matter was found in soils with cover crops, compared to fallows, in some comparisons in the spring (e.g., spring 1994: 1.05–1.15% vs 0.70%, 0–15 cm depth; number of significantly different comparisons not clearly reported). **Nutrients:** More nitrogen was found in soils with cover crops, compared to fallows, in some comparisons in the spring (e.g., spring 1993: 0.75% vs 0.90% total nitrogen, 0–15 cm depth; number of significantly different comparisons not clearly reported). **Soil**

erosion and aggregation: More stable soils were found in plots with cover crops, compared to fallows (data on percentage of water-stable aggregates reported as model results). **Methods:** There were four plots (93 x 7 m plots) for each of three winter cover crops and one control (winter fallow). The cover crops were *Hordeum vulgare* barley, *Vicia dasycarpa* Lana woollypod vetch, or a barley-vetch mixture, seeded in October 1991–1993 and incorporated into the soil in March 1992–1994 (15–20 cm depth, rotary tiller). Soil samples were collected in spring and autumn (0–15 cm depth).

A replicated, controlled study in 1996–1998 in an irrigated tomato field in the San Joaquin Valley, California, USA (6) (same study as (7)), found more soil carbon and earthworms in plots with winter cover crops (and no tillage), compared to plots with bare fallows (and tillage in spring). **Organic matter:** More soil carbon was found in plots with cover crops, compared to fallows (0.66–0.72% vs 0.62% carbon, 0–0.6 inches depth). **Soil organisms:** More earthworms were found in plots with cover crops, compared to fallows (2.1 vs 0.6 earthworms/square foot). **Methods:** There were 12 plots (4.5 x 27.5 m plots) for each of two treatments (two grass-legume mixtures as winter cover crops, sown in October 1996–1997, killed and retained as mulch, with no tillage, in March 1997–1998) and there were 12 control plots (bare fallow in winter, with herbicide, and conventional tillage in spring). Soil carbon was sampled in September 1998 (eight subsamples/plot, 0–0.6 inches depth). Earthworms were sampled in March 1998 (two cylinders/plot, 16.5 inches diameter, 6 inches depth, sprinkled with mustard powder so that earthworms would come to the surface). It was not clear whether these results were a direct effect of cover crops or tillage.

A replicated, controlled study in 1996–1998 in an irrigated tomato field in the San Joaquin Valley, California, USA (7) (same study as (6)), found less nitrate in winter and spring, but more nitrate in summer, in plots with winter cover crops (and no tillage in spring), compared to plots with bare fallows (and tillage in spring). **Nutrients:** Less nitrate was found in plots with cover crops, compared to fallows, when measured in winter or spring (19 of 32 comparisons: 0.9–4.1 vs 3.8–7.9 ppm, 0–30 cm depth), but more nitrate was found when measured in summer (27 of 32 comparisons: 21–41 vs 8–14 ppm, 0–30 cm depth). **Methods:** There were 12 plots (4.5 x 27.5 m plots) for each of four treatments (two grass-legume mixtures, or two legumes without grasses, as winter cover crops, sown in October 1996–1997, killed and retained as mulch, with no tillage, in March 1997–1998) and each of two controls (bare fallows in winter, with or without herbicide, and conventional tillage in spring). Tomato seedlings were transplanted in April 1997–1998. The tomatoes were irrigated (two inches/week) and fertilized (0, 100, or 200 lb N/acre, in March 1997 and May 1998). Soil nitrate was sampled four times in 1998 (0–30 cm depth, three samples/plot). It was not clear whether these results were a direct effect of cover crops or tillage.

A replicated, randomized, controlled study in 1995–1998 in an irrigated tomato field in Davis, California, USA (8), found more nitrogen, more nematodes, and a higher proportion of bacteria-feeding nematodes, in soils with cover crops, compared to soils without cover crops. **Nutrients:** More nitrogen was found in soils with winter cover crops, compared to plots without cover crops, in two of three comparisons (10–31 vs 7–16 µg N/g dry soil, cumulative). **Soil organisms:** A higher proportion of bacteria-feeding nematodes, compared to fungus-feeding nematodes, were found in soils with cover crops, compared to soils without cover crops, in four of six comparisons (data reported as the Channel Index). Similar numbers of nematodes were found in soils with or without winter cover crops, in 1995–1996 (bacterial or fungal feeders: 3,100–9,800 vs 3,800–8,300 nematodes/litre soil). More nematodes were found in soils with summer cover crops, compared to soils without cover crops, in one of two comparisons in 1995–1996 (bacterial feeders: 12,000 vs 3,900 nematodes/litre soil). More nematodes were found in soils with summer and/or winter cover crops, compared to soils without cover crops, in four of six comparisons in 1996–1997 (bacterial and fungal feeders, in plots with irrigation: 2,300–3,600 vs 400–500 nematodes/litre soil), but similar numbers were found in soils with or without winter cover crops in 1997–1998 (bacterial and fungal feeders: 1,200–3,800). Similar numbers of other nematodes (omnivores and predators) were found in soils with or without cover crops (data not reported). **Greenhouse gases:** Similar amounts of carbon dioxide were found in soils with or without cover crops (soil basal respiration in 1995–1996: 10–13 µg CO_2/g dry soil/hour). **Methods:** Cover crops were planted in different numbers of plots in different years (1995–1996: 16 plots with winter cover crops, eight plots with summer cover crops, 16 control plots without cover crops; 1996–1997: 12 winter, four summer, eight controls; 1997–1998: 28 summer and/or winter, four controls). Plots were 3–4 beds wide and 10 m long. Some summer cover crops were retained over winter, and some were mown and replaced with winter cover crops. Summer cover crops were mixtures of oats and legumes, planted in August–September. Winter cover crops were legumes (*Vicia sativa* common vetch), planted in November. In spring, cover crop residues were mown and either removed or evenly distributed among all plots and incorporated into the soil. Some plots were irrigated during the cover-cropping seasons. All plots were irrigated during the tomato-growing season. Herbicide was used on all plots, but no inorganic fertilizer was used. Soil samples (16 soil cores/plot, 30 cm depth, 2.5 cm diameter) were collected at different times for nutrients (once per week, 1–7, 11, and 14 weeks after incorporating cover crop residues, in spring), greenhouse gases (after 1, 4, and 7 weeks), or soil organisms (four times in summer/autumn, and 1, 4, 7, 11, 14, and 18 weeks after incorporating residues), in 1995–1996. In 1996–1998, soil samples for nutrients and soil organisms were collected less frequently (1996–1997: four times in spring; 1997–1998: once in autumn, once in spring, and once when tomatoes were harvested).

A replicated, randomized, controlled study in 1998–2000 in an irrigated vegetable field in the Salinas Valley, California, USA (9), found more organic matter, more microbial biomass, less nitrate, and/or less ammonium in soils with winter cover crops, compared to soils without cover crops, in most comparisons. More ammonium was found in two of 12 comparisons. **Organic matter:** More carbon was found in soils with cover crops (15 vs 14 g total C/kg soil; 0–15 cm depth). **Nutrients:** More total nitrogen was found in soils with cover crops (1.6 vs 1.5 g total N/kg soil; 0–15 cm depth). At depths of 0–90 cm, less nitrate was found in soils with cover crops (4–54 vs 5–64 g NO_3–N/g soil), and less nitrate was also found at depths of 0–15 cm, in seven of 12 comparisons (2–18 vs 3–64 µg NO_3-N/g soil). At depths of 0–15 cm, less ammonium was found in soils with cover crops, in six of 12 comparisons (1–4 vs 5–7 µg NH_4–N/g soil), but more ammonium was found in two of 12 comparisons (4–7 vs 1–4). **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with cover crops, in 10 of 12 comparisons (120–220 vs 80–130 µg C/g soil). More microbial biomass (measured as nitrogen) was found in soils with cover crops, in 11 of 12 comparisons (14–27 vs 5–17 µg N/g soil). **Methods:** There were four plots (0.52 ha), for each of four treatments (reduced tillage or conventional tillage, with or without added organic matter). In plots with added organic matter, compost was added two times/year, and a cover crop (*Secale cereale* Merced rye) was grown every autumn or winter. Lettuce or broccoli crops were grown on raised beds. Sprinklers and drip irrigation were used in all plots. Soils were disturbed to different depths (conventional tillage: disking to 50 cm depth, cultivating, sub-soiling, bed re-making, and bed-shaping; reduced tillage: cultivating to 20 cm depth, rolling, and bed-shaping). Soils were collected, along the planting line, with 6 cm soil cores. It was not clear whether these results were a direct effect of adding compost or growing cover crops.

A replicated, randomized, controlled, before-and-after study in 1999–2004 in an irrigated tomato-cotton field in the San Joaquin Valley, California, USA (10) (same study as (27)), found more carbon and potassium in soils after four years with winter cover crops, but found less carbon and no changes in potassium after four years without cover crops. Cover crops had inconsistent effects on nitrogen in soils. **Organic matter:** Carbon increased in soils with cover crops, after four years (before: 10,000 lb/acre; after: 12,000), and decreased in soils without cover crops, after four years (before: 10,000; after: 9,000). **Nutrients:** After four years, nitrogen increased in soils with cover crops (before: 1,300 lb/acre; after: 1,400–1,600), but decreased in soils without cover crops, in one of two comparisons (before: 1,400; after: 1,300), and increased in one of two comparisons (before: 1,300; after: 1,600). After four years, nitrate did not change in soils with cover crops (before: 16–19 ppm; after: 10–16), but increased in soils without cover crops, in one of two comparisons (before: 18; after: 25). After four years, potassium increased in soils with cover crops (before: 258–271 ppm; after: 314–319), but did not change in soils without cover crops (before: 271–278; after: 300–303). **Methods:** Rainfed winter cover crops (triticale, rye, and vetch) were planted on 16 treatment plots, but not on 16 control plots, in October 1999–2003. Crop residues were chopped in March. The plots (9 x 82 m) had six raised beds each. Tomatoes were grown in rotation with cotton. Fertilizer and herbicide was used in all plots, and tomatoes and cotton were irrigated. Soil samples were collected in spring (before planting) and in autumn (after harvest), in 2000–2004 (0–30 cm depth; number and volume of samples not reported).

A replicated, randomized, controlled study in 2001–2004 in an irrigated maize field in southwest Spain (11) found more organic matter, nitrogen, and microorganisms, and higher soil stability, in soils with winter cover crops, compared to soils without cover crops. **Organic matter:** Similar amounts of organic carbon were found in soils with short-term cover crops, compared to soils without cover crops (0–30 cm depth: 6–13 g C/kg soil), but more organic carbon was found in soils with long-term cover crops, compared to soils without cover crops, in eight of nine comparisons (8–32 vs 6–13). **Nutrients:** Similar amounts of nitrogen were found in soils with short-term cover crops, compared to soils without cover crops (0–30 cm depth: 0.07–0.15 g total N/kg soil), but more nitrogen was found in soils with long-term cover crops, compared to soils without cover crops, in eight of nine comparisons (0.08–0.25 vs 0.07–0.13). **Soil erosion and aggregation:** Higher soil stability was found in plots with short-term cover crops, compared to plots without cover crops, in two of nine comparisons (0–5 cm depth, in 2002–2003: 57%–79% vs 44–69% of aggregates were water-stable), and higher soil stability was also found in plots with long-term cover crops, compared to plots without cover crops, in eight of nine comparisons (57–88% vs 26–69%). **Soil organisms:** More microorganisms were found in soils with short-term cover crops, compared to soils without cover crops, in one of three years (2003: 662 vs 470 colony forming units/g dry soil), and more microorganisms were also found in soils with long-term cover crops, compared to soils without cover crops, in two of three years (576–694 vs 350–470). **Implementation options:** More organic carbon in eight of nine comparisons (8–32 vs 6–13 g C/kg soil), more nitrogen in seven of nine comparisons (0.08–0.23 vs 0.07–0.15 g total N/kg soil), higher stability in six of nine comparisons (58–75% vs 29–48% of aggregates were stable), and more microorganisms in one of three years (2002: 576 vs 389 colony forming units/g dry soil) were found in soils with long-term cover cropping, compared to short-term. **Methods:** Cover crops (*Avena strigosa* lopsided oats) were sown on eight plots in September 2001–2003. Four of these plots had winter cover crops for six years before this (long-term cover crops), and four plots did not (short-term cover crops). Four other plots did not have winter cover crops from 2001–2004 or before. All plots were 20 x 10 m. Cover crops were suppressed with herbicide in April 2002–2004. For organic carbon, nitrogen, and aggregate stability, soil samples were collected in March, June, and October 2002–2004 (three samples/plot, 0–30 cm depth). For microorganisms (bacteria and fungi), soils samples were collected every two months (0–5 cm depth).

A replicated, randomized, controlled study in 2005–2007 in an irrigated tomato-maize field in Davis, California, USA (12), found more carbon, ammonium, and nematodes in soils with winter cover crops, compared to bare fallows. **Organic matter:** More carbon was found in soils with cover crops, compared to bare fallows (1.04% vs 0.94% total carbon). **Nutrients:** Similar amounts of nitrate and total nitrogen were found in soils with cover crops or bare fallows (7 vs 5–8 NO_3-N ppm; 0.11% vs 0.10% total nitrogen), but more ammonium was found in soils with cover crops, for one of three mixtures of cover crops (legumes: 6 vs 5 NH_4-N ppm). **Soil organisms:** More nematodes were found in soils with cover crops, compared to bare fallows, for two of three mixtures of cover crops (mixtures with legumes: 588–617 vs 435 nematodes/100 g soil). **Implementation options:** Similar amounts of carbon, total nitrogen, and nitrate, and similar numbers of nematodes, were found in soils with different mixtures of cover crops (0.99–1.04% total carbon; 0.11% total nitrogen; 5–8 NO_3-N ppm; 512–617 nematodes/100 g soil), but more ammonium was found in soils that were cover cropped with legumes, compared to grains or a mixture of legumes and grains (6 vs 5 NH_4-N ppm). **Methods:** Three mixtures of winter cover crops (legumes only, legumes and grains, or grains only) were grown on five plots each, and five control plots were bare fallows on which weeds were controlled by burning (111 m^2 plots; six raised beds/plot). Tomatoes were grown in 2006, and maize was grown in 2007, without fertilizer. Soil samples were collected in May and September 2006–2007 (four times in the spring of 2007), with soil cores (12 cores/plot, 15 cm depth, 2.5 cm width).

A replicated site comparison in 2004–2005 in nine irrigated tomato fields in the Sacramento Valley, California, USA (13), found similar numbers of earthworms in fields with winter cover crops or bare fallows. **Soil organisms:** Similar numbers of earthworms were found in fields with cover crops or fallows (26 vs 19 g earthworms/m^2). **Methods:** Earthworms were collected from nine tomato fields (five fields with cover crops, four with bare fallows; three 30 cm^3 soil pits/field), in February–April 2005. Organic matter and nutrients were measured in horizontal soil cores, collected from the walls of the soil pits (0–15 cm length). All fields were tilled in 2004, after the tomatoes were harvested, and before the cover crops were planted. The cover crops were legumes. All fields were fertilized and irrigated.

A replicated, randomized, controlled study in 2006–2007 in an irrigated tomato field near Davis, California, USA (14), found more nitrate, higher greenhouse-gas emissions, and more carbon in soils with winter cover crops, compared to soils without cover crops. **Organic matter:** More carbon was found in soils with cover crops (maximum: 1.3% of soil was carbon), compared to those without cover crops (minimum: 1.1%). **Nutrients:** More nitrate was found in soils with cover crops, in five of seven comparisons (March–September: 20–70 vs 10–60 µg nitrate/g soil). Similar amounts of total nitrogen were found in soils with or without cover crops (0.1% of soil was nitrogen). **Greenhouse gases:** Higher nitrous oxide emissions were found in soils with cover crops, in two of four comparisons (80–150 vs 25–45 µg N_2O/m²/hour), and higher carbon dioxide emissions were found in one of four comparisons (350 vs 215 mg CO_2/m²/hour). **Methods:** Legume cover crops (*Vicia villosa* hairy vetch and *Lathyrus hirsutus* Australian winter peas) were grown on eight treatment plots, but not on eight control plots (0.075 ha plots). Cover crops were mown in late April, and mulched and incorporated into the soil in early May. All plots were irrigated and fertilized. Greenhouse gases were measured at least every 10 days in the growing season and every 2–3 weeks in the rainy season (three chambers/plot). Soil samples were collected every three weeks in the growing season, but less frequently in the rainy season (0–30 cm depth, 2.54 cm diameter soil cores).

A replicated, randomized, controlled study in 2006–2008 in an irrigated maize field in the Ebro river valley, Spain (15), found less nitrogen in soils with winter cover crops, compared to bare soils, in spring, but found more nitrogen in autumn. **Nutrients:** In spring (after the cover crops), less nitrogen was found in soils with cover crops, compared to bare soils, in 19 of 20 comparisons (1–11 vs 3–43 mg inorganic N/kg soil, 0–120 cm depth). However, in autumn (after the maize was harvested), more nitrogen was found in plots with cover crops, compared to bare soils, in two of 20 comparisons (barley as the cover crop, 0–30 cm depth: 14–15 vs 4–7 mg inorganic N/kg soil). **Methods:** There were three plots (5.2 m²) for each of three winter cover crops (*Hordeum vulgare* barley, *Brassica rapa* winter rape, or *Vicia sativa* common vetch, sown in October 2006–2007), and three control plots with bare soil in winter. Similar amounts of nitrogen were added to all plots (300 kg N/ha), but less of it came from mineral fertilizer in plots with cover crops, to compensate for the organic nitrogen that was added to these plots when the cover crop residues were tilled into the soil. All plots were tilled in spring (March 2007–2008) and autumn (October 2006–2007). All plots were irrigated twice/week (drip irrigation, based on evapotranspiration). Maize was planted in April and harvested in October 2007–2008. Soil samples were collected before the cover crops were incorporated and after the maize was harvested (two soil cores/plot, 5 cm diameter, 0–120 cm depth). It was not clear whether these results were a direct effect of cover cropping or adding fertilizer.

A replicated, randomized, controlled study in 2005–2006 in an irrigated, organic tomato field in Yolo County, California, USA (16), found less nitrate, more ammonium and microbial biomass, and higher carbon dioxide emissions in soils with winter cover crops, compared to winter fallows. **Nutrients:** Less nitrate was found in soils with cover crops, compared to fallows, in two of five comparisons (7 days after planting tomatoes: 3.3 vs 5.3 g N/m²; 32 days before: 0.2 vs 0.5). More ammonium was found in soils with cover crops, compared to fallows, in one of five comparisons (7 days after planting: 2.1 vs 1.7 g N/m²). Similar amounts of potentially mineralizable nitrogen were found in soils with cover crops or fallows (4.1–8.8 g N/m²). **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with cover crops, compared to fallows, in one of four comparisons (7 days after planting: 95 vs 75 g C/m²). **Greenhouse gases:** More carbon dioxide was emitted from plots with cover crops, compared to fallows (28 days after planting: 223 vs 140 mg CO_2-C/m²/hour). **Methods:** The field was levelled and fertilized (17 Mg compost/ha). Eight plots had winter cover crops (mustard *Brassica nigra*, planted on 3 November 2005) and eight plots had winter fallows. Each plot was 16 x 9 m. Cover crops were mown on 26 April 2006, sprinkler irrigated, and tilled into the soil (10 cm depth) after 19 days, when fallow plots were also tilled. Plots were weeded and sulfur was used against mites and diseases. Tomatoes were furrow irrigated (approximately every 11 days: 88 mm/event). Soil samples were collected on a total of five dates, before and after planting tomatoes (nutrients: 0–60 cm depth; microbial biomass: 0–30 cm depth). Greenhouse gas samples were collected after irrigation events, 28, 77, and 100 days after planting (closed chambers, for 30 minutes).

A replicated, randomized, controlled before-and-after study in 1993–2008 in a rainfed wheat-maize-wheat-sunflower field in central Italy (17) found more organic matter and nitrogen in soils with winter cover crops, compared to soils without cover crops. **Organic matter:** After 15 years, more carbon was found in soils with cover crops, compared to soils without cover crops, in four of six comparisons (legume cover crops, organic carbon concentration, 0–30 cm depth, in 2008: 11–14 vs 10–12 g/kg soil), and carbon increased more over time, in two of three comparisons (legume cover crops: 6–6.5% vs 1.5% increase in Mg organic C/ha, 0–30 cm depth). **Nutrients:** After 15 years, more nitrogen was found in soils with cover crops, compared to soils without cover crops, in five of six comparisons (total nitrogen concentration, 0–30 cm depth, in 2008: 1.2–1.5 vs 1.1–1.3 g/kg soil), and nitrogen increased over time, rather than decreased, in two of three comparisons (0.14–0.3% increase vs 0.7% decrease in Mg total N/ha, 0–30 cm depth). **Implementation options:** More carbon was found in soils that were cover cropped with high-nitrogen-supply legumes, compared to non-legumes (organic carbon concentration, 0–30 cm depth: 11–14 vs 10–13 g/kg soil), and more nitrogen was found at one of two depths (total nitrogen, 0–10 cm depth: 1.5 vs 1.4 g/kg soil). **Methods:** There were 32 plots (21 x 11 m sub-sub-plots) for each of three treatments (non-legumes, low-nitrogen-supply legumes, or high-nitrogen-supply legumes as winter cover crops) and one control (no cover crops: crop residues and weeds). Different species of cover crops were used in different years. Half of the plots were tilled, and half were not tilled (but pre-emergence herbicide was used). Post-emergence herbicide and fertilizer were used on all plots. Soil cores were collected in 1993, 1998, and 2008 (0–30 cm depth; two samples/plot in September).

A replicated, randomized, controlled study in 2006–2009 in an irrigated maize field in the Tajo river basin, near Madrid, Spain (18), found that winter cover crops had inconsistent effects on nitrogen. **Nutrients:** Less nitrogen was found in soils that were cover cropped with barley, compared to fallows, in one of four comparisons (31 vs 156 kg N/ha). More nitrogen was found in soils that were cover cropped with vetch, compared to fallows, in one of four comparisons (113 vs 43 kg N/ha). **Implementation options:** Less nitrogen was found in soils that were cover cropped with barley, compared to vetch, in two of four comparisons during the cover-cropping seasons (45–49 vs 113–184 kg N/ha), and one of three comparisons during the maize-growing seasons (99 vs 253). **Methods:** There were four plots (12 x 12 m plots) for each of two treatments (barley or vetch, as winter cover crops) and there were four control plots (fallow). Cover crops were sown in October 2006–2009 and maize was sown in April 2007–2009. The maize was irrigated (sprinklers) and fertilized (210 kg N/ha, split into two applications, 120 kg P/ha, and 120 kg K/ha). Soil water content was measured every hour with capacitance probes (10–130 cm depth, three probes/plot, after the cover crops and after the harvest), and nitrate in soil water was measured with ceramic suction cups (buried at 122–124 cm depth, 1 µm pore size).

A controlled study in 2005–2006 in an irrigated tomato field in the Sacramento Valley, California, USA (19), found less erosion of the part of the field that was cover cropped, compared to the part that was fallow. **Soil erosion and aggregation:** Less sediment was lost in runoff from the cover-cropped part, compared to the fallow part, in two of four comparisons (concentrations, in winter: 0.1 vs 0.7 g total suspended solids/litre; loads, in winter: 0.9 vs 5 kg/ha/rainfall event). **Greenhouse gases:** Similar amounts of greenhouse gas were emitted from each part of the field (<5 g N_2O-N/ha/day;

35–440 mg CO_2-C/m^2/hour). **Methods:** A field was divided into two parts: one part with a winter cover crop (mustard *Brassica nigra*, planted in autumn 2005, and disked into the soil in spring 2006), and one part fallow. Greenhouse gases were measured one day/month (in chambers) in randomly located 16 m^2 plots (three plots in each part of the field). Runoff water was collected in autosamplers (250 mL samples, every four hours, if there was >5 cm of water in the flow meter).

A meta-analysis from 2013 of studies in multiple countries with Mediterranean-type climates (20) found a higher percentage of organic matter in soils with cover crops, compared to bare soils. **Organic matter:** A higher percentage of organic carbon was found in soils with cover crops, compared to bare soils (10% higher). **Methods:** The Web of Knowledge database was searched, using the keywords, "Mediterranean", "soil", and "conventional", and 13 data sets from 10 studies of cover cropping were found and meta-analysed. The most recent studies included in this meta-analysis were published in 2011. It was not clear how many of these studies were from arable fields, orchards, or vineyards.

A replicated, randomized, controlled study in 2003–2005 on an irrigated vegetable farm in the Salinas Valley, California, USA (21), found more nitrogen in plots with winter cover crops, compared to bare fallows. **Nutrients:** More nitrogen (ammonium and nitrate) was found in plots with cover crops, compared to bare fallows, in some comparisons, for some cover crops (data not clearly reported; in 2005, plots that were cover cropped with legumes and rye consistently had more nitrogen than bare fallows: 5–15 vs 4–5 µg mineral N/g dry soil; in 2004, all cover cropped plots had more nitrogen in one of five comparisons: 10–17 vs 5). **Implementation options:** In 2005, less nitrogen was found in plots that were cover cropped with oats (3–7 µg mineral N/g dry soil), compared to legumes and rye (5–13 µg) or mustard (6–13 µg, in five of seven comparisons). In 2004, there were inconsistent differences between cover crops. **Methods:** Twenty-four 12 x 20 m plots were planted with winter cover crops in October 2003–2004. Each plot had one of three cover crops: *Secale cereale* Merced rye, mustard (*Sinapis alba* and *Brassica juncea*), or legumes and rye (Merced rye, *Vicia faba, Pisum sativum, Vicia sativa,* and *Vicia benghalensis*). The number and size of the control plots (fallows) was not clearly reported. After the cover crops were incorporated into the soil (March), soil cores were collected every 7–10 days, for six weeks (30 cm depth, 1.9 cm width, 20 bulked samples/plot).

A replicated, randomized, controlled study in 2009–2012 in two irrigated vegetable fields in central Italy (22) found more nitrate in soils with winter cover crops, compared to bare soils. **Nutrients:** More nitrate was found in soils with cover crops, compared to bare soils, in two of 12 comparisons (in plots with hairy vetch as the cover crop: 6–12 vs 3–8 mg NO_3-N/kg dry soil), but there were similar amounts of ammonium (0–4 mg NH_4-N/kg dry soil). **Implementation options:** More nitrate was found in soils with hairy vetch as the cover crop, compared to oats or oilseed rape, in two of four comparisons (6–12 vs 2–6 mg NO_3-N/kg dry soil), but similar amounts of ammonium were found (1–4 mg NO_3-N/kg dry soil). **Methods:** There were nine plots (6 x 4 m plots) for each of three winter cover crops (hairy vetch, oats, or oilseed rape) and nine control plots (bare soil, maintained with herbicide). Cover crops were sown in September 2009–2010 and suppressed in May 2010–2011 (chopped and incorporated into the soil with a mouldboard plough, 30 cm depth). Pepper seedlings were transplanted into these plots in May 2010–2011 and were last harvested in October 2010 and September 2011. After the pepper harvest, endive and savoy cabbage seedlings were transplanted into these plots, and they were harvested in December 2010 and November 2011 (endive) or March

2011 and February 2012 (cabbage). No fertilizer was added while the crops were growing, but the plots were irrigated. Nitrogen was measured in soil samples (10 samples/plot, 0–30 cm depth, when the endive and cabbages were harvested).

A replicated, randomized, controlled study in 2011–2014 in irrigated potato fields in Israel (23) found less soil erosion in plots with cover crops, compared to bare soil. **Soil erosion and aggregation:** Less erosion was found in plots with cover crops, compared to bare soil (2012–2013: 0.1–0.3 vs 3.5–4.5 mm soil loss). **Methods:** Different plots were used in different years (2011–2012: 350 m^2 plots, 20 plots with cover crops, eight plots without cover crops; 2012–2013: 695 m^2 plots, 10 with, 10 without; 2013–2014: 1,800 m^2 plots, four with, four without). Different mixtures of cover crops were used in different years, but oats were used in all years, and triticale was used in Years 1 and 2 (2011–2013). Plots without cover crops were weeded (tilled bare; some plots in all years) or weedy (not tilled; some plots in Year 1). Herbicide and fertilizer were used on all plots. Soil loss was measured in buckets, after each rainfall event (one 10 litre bucket/plot). Plots had a 5–7% slope.

A replicated, randomized, controlled study in 1993–2011 in arable farmland in Davis and the Salinas Valley, California, USA (24), found more soil organisms, but no difference in nutrients, in soils with winter cover crops, compared to soils without cover crops. **Nutrients:** No difference was found in phosphorus, or the change in phosphorus over time, in soils with or without cover crops (2011: 519 vs 517 mg total phosphorus/kg soil; 1994–2011: 23 vs 21 mg less total phosphorus/kg soil; experiment in Davis). **Soil organisms:** More microbial biomass (measured as phosphorus) was found in soils with cover crops, compared to soils without cover crops (1.4 vs 1 mg phosphorus/kg soil; experiment in Davis). **Implementation options:** No differences in phosphorus or microbial biomass (measured as phosphorus) were found between soils with different species of cover crops (513–535 mg total phosphorus/kg soil; 3.1–3.7 mg microbial phosphorus/kg soil), or in soils with cover crops grown every year, compared to every four years (513 vs 497 total; 3.8 vs 2.0 microbial; experiment in the Salinas Valley). **Methods:** In one experiment (in Davis), nitrogen-fixing cover crops (peas, vetch, and/or fava beans) were grown in six treatment plots, but not in six control plots. Wheat was grown in rotation with cover crops (once every two years) or in rotation with fallows. In another experiment (in the Salinas Valley), there were four plots (240 m^2) for each of four treatments (legume-rye, mustard, or rye cover crops grown every year, or legume-rye cover crops grown every four years). Lettuce and broccoli were grown in rotation (two crops/year). Soil samples were collected in soil cores (20 cores/plot; 0–30 cm depth) in 2011. Soil cores were also collected in 1993 (number of samples not reported).

A replicated, randomized, controlled study in 2011–2013 in two irrigated tomato fields in central Italy (25) found more organic matter and greater carbon accumulation in plots with winter cover crops, compared to plots without cover crops, but cover crops had inconsistent effects on nitrogen. **Organic matter:** When the tomatoes were harvested, more organic carbon was found in soils with winter cover crops, in 17 of 24 comparisons (1.1–1.8% vs 1–1.6% of soil was organic carbon). **Nutrients:** When the tomatoes were harvested, more organic nitrogen was found in soils with winter cover crops, in 14 of 24 comparisons (0.12–0.2% vs 0.11–0.15% of soil was organic nitrogen), but less was found in five of 24 comparisons (0.12–0.13% vs 0.14–0.15%). **Greenhouse gases:** Similar amounts of carbon dioxide were emitted from soils with or without cover crops (3.2–4.2 Mg C/ha), but more carbon accumulated in soils with cover crops, in four of six comparisons (1.1–2.1 vs 0.4–0.7 ratio of C input to output). **Implementation options:** More carbon accumulated in soils that were cover cropped and mulched with hairy vetch, compared to other species, in three of four comparisons (1.9–2.1 vs 1.1–1.4 ratio of C input to output). **Methods:** Three species of winter cover crops (*Vicia villosa* hairy vetch, *Phacelia tanacetifolia* lacy phacelia, or *Sinapis alba* white mustard) were sown on three plots each, in September, and winter weeds were controlled with herbicide on three control plots (18 x 6 m plots). The cover crops were mown and mulched (strips, 80 cm width) in May, and the control plots were tilled (depth not reported). Tomato seedlings were transplanted in May (transplanted into the mulch in treatment plots) and harvested in August. All plots were tilled (30 cm depth) and fertilized (100 kg P_2O_5/ha, harrowed to 10 cm depth) in September. Some plots were also fertilized (100 kg N/ha) in June–July. Soil samples were collected after the tomatoes were harvested (0–20 cm depth). Carbon dioxide emissions (closed chambers, 1,334 cm^3 volume, 30–180 seconds/sample) were measured weekly, or within 48 hours of rainfall, in the tomato-growing season. It was not clear whether these results were a direct effect of cover cropping, mulching, herbicide, or tillage.

A replicated, randomized, controlled before-and-after study in 2012–2013 in two irrigated tomato fields in central Italy (26) found more organic matter, nitrogen, and soil organisms in soils with cover crops (and no tillage), compared to soils without cover crops (with tillage), in spring. By the end of summer, less organic matter, but more nitrogen, had accumulated in soils with cover crops, and there were inconsistent effects on soil organisms. **Organic matter:** In May, more organic carbon was found in soils that had been cover cropped and mulched, compared to soils that had not, in two of six comparisons (lacy phacelia or white mustard, in 2013: 16 vs 12 mg C/g soil). By August, less organic carbon had accumulated in soils with mulch, compared to soils without mulch, in two of six comparisons (lacy phacelia or white mustard, in 2013: –1% to 4% vs 28% increase in organic carbon). **Nutrients:** In May, more nitrogen was found in soils that had been cover cropped and mulched, compared to soils that had not, in one of two years (all cover crops, in 2013: 1.3–1.5 vs 1.1 mg N/g soil). By August, more nitrogen had accumulated in soils with mulch, compared to soils without mulch, in one of six comparisons (white mustard, in 2013: 44% vs 2% increase in nitrogen). **Soil organisms:** In May, more microbial biomass (measured as carbon) was found in soils that had been cover cropped and mulched, compared to soils that had not (140–330 vs 100–150 µg C/g soil), and more microbial biomass was also found in two of three comparisons in August 2012 (175 vs 135 µg C/g soil), but less was found in two of three comparisons in August 2013 (175–210 vs 270 µg; 2012 was hotter and drier than 2013). **Methods:** Three species of winter cover crops (*Vicia villosa* hairy vetch, *Phacelia tanacetifolia* lacy phacelia, or *Sinapis alba* white mustard) were sown on three plots each, but not on three control plots (plot size not reported), in September. The cover crops were mulched in May, and the control plots were tilled (depth not reported). Tomato seedlings were transplanted in May (transplanted into the mulch) and harvested in August. All plots were tilled in September. Soil samples were collected at the beginning (May) and end (August) of the tomato-growing season (0–20 cm depth). It was not clear whether these results were a direct effect of cover cropping, mulching, or tillage.

A replicated, randomized, controlled study in 1999–2009 in an irrigated tomato-cotton field in the San Joaquin Valley, California, USA (27) (same study as (10)), found more organic matter in soils with winter cover crops, compared to soils without cover crops. **Organic matter:** More carbon was found in soils with cover crops (26–29 vs 23–24 t total C/ha). **Methods:** Rainfed winter cover crops (triticale, rye, and vetch) were planted on 16 treatment plots, but not on 16 control plots, in October 1999–2008. Crop residues were chopped in March. The plots (9 x 82 m) had six raised beds each. Tomatoes were grown in rotation with cotton. Fertilizer and herbicide were used in all plots, and tomatoes and cotton were irrigated. Soil samples were collected in autumn 2007 (0–30 cm depth, 7.6 diameter soil cores, 6–8 subsamples/plot).

A replicated, controlled study in 2011–2012 in an irrigated tomato field near Pisa, Italy (28), found that similar numbers of tomato roots were colonized by mycorrhizae (beneficial fungi), but found more mycorrhizae spores, and more mycorrhizae species, in soils with planted cover crops, compared to resident (unplanted) vegetation. **Soil organisms:** Similar numbers of tomato roots were colonized by symbiotic fungi in plots with cover crops, compared to resident vegetation (28–42% vs 30–37% of roots were colonized). More mycorrhizae spores were found in soils with cover crops, in three of six comparisons (10.3–18.5 vs 7–8.5 spores/g soil). More mycorrhizae species were found in soils with cover crops, in two of six comparisons (when tomatoes were harvested, in plots that were cover cropped with *Brassica juncea* or a mixture of species: 29–30 vs 24 species). **Implementation options:** More tomato roots were colonized by mycorrhizae in plots that were cover cropped with *Vicia villosa* (42% of roots were colonized) or a mixture of species (35% of roots were colonized), compared to *B. juncea* (28%), in one of two comparisons (when tomatoes were flowering). More mycorrhizae spores were found in plots that were cover cropped with *V. villosa* (14.2–18.5 spores/g soil), compared to the other two cover crops (species mixture: 10.3–10.8; *B. juncea*: 7.8–9.1), and more spores were also found in plots with the species mixture, compared to *B. juncea*, in one of two comparisons (when tomatoes were flowering: 10.3 vs 7.8). More mycorrhizae species were found in plots that were cover cropped with *B. juncea* or the species mixture, compared to *V. villosa* (29–30 vs 25 species). **Methods:** There were three plots (plot size not reported) for each of three winter cover crops (*B. juncea*, *V. villosa*, or a mixture of seven species) and three control plots (without cover crops, but with resident vegetation). Cover crops were sown on 19 October 2011, and then mown and incorporated into the soil in spring 2012. Tomato seedlings were transplanted into the plots (into raised beds) on 30 May 2012. Tomatoes were drip irrigated. Soil samples were collected when the tomatoes were flowering (10 April 2012) and when they were harvested (20 September 2012) (four soil cores/plot, 0–20 cm depth). Half of the seedlings were inoculated with two species of mycorrhizae.

A replicated, randomized, controlled study in 2009–2011 in an irrigated eggplant field in central Italy (29) found more nitrogen in soils with winter cover crops, compared to bare soil. **Nutrients:** More nitrogen was found in soils with cover crops, compared to bare soil, for one of three cover crops (hairy vetch: 34 vs 23 mg inorganic N/kg dry soil). **Implementation options:** More nitrogen was found in soils with hairy vetch as the winter cover crop, compared to oats or oilseed rape (34 vs 20 mg inorganic N/kg dry soil), and no differences in nitrogen were found between soils with oats or oilseed rape as the winter cover crop. **Methods:** Three species of winter cover crops (*Vicia villosa* hairy vetch, *Brassica napus* oilseed rape, or *Avena sativa* oats) were sown on three plots each (6 x 12 m plots) in September 2009–2010, and no cover crops were sown on three plots (weeded, bare soil). The cover crops were mown and used as mulch (50 cm wide) in eggplant rows, in May 2010–2011. Eggplant seedlings were transplanted into the plots in May, and fruits were harvested four times/year in July–September 2010–2011. Soil samples were collected when the seedlings were transplanted and when the last fruits were harvested each year (0–30 cm depth, six samples/plot). All plots were fertilized before the cover crops were grown, but not after. All plots were irrigated.

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3.7. Plant or maintain ground cover in orchards or vineyards: Soil (22 studies)

- **Organic matter (12 studies):** Ten studies (eight replicated, randomized, and controlled, and two site comparisons) from Chile[17], France[21], Spain[1,5,10-13], and the USA[6,7] found more organic matter in soils with ground cover, compared to soils without ground cover, in some comparisons[5,12,21] or all comparisons[1,6,7,10,11,13,17]. Two meta-analyses of studies from Mediterranean climates[16,22] also found more organic matter in plots with ground cover.
    - **Implementation options (4 studies):** One study from France[21] found more organic matter in soils with permanent ground cover, compared to temporary ground cover, in one of three comparisons. Two studies from the USA[4,14] found similar amounts of organic matter in soils with resident vegetation or seeded cover crops. One study from Spain[5] found more organic matter where cover crops were incorporated into the soil.
- **Nutrients (12 studies)**
    - Nitrogen (9 studies): Five studies (four replicated, randomized, and controlled, and one site comparison) from Chile[17] and Spain[5,10,12,13] found more nitrogen in soils with ground cover, compared to soils without ground cover, in some comparisons[5,12] or all comparisons[10,13,17]. One replicated, randomized, controlled study from the USA[6] found less nitrogen in soils with ground cover, in some comparisons. Two replicated,

randomized, controlled studies from Spain[20] and the USA[8] found inconsistent differences in nitrogen between soils with or without ground cover. One replicated site comparison from France[21] found similar amounts of nitrogen in soils with or without ground cover.

- **Implementation options (5 studies):** Two studies from Spain[20] and the USA[3] found more nitrogen in soils that were cover cropped with legumes, compared to non-legumes, in some comparisons[20] or all comparisons[3]. Two studies from vineyards in the USA[4,19] found similar amounts of nitrogen in soils with resident vegetation or seeded cover crops. One of these studies[19] also found similar amounts of nitrogen in soils with different types of seeded cover crops, and in soils with or without tillage (both with ground cover). One study from Spain[5] found more nitrogen where cover crops were incorporated into the soil.

- Phosphorus (4 studies): One replicated site comparison from France[21] found more phosphorus in soils with ground cover, compared to bare soils, in one of six comparisons. Two studies (one replicated, randomized, and controlled, and one site comparison) from Spain[13] and the USA[6] found less phosphorus in soils with seeded cover crops, compared to tilled soils, in some comparisons. One replicated, randomized, controlled study from Chile[17] found similar amounts of phosphorus in soils with seeded cover crops and bare soils.
  - **Implementation options (3 studies):** One study from France[21] found more phosphorus in soils with permanent ground cover, compared to temporary ground cover, in one of three comparisons. One study from the USA[4] found similar amounts of phosphorus in soils with resident vegetation or seeded cover crops. One study from Spain[13] found different amounts of phosphorus in soils with different types of seeded cover crops.
- Potassium (3 studies): One replicated, randomized, controlled study from Chile[17] found more potassium in soils with seeded cover crops, compared to bare soils. Two site comparisons (one replicated) from France[21] and Spain[13] found similar amounts of potassium in soils with ground cover, compared to tilled or bare soil.
  - **Implementation options (1 study):** One study from the USA[4] found similar amounts of potassium in soils with resident vegetation or seeded cover crops.
- pH (4 studies): Two studies (one replicated, randomized, and controlled, and one site comparison) from Spain[13] and the USA[6] found lower pH levels in soils with ground cover, compared to soils without ground cover. One replicated, randomized, controlled study from Chile[17] found higher pH levels in soils with ground cover. One replicated site comparison from France[21] found similar pH levels in soils with or without ground cover.

- **Soil organisms (6 studies)**
  - Microbial biomass (4 studies): Four replicated studies (three randomized and controlled, one site comparison) from France[21] and the USA[6-8] found more microbial biomass in soils with ground cover, compared to bare or tilled soils, in some comparisons[6,8,21] or all comparisons[7].
    - **Implementation options (1 study):** One study from France[21] found more microbial biomass in soils with permanent ground cover, compared to temporary ground cover, in some comparisons.
  - Fungi (2 studies): One replicated, controlled study from the USA[2] found more symbiotic fungi (mycorrhizae) in soils with seeded cover crops, compared to tilled soils, in some

comparisons, but found similar numbers of roots that were colonized by mycorrhizae. One replicated, randomized, controlled study from the USA[6] found inconsistent differences in mycorrhizae in soils with seeded cover crops or tilled soils.

- Bacteria (1 study): One replicated, randomized, controlled study from Spain[11] found more bacteria, but similar levels of bacterial diversity, in soils with ground cover, compared to bare soils.
- Nematodes (1 study): One replicated site comparison from France[21] found more nematodes in soils with ground cover, compared to bare soils.
  - **Implementation options (1 study):** One study from France[21] found more nematodes in soils with permanent ground cover, compared to temporary ground cover, in one of three comparisons.

- **Soil erosion and aggregation (10 studies)**
  - Soil erosion (7 studies): Six replicated, randomized, controlled studies from Chile[17], Italy[15], Spain[1,10,18], and the USA[6] found less erosion of soils with ground cover, compared to bare or tilled soils, in some comparisons[1,6,10,18] or all comparisons[15,17]. One replicated, controlled study from France[9] found similar amounts of erosion in plots with or without ground cover.
    - **Implementation options (1 study):** One study from Italy[15] found the least erosion with permanent cover crops, and the most erosion with temporary cover crops.
  - Soil aggregation (5 studies): Four replicated, randomized, controlled studies from Chile[17] and Spain[1,10,12] found that soil aggregates were more water-stable in plots with seeded cover crops, compared to tilled or bare soils, in some comparisons[1,10,12] or all comparisons[17]. One site comparison from Spain[13] found inconsistent differences in water stability between soils with seeded cover crops and bare soils.
- **Greenhouse gases (3 studies):** Two replicated, randomized, controlled studies from a vineyard in the USA[7,8] found more carbon dioxide[7] or nitrous oxide[8] in soils with cover crops, compared to tilled soils. One replicated, randomized, controlled study from an olive orchard in Spain[10] found similar amounts of carbon dioxide in soils with cover crops, compared to tilled soils.
  - **Implementation options (1 study):** One study from the USA[14] found similar amounts of carbon dioxide in soils with different types of ground cover.

A replicated, randomized, controlled study in 2000–2003 in a rainfed olive orchard near Cordoba, Spain (1) (partly the same study as (10)), found more organic matter, less erosion, and higher soil stability in plots with cover crops, compared to conventional tillage or bare fallows. **Organic matter:** More organic matter was found in soils with cover crops (1.5%), compared to conventional tillage (1.2%) or bare fallows (0.9%). **Soil erosion and aggregation:** Less soil was lost in runoff from plots with cover crops, compared to bare fallows (1.2 vs 8.5 t/ha/year), but similar amounts were lost from plots with cover crops or conventional tillage (1.2 vs 4.0). Higher stability was found in soils with cover crops, compared to bare fallows (83% vs 60% of aggregates were water-stable), but similar stability was found in soils with cover crops or conventional tillage (82% vs 72%). **Methods:** There were three plots (6 x 12 m plots, with two olive trees each, on a 13% slope) for each of three treatments: cover crops (2 x 12 m barley strips, sown in October), conventional tillage (15 cm depth, 3–4 passes from September), or bare fallows (with herbicide, weed-free). Plots with cover crops were tilled before the barley was sown (10 cm depth). Runoff was collected with tipping-bucket gauges, and sediment was collected in barrels, from autumn 2000. Soil samples were collected in summer 2003 (0–5 cm depth).

A replicated, controlled study in 2001–2003 in an irrigated vineyard in the Salinas Valley, California, USA (2) (same study as (6)), found more fungal spores in soils between vine rows with cover crops, compared to those without cover crops. **Soil organisms:** More fungal spores (mycorrhizae) were found in soils with cover crops, in at least one of three seasons (spring: 110–130 vs 70 spores/g soil). Similar numbers of vine roots were colonized by mycorrhizae in vine rows with or without cover crops (data not reported). **Methods:** There were nine plots (0.045 ha) for each of two cover crops (*Secale cereale* Merced rye or *Triticosecale* triticale, in the central 80 cm of the 240 cm between vine rows, which were disked every year in November, before they were planted, and were mown every year in spring), and there were nine control plots (bare soil between the vine rows, which were disked every month). Soil and vine roots (8 cm root and 10 g soil from 20 vines/plot, 0–30 cm depth) were collected in summer (July 2002), winter (February 2003), and spring (April 2003). Cover-crop roots were collected in winter and spring. Spores and fungal colonies were measured in soil and roots.

A study in 1998–2002 in an irrigated vineyard in the Sacramento Valley, California, USA (3), found more nitrogen in soil that was cover cropped with legumes, compared to grasses. **Implementation options:** More nitrogen was found in soil that was cover cropped with legumes, compared to grasses (0.26% vs 0.22% total nitrogen). **Methods:** A leguminous cover crop (*Trifolium fragiferum* perennial strawberry clover) was planted in the southern half of the vineyard, and three native Californian, perennial, summer-dormant grasses (*Elymus glaucus* blue wildrye, *Hordeum brachyantherum* meadow barley, and *Bromus carinatus* California brome) were planted in the northern half. These cover crops were planted between every other vine row. They were mown 4–5 times/year and their residues were retained. The vineyard was fertigated with drip lines. Soil samples were collected in five sub-plots, in one 10 x 15 m plot, in each cover crop (0–10 cm depth, 3 cm diameter, nine times in July 2001–October 2002).

A replicated, randomized, controlled study in 2002–2005 in an irrigated vineyard in the Napa Valley, California, USA (4), found similar amounts of organic matter and nutrients in soils with seeded cover crops or resident vegetation. **Implementation options:** Similar amounts of organic carbon were found in soils with seeded cover crops or resident vegetation (21–24 mg organic matter/g dry soil). Similar amounts of nitrogen (1.6–1.8 mg total N/g dry soil), phosphorus (17–22 µg Olsen P/g dry soil), and potassium (7.3–7.7 µmol exchangeable K/g dry soil) were found in soils with seeded cover crops or resident vegetation. **Methods:** No tillage or conventional tillage was used on eight plots each, between the vine rows (three vine rows/plot). A disk plough was used for conventional tillage (15 cm depth, once/year in April–June). Four plots with conventional tillage had annual cover crops (seeded in October 2002–2004) and four plots had no seeded cover crops. Four plots with no tillage had annual cover crops (seeded in October 2002–2004), and four had perennial cover crops (seeded in October 2002). All plots were drip irrigated in July–October (85 kl/ha/week). Soil samples were collected under grape vines and between the rows (0–15 cm depth, 4.6 cm diameter, four samples/plot in each location).

A replicated, randomized, controlled study in 1976–2004 a rainfed olive orchard in southeast Spain (5) (same study as (11)) found more organic matter and nitrogen in soils with cover crops, compared to soils without cover crops. **Organic matter:** More organic carbon was found in soils with cover crops, in two of four comparisons (23 vs 39–42 Mg C/ha, 0–30 cm depth). **Nutrients:** More nitrogen was found in soils with cover crops, in two of four comparisons (2.9 vs 4.4–6.5 Mg total N/ha, 0–30 cm depth). **Implementation options:** More organic carbon and nitrogen were found in plots with cover crops that were incorporated into the soil in spring, compared to cover crops that were suppressed with herbicides or mown in spring and retained on the surface (39–42 vs 26–30 Mg C/ha, 4.4–6.5 vs 3.4–3.9 Mg total N/ha). **Methods:** Herbicide was used on seven plots in autumn, but not on 28 other plots, which had resident vegetation over winter. The resident vegetation was controlled in spring with herbicide (seven plots), tillage (seven plots, 0–25 cm depth), mowing (seven plots), or mowing and tillage (seven plots, 0–25 cm depth). Plots had 16 olive trees each. Foliar fertilizer was used. Two soil samples were collected in each plot (0–30 cm depth, in February 2004, before spring tillage).

A replicated, randomized, controlled study in 2000–2005 in an irrigated vineyard in the Salinas Valley, California, USA (6) (same study as (2)), found more organic matter and microbial biomass, less nitrate, phosphorus, and soil erosion, and lower pH levels in soils with cover crops, compared to bare soils, between vine rows. **Organic matter:** More organic matter was found in soils with cover crops, compared to bare soils (1.15–1.55% vs 0.95–1.10%). **Nutrients:** Less nitrate and phosphorus was found in soils with cover crops, compared to bare soils, in five of six comparisons (3–11 vs 17–28 ppm nitrate-N; 20–22 vs 24–25 ppm Olsen-P). Lower pH was found in soils with cover crops, compared to bare soils (data not reported). **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with cover crops, compared to bare soils, in one of two comparisons (plots that were cover cropped with rye: 105 vs 83 µg C, in vine rows; 190 vs 100 µg C, between vine rows; 0–12 inches depth). More beneficial fungus colonies (mycorrhizae) were found on vine roots in plots with cover crops, compared to bare soils, in two of six comparisons (with rye as the cover crop, and with pre-emergence herbicide or cultivation under the vines: 26–27% vs 21–21% of root length was colonized), but fewer colonies were found in one of six comparisons (with rye, and with post-emergence herbicide under the vines: 17% vs 26%). **Soil erosion and aggregation:** In winter, less sediment was lost in runoff from plots with cover crops, compared to bare soils, in one of two comparisons (with triticale as the cover crop: 508 vs 1,735 mg/litre). **Methods:** There were nine plots for each of two treatments and one control. The treatments were triticale (X *Triticosecale*) or *Secale cereale* Merced rye, planted in November 2000–2004 as cover crops (32 inches width) between the vine rows (8 feet width), mown in spring, and disked into the soil in the following November. Bare soils were maintained in the controls through disking in spring and summer (depth not reported). Each plot had 100 vines and the adjacent areas between the vine rows. All plots were drip-irrigated in April–October. Soil samples were collected when the vines were flowering (May 2003–2005, 10 samples/plot, 0–12 inches depth, between the vine rows). Vine roots were collected in April 2003, May 2004, and June 2005 (for mycorrhiza measurements). Runoff was measured with sumps (16 inches diameter, 5 feet depth) at the lower end of each plot. It was not clear whether these results were a direct effect of cover crops or tillage.

A replicated, randomized, controlled study in 2001–2006 in an irrigated vineyard in the Central Coast, California, USA (7) (same study as (8)), found more organic matter, soil organisms, and greenhouse-gas emissions in soils with cover crops, compared to tilled soils, between the vine rows. **Organic matter:** More carbon was found in soils with cover crops, compared to tilled soils (9.5–11 vs 7.2 mg total C/kg soil, 0–15 cm depth). **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with cover crops, compared to tilled soils (150–330 vs 50–190 µg C/g soil, 0–15 cm depth).

Greenhouse gases: Higher carbon dioxide emissions were found in soils with cover crops, compared to tilled soils (268–291 vs 153 g CO_2-C/m^2/year). **Methods:** There were six plots for each of two cover crops (*Secale cereale* rye or *Triticale x Triosecale* Trios, sown between the vine rows in autumn, mown in spring), and there were six control plots (tilled between the vine rows every two months; depth not reported). All plots were tilled in autumn. The plots were each 84 x 1.8 m, between two vine rows. Soil samples were collected every 2–3 weeks in November 2005–2006 (two samples/plot, 0–15 cm depth).

A replicated, randomized, controlled study in 2001–2006 in a vineyard in the Central Coast, California, USA (8) (same study as (7)), found more soil organisms and higher greenhouse-gas emissions in plots with cover crops between the vine rows, compared to tilled soils without cover crops, but found inconsistent effects on nitrogen. **Nutrients:** Less nitrate was found in soils with cover crops, compared to tilled soils, between vine rows, in 12 of 19 comparisons (0–1 vs 1.4–5.7 µg NO_3-N/g dry soil). In contrast, more ammonium was found in soils with cover crops, in six of 19 comparisons (during the spring rains: 1.3–3 vs 0.7–1.7 µg NH_4-N/g dry soil), and more available nitrogen was found in 18 of 19 comparisons (potentially mineralizable nitrogen: 21–55 vs 2–15 µg NH_4-N/g dry soil). **Soil organisms:** More microbial biomass (measured as nitrogen) was found in soils with cover crops, compared to tilled soils, in 15 of 38 comparisons (during the spring and autumn rains: 21–61 vs 4–39 µg N/g dry soil). **Greenhouse gases:** Higher nitrous oxide emissions were found in soils with cover crops, compared to tilled soils (1.9–2.3 vs 1.6 g N_2O-N/ha/day). **Methods:** There were six plots (84.3 x 2.4 m interrows between vines) for each of two cover crops, and there were six control plots (cultivated every two months to control weeds). The cover crops (1.8 m width) were *Triticale* x *Triticosecale* Trios or *Secale cereale* rye, seeded in November 2001–2005 (interrows disked before seeding), and mown in April 2002–2006. Soil samples were collected every 2–3 weeks in December 2005–November 2006 (19 samples/plot, two cores/sample, 0–15 cm depth). Nitrous oxide was measured in 5.2 litre chambers (13 mL samples, every 30 minutes from solar noon, for 1.5 hours). It was not clear whether these results were a direct effect of cover crops or tillage.

A replicated, controlled study in 1999 in a vineyard in southern France (9) found similar amounts of erosion in plots with grass or bare soil between the vine rows. **Soil erosion and aggregation:** Similar amounts of soil were lost in runoff water from plots with grass or bare soil between the vine rows (26–112 vs 45–207 g soil/m^2). **Methods:** One interrow was cultivated (10 cm depth) and planted with grasses, and one interrow was managed conventionally (with herbicide), for four months each. Rainfall was simulated in three plots, in each interrow, in June 1999 (1 x 1 m plots, 60 mm water/hour, for 60 minutes). Soil loss was measured in each plot (200 observation points/m^2).

A replicated, randomized, controlled study in 2000–2006 in a rainfed olive orchard near Cordoba, Spain (10) (partly the same study as (1)), found more organic matter and nitrogen, less erosion, and higher soil stability in plots with cover crops, compared to soils with no tillage or conventional tillage. **Organic matter:** More organic matter was found in soils with cover crops, compared to bare fallows (1.2–2% vs 0.8–1%). **Nutrients:** More nitrogen was found in soils with cover crops, compared to bare fallows (0.08–0.11% vs 0.06–0.08% organic nitrogen). **Soil erosion and aggregation:** Less soil was lost in runoff from plots with cover crops, compared to bare fallows, in five of seven years (0–5 vs 1–19 t/ha/year), or compared to plots with conventional tillage, in two of seven years (0.1–5 vs 0.4–14). Higher stability was found in soils with cover crops, compared to bare fallows, in one of two comparisons (macroaggregates: 452–524 vs 258–333 g water-stable macroaggregates/g soil). **Greenhouse gases:** Similar amounts of carbon dioxide were found in soils with cover crops, bare fallows, or conventional tillage (soil respiration: 0.5–1.1 kg CO^2/kg soil). **Methods:** There were three plots (6 x 12 m plots, with two olive trees each, on a 13% slope) for each of three treatments: cover crops (2 x 12 m barley strips, sown in October), conventional tillage (15 cm depth, 3–4 passes from September), or bare fallows (no tillage, with herbicide). Plots with cover crops were tilled before the barley was sown (10 cm depth). Runoff was collected with tipping-bucket gauges, and sediment was collected in barrels, from autumn 2000. Soil samples were collected in summer 2006 (0–10 cm depth, two samples/plot).

A replicated, randomized, controlled study in a rainfed olive orchard in southeast Spain (11) (years of study not reported, but same study as (5)) found more organic matter and soil organisms in soils with cover crops, compared to soils without cover crops, under olive trees. **Organic matter:** More organic carbon was found in soils with cover crops, compared to soils without cover crops (8.3–9.9 vs 5.4 g C/kg soil). **Soil organisms:** More bacteria were found in soils with cover crops, compared to soils without cover crops (950–1,400 vs 32–230 million 16S rRNA copies/g soil). Bacterial diversity was similar in soils with or without cover crops (data reported as Shannon diversity index). **Methods:** Herbicide was used on four control plots in autumn, but not on eight treatment plots, which had resident vegetation. The resident vegetation was controlled in spring with herbicide (four plots) or mowing (four plots). Plots had 16 olive trees each. Plots were not tilled. Foliar fertilizer was used. Two soil samples were collected in each plot (0–30 cm depth, sampling date not reported).

A replicated, randomized, controlled study in 2004–2008 in a vineyard in northern Spain (12) found more organic matter and nitrogen, and higher stability, in soils with cover crops, compared to conventional tillage, between the vine rows. **Organic matter:** More organic carbon was found in soils with cover crops, compared to conventional tillage, in three of eight comparisons (three of four comparisons at 0–5 cm depth: 8–20 vs 6 g C/kg soil). **Nutrients:** More nitrogen was found in soils with cover crops, compared to conventional tillage, in three of eight comparisons (0–2.5 cm: 99–107 vs 21 mg N-NH_4/kg soil; 15–25 cm: 25 vs 12). **Soil erosion and aggregation:** Higher stability was found in soils with cover crops, compared to conventional tillage, in two of eight comparisons (0–2.5 cm depth: 37–42% vs 12% of aggregates were water-stable). **Methods:** There were three plots (three vine rows/plot) for each of two cover crops (sown *Festuca longifolia* grass or resident vegetation between the vine rows), and there were three control plots (conventional tillage between the vine rows: cultivator, 0–15 cm depth, every 4–6 weeks). No plots were fertilized, but herbicide was used under the vine rows. Soil samples were collected in June 2008 (six augers/plot, 0–25 cm depth).

A site comparison in 2006 in two rainfed almond orchards near Granada, Spain (13), found more organic matter and nitrogen, less phosphorus, and lower pH in soils with cover crops (without tillage), compared to soils with conventional tillage (without cover crops). **Organic matter:** More organic carbon was found in soils with cover crops (without tillage), compared to soils with conventional tillage (without cover crops) (8.4–9 vs 5.4 g total organic C/kg soil). **Nutrients:** More nitrogen was found in soils with cover crops (without tillage), compared to soils with conventional tillage (without cover crops) (1.1 vs 0.83 g total N/kg soil), but less phosphorus was found in one of two comparisons (oat-vetch cover crop: 1.6 vs 2.1 mg available P/kg soil), and lower pH was found (8.3 vs 8.5), but similar amounts of potassium were found (148–162 vs 186 mg available K/kg soil). **Soil erosion and aggregation:** Higher soil stability was found in plots with cover crops (without tillage), compared to plots with conventional tillage (without cover crops), in one of two comparisons (61–62% vs 44% of aggregates were water-stable), but lower soil stability was found in two of four comparisons (15% vs 13% change in the mean weight diameter of soil aggregates after sieving). **Implementation options:** More phosphorus was found in soils that were cover cropped with oats, compared to oats and vetch (2.1 vs 1.6 mg available P/kg soil). **Methods:** Conventional tillage (chisel plough, 20–25 cm depth, 3–4 times/year in 2001–2005, October 2005, and April and June 2006) was used in one orchard, and no tillage was used in another orchard with two cover crops (oats and vetch or oats only, sown in January 2006 on one 1 ha plot each). Both orchards were fertilized (30 t compost/ha), but the orchard with cover crops got more fertilizer (1,500 kg organic fertilizer/ha on one-third of each plot, 250 kg mineral fertilizer/ha on one-third). The orchard with cover crops had cereal-fallow rotations before the cover crops, and it was tilled in November. Soil samples were collected on 18 July 2006 (0–20 cm depth). It was not clear whether these results were a direct effect of cover crops, tillage, fertilizer, or site.

A replicated, randomized, controlled study in 2003–2005 in a vineyard in Napa Valley, California, USA (14), found similar amounts of carbon and carbon dioxide in soils with cover crops or resident vegetation. **Implementation options:** Similar amounts of carbon were found in soils with cover crops or resident vegetation (1.64 g total C/g dry soil). Similar amounts of carbon dioxide were found in soils with cover crops or resident vegetation (9.02–10.11 vs 8.40–10.99 Mg CO_2-C/ha). **Methods:** Short-stature barley was grown as a winter cover crop on three treatment plots (518 m^2 each, four vine alleys each), but not on three control plots. All plots were disked (5 cm depth) and rolled in November 2003–2004, before the cover crops were planted. Resident vegetation regrew on control plots.

A replicated, randomized, controlled study in 2005–2007 in irrigated vineyards in Sicily, Italy (15), found less erosion in plots with cover crops, compared to conventional tillage (without cover crops), between the vine rows. **Soil erosion and aggregation:** Less erosion was found in plots with cover crops, compared to plots with conventional tillage (0–61 vs 31–89 Mg soil loss/ha). **Implementation options:** In plots with cover crops, the least erosion was found in plots with permanent cover crops (*Trifolium* clover and *Festuca* grass species: 0–40 Mg soil loss/ha), and the most erosion was found in plots with temporary *Vicia faba* cover crops (12–61 Mg/ha). **Methods:** There were three plots (three vine interrows/plot; 2.2 x 3 m interrows) for each of four temporary cover-crop treatments (*V. faba*; *V. faba* and *V. sativa*; *Triticum durum*; or *T. durum* and *V. sativa*), two permanent cover-crop treatments (*T. subterraneum*, *F. rubra*, and *Lolium perenne*, or *T. subterraneum*, *F. rubra* and *F. ovina*), and three control plots (conventional tillage in the interrows, 3–4 times/year, 15 cm depth). Cover crops were sown in October. Temporary cover crops were tilled into the soil in April, but permanent cover crops were not tilled. The slope of the vineyard was 16%. Erosion was measured after each significant rainfall event (15 events in November 2005–October 2007) with sediment traps (Gerlach traps: 1 m diameter, 40 litres).

A meta-analysis from 2013 of studies from multiple Mediterranean countries (16) found a higher percentage of organic matter in soils with cover crops, compared to bare soils. **Organic matter:** A higher percentage of organic carbon was found in soils with cover crops, compared to bare soils (10% higher). The Web of Knowledge database was searched, using the keywords, “Mediterranean”, “soil”, and “conventional”, and 13 data sets from 10 studies of cover cropping were found and meta-analysed. The most recent studies included in this meta-analysis were published in 2011. It was not clear how many of these studies were from arable fields, orchards, or vineyards.

A replicated, randomized, controlled study in 2008–2011 in an irrigated avocado orchard in Chile (17) found more organic matter and nitrogen, higher pH, less erosion, and higher stability in soils with cover crops, compared to bare soils, between avocado rows. **Organic matter:** More organic matter was found in soils with cover crops, compared to bare soils (2.6–2.8% vs 2.1–2.2%). **Nutrients:** More nitrogen (1.0–1.1 vs 0.8–0.9 mg total N/g soil), but similar amounts of nitrate (11–59 vs 8–67 mg NO_3/kg soil), and more potassium (162–197 vs 100–122 mg K/kg soil), but similar amounts of phosphorus (11–15 vs 9–10 mg P/kg soil), were found in soils with cover crops, compared to bare soils. Higher pH was found in soils with cover crops, compared to bare soils (6.8–7.2 vs 6.6–6.9). **Soil erosion and aggregation:** Less soil was lost in runoff water from plots with cover crops, compared to bare soil (0 vs 1,000–3,400 vs kg/ha/year). More stable soils were found in plots with cover crops, compared to bare soil (32–39% vs 22–29% of soil aggregates were water-stable). **Methods:** Cover crops were grown in five treatment plots, and bare soil was maintained with herbicide in five control plots, in an avocado orchard, on a 47% slope (10 x 50 m plots). The groundcover (*Lolium rigidum* ryegrass and a legume, *Medicago polymorpha*) was sown in August 2008 and mown in February 2009–2010 (residues were retained). All plots were fertilized and irrigated. Soil samples were collected along the tree rows in winter 2009–2011 (0–10 cm depth, 2 cm diameter soil cores). Soil loss was measured in runoff water, in buried barrels downslope of each plot.

A replicated, randomized, controlled study in 2003–2005 in eight rainfed olive orchards in southern Spain (18) found less erosion in plots with cover crops, compared to tilled plots. **Soil erosion and aggregation:** Less soil was lost in runoff from plots with cover crops, compared to tilled plots, on seven of eight farms (63–89% less soil). **Methods:** On each of eight farms, cover crops were grown (two of eight farms) or weeds were not controlled (six of eight farms) on three plots, but weeds were controlled by conventional tillage (depths not reported) on three plots (1 m^2 microplots). Plots were surrounded by steel sheets, which routed the runoff into plastic containers. Soil loss was measured in water samples, after each rainfall event.

A replicated, randomized, controlled study in 2008–2010 in an irrigated vineyard in the San Joaquin Valley, California, USA (19), found similar amounts of nitrogen in different treatments. **Implementation options:** Similar amounts of nitrogen were found in soils with cover crops or resident vegetation (amounts of nitrogen not reported), in soils with different types of cover crops (oats only, or oats and legumes: amounts of nitrogen not reported), and in soils with or without tillage (amounts of nitrogen not reported). **Methods:** Either seeded cover crops or resident vegetation was grown between the vine rows on 16 plots each (two vine rows/plot, 190 vines/row). The cover crops were either oats or oats and legumes, on eight plots each, seeded in November. The plots were mown in spring, before tillage. No tillage was used on half of the plots, and conventional tillage was used on the other half. A disk plough (15–20 cm depth) was used for conventional tillage, in spring, summer (three times), and autumn. Herbicide was used to control weeds in the vine rows (50 cm width). Soil samples were collected in spring, before mowing and tillage (five soil cores/plot, on 40 m transects; depths not reported).

A replicated, randomized, controlled study in 2009–2011 in a rainfed vineyard in northern Spain (20) found more nitrogen and ammonium in soils with cover crops, compared to conventional tillage, between the vine rows, but found inconsistent differences in nitrate. **Nutrients:** More nitrogen was found in soils with cover crops, compared to conventional tillage, in one of 12 comparisons (clover, 0–15 cm depth: 2,050 vs 1,900 kg total N/ha), and more ammonium was found in two of 12 comparisons (clover, 0–15 cm depth: 5.1–6.3 vs 3.5–4.8 kg NH_4-N/ha). Less nitrate was found in soils with cover crops, compared to conventional tillage, in some comparisons, but more nitrate was found in other comparisons (2–35 vs 2–26 kg N-NO_3/ha). **Implementation options:** Less nitrate (0–15 cm depth: 2–5 vs 11–35 kg N-NO_3/ha; 15–45 cm depth: 2–9 vs 15–50), and less ammonium at one of two depths (0–15 cm depth: 3–5 vs 5–6.3 kg NH_4-N/ha), were found in soils that were cover cropped with grass (barley) compared to legumes (clover), after one year of cover cropping, but not before. **Methods:** There were three plots (four vine rows/plot, 20 vines/row) for each of two cover crops (*Hordeum vulgare* barley or *Trifolium resupinatum* Persian clover between the vine rows, sown in February 2009 and 2011), and there were three control plots (conventional tillage between the vine rows: disk plough, 0–15 cm depth, every 4–6 weeks in February–August). No plots were fertilized. Herbicides were used under the vine rows. Vine prunings were retained between the rows. Soil samples (0–45 cm depth, three samples/plot) were collected five times/season (April–September).

A replicated site comparison in 2009 in rainfed vineyards in southern France (21) found more organic matter, phosphorus, and soil organisms in soils with ground cover, compared to bare soils. **Organic matter:** More organic carbon was found in soils with ground cover, compared to bare soils, in three of six comparisons (permanent cover crops: 12–20 vs 6–14 g C/kg soil). **Nutrients:** More phosphorus was found in soils with ground cover, compared to bare soils, in one of six comparisons (permanent ground cover: 11 vs 7 mg available P/kg soil). Similar amounts of nitrogen and potassium, and similar pH levels, were found in soils with ground cover, compared to bare soils (data not reported). **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with ground cover, compared to bare soils, in four of six comparisons (50–140 vs 30–90 mg C/kg soil), and more nematodes were found in one of three comparisons (747–1,371 vs 351 total nematodes/100 g soil). **Implementation options:** More organic carbon was found in soils with permanent ground cover, compared to temporary ground cover, in one of three comparisons (18 vs 13 g C/kg soil), and more phosphorus was found in one of three comparisons (11 vs 7 mg available P/kg soil). More microbial biomass (measured as carbon) was found in soils with permanent ground cover, compared to temporary, in two of three comparisons (120–150 vs 90–120 mg C/kg soil), and more nematodes were found in one of three comparisons (1,371 vs 747 total nematodes/100 g soil). **Methods:** In 146 plots of three soil types, there was permanent vegetation (4–22% of plots in each soil type), temporary vegetation (48–68%), or bare soil (16–42%) between the vine rows, for at least five years before soil sampling. Soil samples were collected from the interrows in March–May 2009 (10 homogenized samples/plot, 0–15 cm depth).

A meta-analysis from 2016 of 24 studies in orchards and vineyards in Spain (22) found more organic matter in soils with winter cover crops, compared to soils with conventional tillage. **Organic matter:** More organic carbon was found in soils with cover crops, compared to conventional tillage (data reported as the response ratio: 1.35). **Methods:** The Scopus database was searched for publications in January 2016, using the keywords, “olive” or “vineyard” or “almond” or the scientific names of these species, and the keywords “soil organic carbon” or “soil organic matter”. Together with publications from another meta-analysis (16), 24 replicated, controlled studies from 2005 to 2015 were meta-analysed. In these studies, soil samples were collected from depths of 0–10 to 0–90 cm in almond orchards, olive orchards, and vineyards in Mediterranean climates in Spain. Plots with cover crops mostly had resident vegetation over the winter, which was controlled by mowing, grazing, or using herbicide in the spring, or reduced tillage in spring and autumn. In plots without cover crops, resident vegetation was controlled throughout the year by using herbicide and/or conventional tillage. It was not clear whether these results were a direct effect of cover crops, tillage, herbicide, mowing, or grazing.

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3.8. Use crop rotations: Soil (14 studies)

- **Organic matter (9 studies):** Five replicated, controlled studies (two randomized) from Italy[12], Portugal[4], and Spain[6,8,14] found less organic matter in soils with crop rotations, compared to continuous crops, in some comparisons. One replicated, controlled study from Syria[3] found more organic matter in soils with crop rotations, compared to continuous crops, in some comparisons. Three replicated, controlled studies from Spain[1,5,7] found similar amounts of organic matter in soils with or without crop rotations.
- **Nutrients (5 studies)**
  - Nitrogen (5 studies): One replicated, randomized, controlled study from Australia[13] found more nitrogen in soils with crop rotations, compared to continuous crops, in one of four comparisons. One replicated, controlled study from Italy[12] found less nitrogen in soils with crop rotations, compared to continuous crops, in some comparisons. One replicated, randomized, controlled study from Spain[11] found inconsistent differences in nitrogen in soils with or without crop rotations. Two replicated, randomized, controlled studies from Portugal[4] and Spain[5] found similar amounts of nitrogen in soils with or without crop rotations.
  - Phosphorus (2 studies): Two replicated, randomized, controlled studies from Portugal[4] and Spain[5] found less phosphorus in soils with crop rotations, compared to continuous crops, in some comparisons.
  - pH (2 studies): Two replicated, randomized, controlled studies from Portugal[4] and Spain[5] found similar pH levels in soils with or without crop rotations.
- **Soil organisms (3 studies)**
  - Microbial biomass (2 studies): One replicated, controlled study from Italy[12] found more microbial biomass in soils with crop rotations, compared to continuous crops, in some comparisons. One replicated, randomized, controlled study from Spain[14] found less microbial biomass in soils with crop rotations, compared to continuous crops, in some comparisons.
  - Bacteria and fungi (1 study): One replicated, randomized, controlled study from Portugal[4] found more fungi, but similar amounts of bacteria, in soils with crop rotations, compared to continuous crops.

- **Soil erosion and aggregation (4 studies):** One replicated, controlled study from Syria[3] found higher water-stability in soils with crop rotations, compared to continuous crops. One replicated, randomized, controlled study from Spain[1] found lower water-stability in soils with crop rotations, compared to continuous crops, in some comparisons. One replicated, randomized, controlled study from Spain[6] found inconsistent differences in water-stability in soils with or without crop rotations. One replicated, randomized, controlled study from Spain[8] found no differences in water-stability.
- **Greenhouse gases (4 studies):** One replicated, controlled study from Italy[12] found higher carbon dioxide emissions from soils with crop rotations, compared to continuous crops, in some comparisons. One replicated, randomized, controlled study from Spain[14] found similar carbon dioxide emissions from soils with or without crop rotations. One replicated, randomized, controlled study from Australia[10] found lower nitrous oxide and methane emissions from soils with crop rotations, compared to continuous crops, but another one[13] found no differences in nitrous oxide emissions.
- **Implementation options (2 studies):** Two studies from Syria[9] and the USA[2] found similar amounts of nitrogen in soils with two-year or four-year rotations. One of these studies[9] also found similar amounts of organic matter.

A replicated, randomized, controlled study in 1983–1996 in a rainfed wheat field in the Henares river valley, Spain (1), found lower stability in soils with crop rotations, compared to soils without crop rotations, in some comparisons. **Organic matter:** Similar amounts of organic carbon were found in soils with or without crop rotations (42.3 vs 40.4 Mg C/ha). **Soil erosion and aggregation:** Lower soil stability was found in soils with crop rotations, compared to soils without crop rotations, in three of four comparisons (in 1–2 mm pre-wetted soil aggregates: 76% vs 79% water stable; in 1–2 mm air-dried soil aggregates: 5.5% vs 6.1%; in 4.38 mm air–dried soil aggregates: 2% vs 7%). **Methods:** Wheat was grown continuously or in rotation with vetch (12 plots each, 20 x 30 m plots). Fertilizer and post–emergence herbicide were used on all plots. Soil samples were collected in June 1996 (plots with rotations) or July 1996 (plots without rotations), with four samples/subplot. Organic carbon was measured at 0–40 cm depth. Aggregate stability was measured at 0–30 cm depth.

A replicated, randomized, controlled study in 1994–1998 in arable farmland in California, USA (2), found similar amounts of nitrogen in plots with four-year or two-year crop rotations. **Implementation options:** Similar amounts of nitrogen were found in plots with four-year or two-year crop rotations (29–42 vs 26–40 mg ammonium and nitate/kg soil, 0–15 cm depth). **Methods:** A four-year rotation (tomato, safflower, corn and wheat, beans) was used on 16 plots (four plots for each phase, each year), and a two-year rotation (tomato, wheat) was used on eight plots (four plots for each phase, each year). Each plot was 68 x 18 m. Fertilizer and pesticide were used on all plots. Soil samples were collected from tomato plots (every 2–3 weeks in the cropping season in 1994–1998, 0–15 cm depth).

A replicated, controlled experiment in 1985–1995 in a rainfed durum wheat field near Aleppo, Syria (3), found more organic matter and greater stability in soils with crop rotations, compared to continuous wheat. **Organic matter:** More organic matter was found in plots with crop rotations, compared to continuous wheat, in five of six comparisons (11.4–13.8 vs 10.9 g/kg). **Soil erosion and aggregation:** More stable soils were found in plots with crop rotations, compared to continuous wheat (30–41% vs 22% of aggregates were water-stable). **Methods:** Durum wheat *Triticum turgidum* var. *durum* was grown continuously or in two-year rotations with lentils *Lens culinaris*, chickpeas *Cicer arietinum,* medic *Medicago sativa*, vetch *Vicia faba*, watermelon *Citrullus vulgaris*, or fallow (one plot for each crop phase, each year). Each plot was 36 x 150 m. Soils samples were collected each year, before planting (0–20 cm depth).

A replicated, randomized, controlled study in 2004–2006 in an occasionally irrigated oat field in Portugal (4) found less organic matter, phosphorus, and fungi in soils with a lupin-oat sequence, compared to an oat-oat sequence. **Organic matter:** Less organic carbon was found in soils with a lupin-oat sequence, in one of two comparisons (tilled plots: 6.2 vs 7.7 g/kg). **Nutrients:** Less phosphorus was found in soils with a lupin-oat sequence, in one of two comparisons (tilled plots: 51 vs 59 mg/kg). Similar amounts of nitrogen, and similar pH levels, were found in soils with both sequences (35–39 vs 41–44 g mineral N/kg, pH 5.2–5.4). **Soil organisms:** Fewer fungi were found in soils with a lupin-oat sequence (0.0023–0.0034 vs 0.0036–0.0045 colony forming units/g soil), but similar numbers of bacteria were found in both sequences (data not reported). **Methods:** Oats or white lupins *Lupinus albus* were grown in six plots each in 2003–2004 (year 1). Oats were grown in all plots in 2004–2005 (year 2). Each plot was 5 x 10 m. Half were tilled (15 cm depth), and half were not (crop residues were retained). All plots were fertilized with phosphorus (60 kg/ha), and oats were also fertilized with nitrogen (100 kg/ha). The seeds were sown in September and the oats were harvested in May. Soil samples were collected in year 2, in October, November, January, March, May, and July (0–15 cm depth). Bacteria and fungi were cultured from soil samples.

A replicated, randomized, controlled study in 1993–2000 in arable farmland in Madrid, Spain (5), found less phosphorus in plots with fallow-barley rotations, compared to continuous barley. **Organic matter:** Similar amounts of organic carbon were found in soils with or without crop rotations (data not reported). **Nutrients:** Less phosphorus was found in soils with crop rotations, compared to continuous barley, in one of six comparisons (compared to fallow-barley at one depth: 16 vs 18 kg/ha). Similar amounts of nitrogen, and similar pH levels, were found in soils with or without rotations (0.9–1.8 Mg/ha; data not reported for pH). **Methods:** Barley was grown continuously (one plot), or in rotation with vetch *Vicia sativa* or fallow (one plot/phase), in each of three tillage treatments (conventional, reduced, or no tillage), in each of four blocks. Plots were 10 x 25 m. The barley phases were fertilized (8-24-8 NPK: 200 kg/ha; ammonium nitrate: 200 kg/ha). Before the experiment, barley was grown in these plots for over 10 years. Barley was harvested in June. Soil samples were collected after each harvest (0–90 cm depth).

A replicated, randomized, controlled study in 2003 in a rainfed barley field in the Ebro river valley, Spain (6), found less organic matter, but inconsistent differences in stability, in soils with barley-fallow rotations, compared to continuous barley. **Organic matter:** Less organic carbon was found in soils with barley-fallow rotations, compared to continuous barley, in one of three comparisons (0–20 cm depth: 2,306 vs 2,743 g C/m^2). **Soil erosion and aggregation:** Fewer large aggregates were found in soils with barley-fallow rotations, compared to continuous barley, in one of nine comparisons (water-stable aggregates >2,000 µm, 0–5 cm depth: 0.09 vs 0.15 g aggregate/g soil), but more were found in one of nine comparisons (53–250 µm, 0–5 cm depth: 0.6 vs 0.5 µm). **Methods:** Barley was grown in rotation with fallows on three plots, but barley was grown continuously on three other plots. Plots were 33 x 10 m. Soil samples were collected with a flat spade (0–20 cm depth) in July 2003.

A replicated, controlled study in 1994–2001 in a rainfed cereal field in the Duero valley, northern Spain (7), found similar amounts of organic matter in soils with or without crop rotations. **Organic matter:** Similar amounts of organic carbon were found in soils with or without crop rotations (36–42 Mg/ha). **Methods:** Cereals (wheat and barley) were grown continuously (one plot/year), in rotation with vetch *Vicia sativa* (two plots/year: one cereal, one vetch), or in rotation with fallow (two plots/year: one cereal, one fallow), in each of three tillage treatments (conventional, reduced, or no tillage), in each of four blocks. Each plot was 450 m^2, and there were 60 plots in total (five plots/three treatments/four blocks). The cereals were fertilized (8-24-8 NPK: 400 kg/ha; ammonium sulphate: 300 kg/ha). Herbicide was used on all plots. Soil samples were collected in October 1994, 1997, and 2000 (three samples/plot, 0–30 cm depth), before tillage in November.

A replicated, randomized, controlled study in 2005–2007 in a wheat field near Madrid, Spain (8), found less organic matter in soils with wheat-fallow rotations, compared to continuous wheat. **Organic matter:** Less organic carbon was found in soils with wheat-fallow rotations, compared to soils with continuous wheat, in one of four comparisons (November 2006, 0–7.5 cm depth: 7 vs 8 Mg/ha). **Soil erosion and aggregation:** No difference in stability was found in soils with or without rotations (25–55% of aggregates were water-stable). **Methods:** Crop rotation (wheat-fallow) or continuous cropping (wheat-wheat) was used on 12 plots each (10 x 25 m plots) in 2005–2007. All plots were fertilized. Soil samples were collected after the seedbeds were prepared (three samples/plot, 0–15 cm depth), in November 2006 and October 2007.

A replicated, randomized, controlled study in 1996–2008 in rainfed farmland near Aleppo, Syria (9), found similar amounts of organic matter and nitrogen in soils with two-course or four-course crop rotations. **Implementation options:** Similar amounts of organic matter and nitrogen were found in soils with two-course or four-course crop rotations (organic matter: 10–18 g/kg soil; nitrogen: 0.76 g/kg soil). **Methods:** The crop rotations were vetch-barley (two-course) or vetch-barley-vetch-wheat (four-course). Each rotation was grown on twenty plots (25 x 25 m). Soil samples were collected in 2003 (0–30 cm depth) and 2008 (0–20 cm depth).

A replicated, randomized, controlled study in 2009–2010 in a rainfed wheat field in the Wongan Hills, Western Australia (10), found that less nitrous oxide was emitted from, and more methane was absorbed by, soils with a lupin-wheat sequence, compared to a wheat-wheat sequence, over two years. **Greenhouse gases:** Less nitrous oxide was emitted from plots with a lupin-wheat sequence, compared to a wheat-wheat sequence, in one of two comparisons (without added lime: 100 vs 130 g N_2O–N/ha, over two years). More methane was absorbed by plots with a lupin-wheat sequence, compared to a wheat-wheat sequence, in one of two comparisons (without added lime: 991 vs 601 g CH_4-C/ha). **Methods:** Wheat or lupin *Lupinus angustifolius* was planted on six 150 m^2 plots each, in June 2009. In June 2010, wheat was planted on all plots. Lime was added to half of the plots (3.5 t/ha). Different fertilizers were used on each crop (e.g., no nitrogen was used on lupin). No plots were tilled. Nitrous oxide and methane were measured with chambers (500 mm x 500 mm chambers, eight measurement/day/plot, for two years beginning in June 2009).

A replicated, randomized, controlled study in 1992–2010 in a rainfed wheat field in southern Spain (11) found inconsistent differences in nitrate between soils with or without crop rotations. **Nutrients:** Less nitrate was found in soils with crop rotations, compared to continuous wheat, in three of four rotations (55–117 vs 124 kg nitrate/ha), but more was found in one of four rotations (wheat-faba bean: 139 kg/ha). **Methods:** Wheat was grown continuously (one plot/year) or in two-year rotations with chickpeas, faba beans, sunflower, or fallows (each with two plots/year: one wheat, one alternate), in each of two tillage treatments (conventional tillage or no tillage), in each of three blocks.

Each plot had four subplots (10 x 5 m), each with a different amount of fertilizer (0–150 kg N/ha). Soil samples were collected every three years (0–90 cm).

A replicated, controlled study in 1999–2010 in a rainfed durum wheat field in Sicily, Italy (12), found less carbon and nitrogen, but more microbial biomass and higher greenhouse-gas emissions, in plots with wheat-bean rotations, compared to continuous wheat. **Organic matter:** Less organic carbon was found in soils with wheat-bean rotations, compared to plots with continuous wheat, in two of three comparisons (29–33 vs 33–36 Mg/ha; 19 vs 21 g/kg). **Nutrients:** Less nitrogen was found in soils with wheat-bean rotations, in two of three comparisons (1–1.1 vs 1.3–1.4 g/kg). **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with wheat-bean rotations, in two of three comparisons (293–509 vs 208–330 mg C/kg). **Greenhouse gases:** More carbon was emitted from plots with wheat-bean rotations, compared to continuous wheat (carbon output, in one of three comparisons: 3.1 vs 2.4 Mg C/ha/year; soil respiration: 17–22 vs 14–19 mg C/kg/day). **Methods:** Durum wheat *Triticum durum* was grown continuously or in a two-year rotation with faba beans *Vicia faba* on four plots each (18.5 x 20 m plots). Fertilizer and herbicide were used on all plots (half were tilled, and half were not). Soil samples were collected after harvest, in June 2009 (three samples/plot, 0–15 cm depth). Carbon dioxide was measured on 36 days in April 2008–April 2009 (closed chambers, 12 measurements/plot, 9–11 am).

A replicated, randomized, controlled study in 2010–2011 in a rainfed field in Western Australia (13) found more nitrogen in plots with canola-wheat or wheat-wheat sequences. **Nutrients:** More nitrogen was found in plots with a canola-wheat sequence, compared to a wheat-wheat sequence, in one of four comparisons (after planting: 106 vs 93 kg total N/ha). **Greenhouse gases:** Similar nitrous oxide emissions were found in plots with different crop sequences (0.03–0.18 g/ha/hour). **Methods:** Wheat or canola was grown on three plots each, in 2010, and wheat was grown on all plots in 2011. Each plot was 1.4 x 40 m. Fertilizer (150 kg/ha/year) and herbicide were used on all plots. Soil samples were collected in September 2010–December 2011 (0–150 cm depth). Nitrous oxide was measured in closed chambers, five times in May–October 2011 (250 mm diameter, 325 mm height, two chambers/plot, one hour/plot).

A replicated, randomized, controlled study in 1994–2013 in a rainfed wheat field near Madrid, Spain (14), found less organic matter and microbial biomass in plots with four-year rotations, compared to continuous wheat. **Organic matter:** Less organic carbon was found in soils with rotations, compared to continuous wheat, in two of 12 comparisons (5–7 vs 6–8 g C/kg soil). **Soil organisms:** Less microbial biomass (measured as carbon) was found in soils with rotations, compared to continuous wheat, in one of 12 comparisons (200 vs 260 mg C/kg soil). **Greenhouse gases:** Similar carbon dioxide emissions were found in plots with or without rotations (20–42 mg CO_2-C/kg soil/day). **Methods:** Continuous wheat crops or four-year crop rotations (fallow-wheat-vetch *Vicia sativa*-barley) were used on 12 plots each (10 x 25 m subplots). The cereals were fertilized (NPK, 200 kg/ha, twice/year, in October and March). The crop residues were shredded and retained (but some of the plots were tilled). Soil samples were collected in October 2010, April 2011, November 2011, May 2012, October 2012 and April 2013 (50 mm diameter, 0–15 cm depth).

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3.9. Use no tillage in arable fields: Soil (40 studies)

- **Organic matter (20 studies):** One meta-analysis of studies from Mediterranean countries[25] found more organic matter in soils without tillage, compared to soils with tillage. Fourteen replicated studies (eleven randomized and controlled, one controlled, one site comparison) from Italy[20], Spain[6,19,21,26,28,29,32,33,38,39], and the USA[1,7,12] found more organic matter in soils without tillage, compared to soils with tillage, in some comparisons[6,7,12,19-21,28,29,32,33,38] or all comparisons[1,26,39]. One replicated, randomized, controlled study from Portugal[18] found less organic matter in soils without tillage, compared to soils with tillage, in some comparisons. One replicated, randomized, controlled study from Spain[37] sometimes found more organic matter, and sometimes found less, in soils without tillage, compared to soils with tillage. Three replicated, controlled studies (two randomized) from Italy[31] and Spain[34,35] found similar amounts of organic matter in soils with or without tillage.
- **Nutrients (19 studies)**

- Nitrogen (18 studies): Six replicated studies (five randomized and controlled, one site comparison) from Italy[20,30,40], Spain[32], and the USA[12,21] found more nitrogen in soils without tillage, compared soil with tillage, in some comparisons[20,21,30,32,40] or all comparisons[12]. Six replicated, randomized, controlled studies from Spain[4,8,23,27,34,36] found less nitrogen in soils without tillage, in some comparisons[4,8,23,34,36] or all comparisons[27]. Two replicated, controlled studies from Spain[6] and the USA[2] sometimes found more nitrogen and sometimes found less nitrogen in soils without tillage, compared to soils with tillage. Four replicated, controlled studies (three randomized) from Italy[31], Portugal[18], Spain[39], and the USA[7] found similar amounts of nitrogen in soils with or without tillage.
- Phosphorus (5 studies): Three replicated, randomized, controlled studies from Spain[6,9] and the USA[7] found more phosphorus in soils without tillage, compared to soils with tillage, in some comparisons[6,7], or all comparisons[9]. One replicated, randomized, controlled study from Portugal[18] found less phosphorus in soils without tillage, compared to soils with tillage, in some comparisons. One replicated, randomized, controlled study from Spain[32] found similar amounts of phosphorus in soils with or without tillage.
- Potassium (3 studies): One replicated, randomized, controlled study from Spain[6] found more potassium in soils without tillage, compared to soils with tillage, in some comparisons. One replicated, randomized, controlled study from the USA[7] sometimes found more potassium and sometimes found less potassium in soils without tillage, compared to soils with tillage. One replicated, randomized, controlled study from Spain[32] found similar amounts of potassium in soils with or without tillage.
- pH (2 studies): One replicated, randomized, controlled study from Portugal[18] found lower pH levels in soils without tillage, compared to soils with tillage, in some comparisons. One replicated, randomized, controlled study from the USA[7] found similar pH levels in soils with or without tillage.

- **Soil organisms (18 studies)**
  - Microbial biomass (13 studies): Five replicated, controlled studies (four randomized) from Italy[31] and Spain[22,26,28,39] found more microbial biomass in soils without tillage, compared to soils with tillage, in some comparisons[22,28] or all comparisons[26,31,39]. Two replicated, randomized, controlled studies from Spain[13,37] sometimes found more microbial biomass, and sometimes found less, in soils without tillage, compared to soils with tillage. Six replicated, randomized, controlled studies from Spain[14,15,33,34,38] and the USA[7] found similar amounts of microbial biomass in soils with or without tillage.
  - Earthworms (2 studies): Two replicated studies (one controlled, one site comparison) from the USA[1,12] found more earthworms in soils without tillage, compared to soils with tillage.
  - Nematodes (2 studies): Two replicated, controlled studies (one randomized) from the USA[7,16] found similar numbers of nematodes in soils with or without tillage. However, one of these studies[16] found different communities of nematodes in soils with or without tillage.
  - Mites (1 study): One replicated, controlled study from the USA[16] found different communities of mites, but similar numbers of mites, in soils with or without tillage.
  - Other soil organisms (1 study): One replicated, randomized, controlled study from Spain[39] found similar amounts of denitrifying bacteria in soils with or without tillage. Another replicated, randomized, controlled study from Spain[8] found more

microorganisms in soils without tillage, compared to soils with tillage, in some comparisons. One replicated, randomized, controlled study from Portugal[18] found more fungus in soils without tillage, compared to soils with tillage.

- **Soil erosion and aggregation (9 studies):** Seven replicated studies (six randomized and controlled, one site comparison) from Spain[5,19,28,29,34,38] and the USA[12] found that soils without tillage were more stable than tilled soils, in some comparisons[5,19,28,29,34,38] or all comparisons[12]. Two replicated, randomized, controlled studies from Spain[3,8] found that soils without tillage were sometimes more stable, and were sometimes less stable, than tilled soils.
- **Greenhouse gases (10 studies)**
    - Carbon dioxide (7 studies): Three replicated, controlled studies (two randomized) from Italy[31] and Spain[17,35] found more carbon dioxide in soils without tillage, compared to soils with tillage. Two replicated, randomized, controlled studies from Spain[5,10] found less carbon dioxide in soils without tillage, compared to soils with tillage, in some comparisons. Two replicated, randomized, controlled studies from Spain[24,37] sometimes found more carbon dioxide, and sometimes found less, in soils without tillage, compared to soils with tillage. One replicated, randomized, controlled study from Spain[34] found similar amounts of carbon dioxide in soils with or without tillage.
    - Nitrous oxide (3 studies): One replicated, randomized, controlled study from Spain[36] sometimes found more nitrous oxide, and sometimes found less, in soils without tillage, compared to soils with tillage. Two replicated, randomized, controlled studies from Spain[34,39] found similar amounts of nitrous oxide in soils with or without tillage.
    - Methane (3 studies): One replicated, randomized, controlled study from Spain[34] found less methane in soils without tillage, compared to soils with tillage. One replicated, randomized, controlled study from Spain[35] sometimes found more methane, and sometimes found less, in soils without tillage, compared to soils with tillage. One replicated, randomized, controlled study from Spain[39] found similar amounts of methane in soils with or without tillage.
- **Implementation options (1 study):** One replicated, randomized, controlled study from Spain[29] found more organic matter in soils that had not been tilled for a long time, compared to a short time, in one comparison. This study also found greater stability in soils that had not been tilled for a long time, in some comparisons.

A replicated, controlled study in 1996–1998 in an irrigated tomato field in the San Joaquin Valley, California, USA (1) (same study as (2)), found more soil carbon and earthworms in plots with winter cover crops and no tillage, compared to plots with bare soil in winter and conventional tillage in spring. **Organic matter:** More soil carbon was found in plots with no tillage, compared to tillage (0.66–0.72% vs 0.62% carbon, 0–0.6 inches depth). **Soil organisms:** More earthworms were found in plots with no tillage, compared to tillage (2.1 vs 0.6 earthworms/square foot). **Methods:** There were 12 plots (4.5 x 27.5 m plots) for each of two treatments (two grass-legume mixtures as winter cover crops, sown in October 1996–1997, killed and retained as mulch, with no tillage, in March 1997–1998) and there were 12 control plots (bare-soil fallow in winter, with herbicide, and conventional tillage in spring). Soil carbon was sampled in September 1998 (eight subsamples/plot, 0–0.6 inches depth). Earthworms were sampled in March 1998 (two cylinders/plot, 16.5 inches diameter, 6 inches depth, sprinkled with mustard powder so that earthworms would come to the surface). It was not clear whether these results were a direct effect of cover crops or tillage.

A replicated, controlled study in 1996–1998 in an irrigated tomato field in the San Joaquin Valley, California, USA (2) (same study as (1)), found less nitrate in winter and spring, but more nitrate in summer, in plots with winter cover crops (and no tillage in spring), compared to plots with winter fallows (and tillage in spring). **Nutrients:** Less nitrate was found in plots with cover crops, compared to fallows, when measured in winter or spring (19 of 32 comparisons: 0.9–4.1 vs 3.8–7.9 ppm, 0–30 cm depth), but more nitrate was found when measured in summer (27 of 32 comparisons: 21–41 vs 8–14 ppm, 0–30 cm depth). **Methods:** There were 12 plots (4.5 x 27.5 m plots) for each of four treatments (two grass-legume mixtures, or two legumes without grasses, as winter cover crops, sown in October 1996–1997, killed and retained as mulch, with no tillage, in March 1997–1998) and each of two controls (bare-soil fallows in winter, with or without herbicide, and conventional tillage in spring). Tomato seedlings were transplanted in April 1997–1998. The tomatoes were irrigated (two inches/week) and fertilized (0, 100, or 200 lb N/acre, in March 1997 and May 1998). Soil nitrate was sampled four times in 1998 (0–30 cm depth, three samples/plot). It was not clear whether these results were a direct effect of cover crops or tillage.

A replicated, randomized, controlled study in 1983–1996 in a rainfed wheat field in the Henares river valley, Spain (3), found that tillage had inconsistent effects on soil stability. **Soil erosion and aggregation:** Lower soil stability was found in plots with no tillage, compared to conventional tillage, in one of four comparisons (1–2 mm pre-wetted soil aggregates: 76.3% vs 78.4% water stable), but higher stability was found in two of four comparisons (1–2 mm air-dried soil aggregates: 11% vs 2.9% water stable; 4.38 mm air-dried soil aggregates: 12% vs 1%). **Methods:** No tillage or conventional tillage was used on four plots each. Each plot had two subplots (20 x 30 m, with or without crop rotation). A mouldboard plough (30 cm depth, in autumn) and a tine cultivator (10–15 cm depth, two passes, in spring) were used for conventional tillage. A seed drill and pre-emergence herbicide were used for no tillage. Fertilizer and post-emergence herbicide were used on all plots. Soil samples were collected in June or July 1996 (0–30 cm, four samples/subplot).

A replicated, randomized, controlled study in 1996–1999 in three rainfed barley fields in the Ebro river valley, Spain (4) (same study as (17,23,24,26)), found less nitrogen in soils with no tillage, compared to conventional tillage. **Nutrients:** Less nitrogen was found in soils with no tillage, compared to conventional tillage, in three of nine comparisons (82–165 vs 104–247 kg/ha). **Methods:** No tillage or conventional tillage was used on 27 plots each (50 x 6 m plots). A mouldboard plough (25–30 cm depth) and a cultivator (15 cm depth, 1–2 passes) were used for conventional tillage, in August–September. Herbicide was used for no tillage. Two-thirds of the plots were fertilized (50–75 or 100–150 kg N/ha). Barley was sown, with a seed drill, in October–November. Soil samples were collected four times/year (0–50 cm in two of three fields, 0–100 cm in one field, two soil cores/plot).

A replicated, randomized, controlled study in 2003–2005 on rainfed farms in the Ebro river valley, Spain (5) (same study as (10)), found less greenhouse gas in soils with no tillage, compared to conventional tillage. **Greenhouse gases:** Less carbon dioxide was found in soils with no tillage, compared to conventional tillage, in 18 of 39 comparisons, in the two days after tillage (0.1–2.3 vs 0.1–13.3 g CO_2/m^2/hour). **Methods:** No tillage or conventional tillage was used on ten plots each (33–50 x 7–10 m plots), on a total of three farms, with multiple crops. A mouldboard or subsoil plough was used on plots with conventional tillage (25–40 cm depth). Herbicide was used on plots with no tillage.

Carbon dioxide was measured with a dynamic chamber (21 cm diameter, 900 mL airflow/minute, two samples/plot), 4–6 times in the 48 hours after tillage.

A replicated, randomized, controlled study in 1993–1997 in a rainfed barley field near Madrid, Spain (6) (same study as (19,37,39)), found more organic matter, phosphorus, and potassium in soils with no tillage, compared to conventional tillage, but tillage had inconsistent effects on nitrogen. **Organic matter:** More organic carbon was found in soils with no tillage, compared to conventional tillage, in six of eight comparisons (8–11 vs 4–6 Mg/ha), but less was found in one of eight comparisons (6 vs 7 Mg/ha). **Nutrients:** More nitrogen was found in soils with no tillage, compared to conventional tillage, in six of eight comparisons (0.7–1.4 vs 0.4–0.9 Mg total N/ha), but less was found in one of eight comparisons (0.5 vs 0.6 Mg/ha). More potassium and phosphorus were found in soils with no tillage, compared to conventional tillage, in two of four comparisons (in 1997: 13–17 vs 7–8 kg extractable P/ha; 250–310 vs 150–190 kg extractable K/ha). Similar pH was found in soils with no tillage or conventional tillage (pH 7.8). **Methods:** No tillage or conventional tillage was used on four plots each (five 10 x 25 m subplots/plot, with barley monocultures or barley rotations). A mouldboard plough (30 cm depth) and a cultivator (10–15 cm depth, when needed for weed control) were used for conventional tillage. Pre-emergence herbicide was used for no tillage. The barley was fertilized (NPK: 200 kg/ha; ammonium nitrate: 200 kg/ha). Soil samples were collected after the harvest in 1994–1997 (0–90 cm depth; organic matter and nitrogen were assessed at 0–30 cm depth).

A replicated, randomized, controlled study in 2003–2004 in irrigated farmland in Davis, California, USA (7), found more organic matter and phosphorus in soils with no tillage, compared to conventional tillage. Tillage had inconsistent effects on potassium. **Organic matter:** More carbon was found in soils with no tillage, compared to conventional tillage, in one of two comparisons (in rotations with fallows: 4 vs 3.8 kg total C/m^2). **Nutrients:** Similar amounts of nitrogen were found in plots with no tillage or conventional tillage (450–460 g total N/m^2). More potassium was found in soils with no tillage, compared to conventional tillage, in two of six comparisons (10.3–12.9 vs 6–7.7 mg K/litre), but less was found in one of twelve comparisons (4.8 vs 6.3 mg/L). More phosphorous was found in plots with no tillage, compared to conventional tillage, in one of six comparisons (27 vs 19 mg P/kg soil). Similar pH levels were found in soils with no tillage or conventional tillage (pH 6.8–7.3). **Soil organisms:** Similar amounts of microbial and nematode biomass (both measured as carbon) were found in plots with no tillage or conventional tillage (60–80 vs 60 g microbial C/m^2; 0.1–0.2 vs 0.2–0.25 g nematode C/m^2). **Methods:** No tillage or conventional tillage was used on six plots each (67 x 4.7 m plots, three beds/plot). Crop residues were incorporated to 20 cm depth, and the beds were shaped, on plots with conventional tillage (disk, lister, and ring roller). Crop residues were flail mown and spread on the plots with no tillage. All plots were fertilized in 2003, but not thereafter (112 kg P/ha phosphorous, 50 kg NPK/ha, and 67 kg N/ha). Cultivation was used to control weeds on plots with conventional tillage. Hand weeding was used on plots with no tillage. Herbicide was used on all plots. Some plots were irrigated. Soil samples were collected in December 2003, and June, September, and December 2004 (0–30 cm depth, three samples/plot).

A replicated, randomized, controlled study in 2002–2004 in an irrigated maize field in southwest Spain (8) found less nitrogen and more microorganisms in soils with no tillage, compared to conventional tillage. Tillage had inconsistent effects on soil stability. **Nutrients:** Less nitrogen was found in soils with no tillage, compared to conventional tillage, in one of nine comparisons (0–5 cm depth, in 2002: 0.11 vs 0.12 g total N/kg soil).

Soil erosion and aggregation: Lower stability was found in soils with no tillage, compared to conventional tillage, in two of nine comparisons (0–10 cm depth, in 2002: 31–35% vs 48–58% of aggregates were stable), but higher stability was found in two of nine comparisons (0–10 cm depth, in 2004: 61–69% vs 41–58%). **Soil organisms:** More microorganisms were found in soils with no tillage, compared to conventional tillage, in one of three years (0–5 cm depth, in 2004: 437 vs 261 colony forming units/g dry soil). **Methods:** Conventional tillage or no tillage was used on four plots each (20 x 10 m plots). A mouldboard plough (0–30 cm depth, in October 2001–2003 and March and April 2002–2004) was used for conventional tillage, and maize residues were burned in September–October 2002–2004. Herbicide was used for no tillage (April and May–June 2002–2004), and maize residues were not burned. For organic carbon, nitrogen, and aggregate stability, soil samples were collected in March, June, and October 2002–2004 (three samples/plot, 0–30 cm depth). For microorganisms, soils samples were collected every two months (0–5 cm depth). It was not clear whether these results were a direct effect of tillage or residue burning.

A replicated, randomized, controlled study in 1982–2003 in a rainfed wheat-sunflower-legume field near Seville, Spain (9), found more phosphorus in soils with no tillage, compared to conventional tillage. **Nutrients:** More phosphorus was found in soils with no tillage, compared to conventional tillage (1,528 vs 776 mg phosphorus/kg soil). **Methods:** No tillage or conventional tillage was used on four plots each (180 x 15 m plots), in 1983–2003. Crop residues were burned, and a mouldboard plough (50 cm depth, once every three years, in summer) and a cultivator (15 cm depth, before seeds were sown) were used, for conventional tillage. Herbicide and a double-disk planter were used for no tillage. Fertilizer was used on wheat crops. Soil samples were collected in September 2003 (15 subsamples/plot, 5 cm depth).

A replicated, randomized, controlled study in 2002–2005 on three rainfed farms in the Ebro river valley, Spain (10) (same study as (5)), found less greenhouse gas in soils with no tillage, compared to conventional tillage. **Greenhouse gases:** Less carbon dioxide was found in soils with no tillage, compared to conventional tillage, in three of 13 comparisons (0.27–0.85 vs 0.54–1.19 g CO_2/m^2/hour). **Methods:** No tillage or conventional tillage was used on ten plots each (Peñaflor: three plots each, 33 x 10 m plots; Agramunt: four plots each, 9 x 50 m plots; Selvanera: three plots each, 7 x 50 m plots). In Peñaflor, a mouldboard plough (30–40 cm depth) and a cultivator (10–15 cm depth) were used for conventional tillage. In Agramunt, a mouldboard plough (25–30 cm depth) and a cultivator (15 cm depth) were used for conventional tillage. In Selvanera, a subsoil plough (40 cm depth) and a cultivator (15 cm depth) were used for conventional tillage. Herbicide and a seed drill were used for no tillage. Carbon dioxide samples were collected from December 2002 (Peñaflor, twice/month) or December 2003 (Agramunt and Selvanera, once/month) to June 2005, with an open chamber (900 mL airflow/minute, 21 cm diameter).

A replicated, randomized, controlled study in 2003–2004 in rainfed farmland in the Ebro river valley, Spain (11), found more stable soils in plots with no tillage, compared to conventional tillage. **Soil erosion and aggregation:** More large aggregates were found in soils with no tillage, compared to conventional tillage (in Selvanera, 0–20 cm depth, aggregates >2,000 µm: 0.17–0.37 vs 0.06–0.15 g aggregate/g soil). More large water-stable aggregates were also found in soils with no tillage, compared to conventional tillage, in four of six comparisons (in Peñaflor, 0–10 cm depth, water-stable aggregates >2,000 µm: 0.08–0.15 vs 0.01–0.03 g aggregate/g soil). **Methods:** No tillage or conventional tillage was used on six plots each (three in Selvanera, 7 x 50 m each; three in Peñaflor, 10 x 33 m each). Herbicide was used for no tillage. In Selvanera, a subsoil plough (50 cm depth) and a cultivator (15 cm depth) were used for conventional tillage. In Peñaflor, a mouldboard plough was used for conventional tillage (30–35 cm depth). Soil samples were collected with a flat spade (0–20 cm depth) in July 2003 and 2004.

A replicated site comparison in 2004–2005 in 11 irrigated tomato fields in the Sacramento Valley, California, USA (12), found more earthworms, more carbon and nitrogen, and greater soil aggregation in soils with no tillage, compared to tillage. **Organic matter:** More carbon was found in soils with no tillage, compared to tilled fallows (1.6 times as much total carbon). **Nutrients:** More nitrogen was found in soils with no tillage, compared to tilled fallows (1.5 times as much total nitrogen). **Soil organisms:** More earthworms, and larger earthworms, were found in soils with no tillage, compared to tilled fallows (85 vs 19 g earthworms/m^2; 2.9 times larger). **Soil erosion and aggregation:** Greater aggregation was found in soils with no tillage, compared to tilled fallows (larger mean weight diameter; data presented as model results). **Methods:** Earthworms were collected from 11 tomato fields (four fields that were tilled, incorporating the tomato residues into the soil, and seven fields that were not tilled, retaining the tomato residues as mulch), in three 30 cm^3 soil pits/field, in February–April 2005. Organic matter and nutrients were measured in horizontal soil cores, collected from the walls of the soil pits (0–15 cm length). All fields were tilled in 2004, after the tomatoes were harvested. All fields were fertilized and irrigated.

A replicated, randomized, controlled study in 1990–2006 in two rainfed barley fields in Spain (13) (same study as (33,38)) found that tillage had inconsistent effects on soil organisms. **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with no tillage, compared to conventional tillage, in three of six comparisons (0–5 cm depth in Lleida and Zaragoza, and 5–10 cm depth in Lleida: 130–370 vs 100–230 mg C/kg dry soil), but less microbial biomass was found in one of six comparisons (10–25 cm depth, in Zaragoza: 70 vs 110). **Methods:** No tillage or conventional tillage was used on nine plots each in Lleida province (50 x 6 m plots, established in 1996) and six plots each in Zaragoza province (33.5 x 10 m plots, established in 1990). A mouldboard plough (25–40 cm depth) and a cultivator (10–15 cm depth, 1–2 passes) were used for conventional tillage. A seed drill and herbicide were used for no tillage. Soil samples were collected in March 2006 (0–25 cm depth).

A replicated, randomized, controlled study in 2005–2008 on two rainfed wheat-sunflower-pea fields near Seville, Spain (14) (same study as (15)), found similar amounts of microbial biomass in soils with no tillage or conventional tillage. **Soil organisms:** Similar amounts of microbial biomass (measured as carbon) were found in soils with no tillage or conventional tillage (291–791 vs 127–472 mg C/kg soil). **Methods:** No tillage or conventional tillage was used on three plots each (200 m^2 each). A mouldboard plough (25–30 cm depth), a cultivator (15–20 cm, 2–3 passes), and a disk harrow (15 cm) were used on plots with conventional tillage. Herbicides and a seed drill were used on plots with no tillage. Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. Soil samples were collected in March and July 2008 (three samples/plot, 0–20 cm depth).

A replicated, randomized, controlled study in 1982–2008 on a rainfed wheat-sunflower-legume field near Seville, Spain (15) (same study as (14)), found similar amounts of microbial biomass in soils with no tillage or conventional tillage. **Soil organisms:** Similar amounts of microbial biomass (measured as carbon) were found in soils with no tillage or conventional tillage (272–766 vs 314–378 mg C/kg soil). **Methods:** No tillage or conventional tillage was used on three plots each (15 x 18 m). A mouldboard plough and a cultivator (depths not reported) were used for conventional tillage, and crop residues were burned. A seed drill and herbicide were used for no tillage, and crop residues were retained. Herbicide was used on all plots. Wheat, sunflowers, and legumes were grown in rotation. Wheat was fertilized, but sunflowers and legumes were not. Soil samples were collected in March 2008 (three samples/plot, 400 g/soil core, 0–20 cm depth).

A replicated, controlled study in 1993–2006 in an irrigated tomato-corn field in Davis, California, USA (16), found similar numbers of soil organisms, but different communities of soil organisms, in soils with no tillage, compared to conventional tillage. **Soil organisms:** Similar numbers of mites and nematodes were found in soils with no tillage or conventional tillage (822 vs 797 individuals/100 g fresh soil). However, the composition of nematode and mite communities differed between soils with no tillage or conventional tillage (reported as distance in multivariate space). **Methods:** No tillage or conventional tillage was used on three plots each (conventional tillage: 0.4 ha plots; no tillage: 3 m^2 microplots). Plots with conventional tillage were tilled about five times/year (depth not reported). Plots with no tillage were hand weeded. All plots were irrigated. Half of the plots were fertilized, and compost was added to the other half. Soil samples were collected eight times in March 2005–November 2006 (three samples/plot). Mites were sampled with soil cores (5 cm diameter, 10 cm depth). Nematodes were sampled in soil cubes (20 x 20 x 20 cm).

A replicated, randomized, controlled study in 1996–2008 in a rainfed barley field in the Ebro river valley, Spain (17) (same study as (4,23,24,26)), found more greenhouse gas in soils with no tillage, compared to conventional tillage. **Greenhouse gases:** More carbon dioxide was found in soils with no tillage, compared to conventional tillage (amounts of carbon dioxide not reported). **Methods:** No tillage or conventional tillage was used on nine plots each (50 x 6 m). A mouldboard plough or a disk plough was used for conventional tillage (25–30 cm depth, 100% incorporation of crop residues). Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Greenhouse gas was sampled in 2005–2008 (two samples/plot, open chamber, 21 cm diameter, 900 mL airflow/minute, several samples within two days before and after tillage).

A replicated, randomized, controlled study in 2003–2005 in an occasionally irrigated oat field in Portugal (18) found less organic matter and phosphorus, lower pH, and fewer fungal colonies in plots with no tillage, compared to tillage. **Organic matter:** Less organic carbon was found in soils with no tillage, compared to tillage, in three of four comparisons (5.6–6.2 vs 6.0–7.7 g organic C/kg soil). **Nutrients:** Similar amounts of nitrogen were found in plots with or without tillage (30–45 mg mineral N/kg soil). Less phosphorus was found in soils with no tillage, compared to tillage, in three of four comparisons (47–70 vs 75–81 mg extractable P/kg soil). Lower pH levels were found in soils with no tillage, compared to tillage, in two of four comparisons (pH 5.5 vs 5.7–5.8). **Soil organisms:** More fungal colonies were found in plots with no tillage, compared to tillage (2004–2005: 3.6 vs 4.5 colonies/mg soil). **Methods:** Tillage or no tillage was used on four plots each (400 m^2 plots). A disk plough was used for tillage (two passes, 15 cm depth). The plots were intercropped with oats and *Lupinus albus* lupins in 2003–2004 (residues were retained, and incorporated into the soil in the plots with tillage) and oats were grown in monoculture in 2004–2005. The plots were fertilized in 2003–2004 (60 kg P/ha; 100 kg N/ha), but not in 2004–2005. Soils samples were collected in October, November, January, March, May, and July each year (15 cm depth, 15 samples/plot).

A replicated, randomized, controlled study in 1994–2007 in a rainfed wheat field near Madrid, Spain (19) (same study as (6,37,39)), found more organic matter and higher stability in soils with no tillage, compared to conventional tillage. **Organic matter:** More organic carbon was found in soils with no tillage, compared to conventional tillage, in two of four comparisons (0–7.5 cm depth: 45% more organic carbon). **Soil erosion and aggregation:** Higher stability was found in soils with no tillage, compared to conventional tillage, in one of four comparisons (0–7.5 cm depth, October 2007: 63% vs 38% of aggregates were water-stable). **Methods:** No tillage or conventional tillage was used on eight plots each (10 x 25 m plots), in autumn 1994–2007. A mouldboard plough (20 cm depth) and a cultivator were used for conventional tillage. Herbicide and direct seeding were used for no tillage. All plots were fertilized. Soil samples were collected after the seedbeds were prepared (three samples/plot, 0–15 cm depth), in November 2006 and October 2007.

A replicated, randomized, controlled before-and-after study in 1993–2008 in a rainfed wheat-maize-wheat-sunflower field in central Italy (20) found more organic matter and nitrogen in soils with no tillage, compared to conventional tillage. **Organic matter:** After 15 years, more carbon was found in soils with no tillage, compared to conventional tillage, at one of two depths (0–10 cm depth, in 2008: 16 vs 11 g C/kg soil), and carbon increased over time (0–30 cm depth, from 1993 to 2008: 9% increase vs 1% decrease in C/ha). **Nutrients:** More nitrogen was found in soils with no tillage, compared to conventional tillage, at one of two depths (0–10 cm depth, in 2008: 1.7 vs 1.2 g total N/kg soil), and nitrogen increased over time (0–30 cm depth, from 1993 to 2008: 0.6% increase vs 0.5% decrease in N/ha). **Methods:** No tillage or conventional tillage was used on 64 plots each (21 x 11 m sub-sub-plots). A mouldboard plough was used for conventional tillage (30–35 cm depth), and crop residues were incorporated into the soil. Pre-emergence herbicide was used for no tillage, and crop residues were mulched onto the surface. Post-emergence herbicide and fertilizer were used on all plots. Some plots had winter cover crops. Soil cores were collected in 1993, 1998, and 2008 for nutrients and organic matter (0–30 cm depth; two samples/plot in September).

A replicated, randomized, controlled study in 1986–2008 in a rainfed wheat field in southern Spain (21) (same study as (27)) found more organic matter and nitrogen in soils with no tillage, compared to conventional tillage. **Organic matter:** More organic carbon was found in soils with no tillage, compared to conventional tillage, in two of five comparisons (772–815 vs 684–699 g/m^2). **Nutrients:** More nitrogen was found in soils with no tillage, compared to conventional tillage, in 10 of 20 comparisons (50–180 vs 30–150 g total N/m^2). **Methods:** No tillage or conventional tillage was used on three plots each (five subplots/plot, 10 x 5 m subplots, with different wheat rotations). Mouldboard ploughing, disk harrowing, and/or vibrating tine cultivation was used for conventional tillage (depth not reported). Pre-emergence herbicide was used for no tillage. The wheat phase was fertilized with nitrogen in some sub-subplots (0–150 kg N/ha/year) and phosphorus in all plots (65 kg P/ha/year). Crop residues were retained. Soil samples were collected in October 2008 (0–50 cm depth), before tilling the soil and sowing wheat.

A replicated, randomized, controlled study in 2008–2010 in a rainfed wheat-legume field in southwest Spain (22) (same study as (28)) found more microbial biomass in soils with no tillage, compared to conventional tillage, in two of 18 comparisons. **Soil organisms:** More microbial biomass (measured as carbon and nitrogen) was found in soils with no tillage, compared to conventional tillage, in two of 18 comparisons (0–5 cm depth, in January 2010: 445 vs 263 mg C/kg soil; 31 vs 17 mg N/kg soil). **Methods:** No tillage or conventional tillage was used on three plots each (30 x 10 m plots). A mouldboard plough was used for conventional tillage (25 cm depth). Herbicides and a seed drill were used for no tillage. All plots were fertilized. Soil samples were collected in

January 2009, June 2009, and January 2010 (three samples/plot, nine soil cores/sample, 0–25 cm depth). No tillage was used on all plots in 1999–2008.

A replicated, randomized, controlled study in 1996–2009 in a rainfed barley field in the Ebro river valley, Spain (23) (same study as (4,17,24,26)), found less nitrate in soils with no tillage, compared to conventional tillage, in one of two comparisons. **Nutrients:** Less nitrate was found in soils with no tillage, compared to conventional tillage (270 vs 852 kg $N–NO_3$/ha), but no differences in ammonium were found (amounts of ammonium not reported). **Methods:** No tillage or conventional tillage was used on nine plots each (50 x 6 m plots). A mouldboard plough was used for conventional tillage (25–30 cm depth, 100% incorporation of crop residues), in October or November. A seed drill and herbicide were used for no tillage. Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Soil samples were collected when sowing the crop in November 2005–2008 (two samples/plot, 4 cm diameter soil auger, 0–100 cm depth).

A replicated, randomized, controlled study in 1996–2009 in a rainfed barley field in the Ebro river valley, Spain (24) (same study as (4,17,23,26)), found that tillage had inconsistent effects on greenhouse-gas emissions from soils. **Greenhouse gases:** Higher carbon dioxide emissions were found in soils with no tillage, compared to conventional tillage, in three of four comparisons, but lower emissions were found in one of four comparisons (amounts of carbon dioxide not clearly reported). **Methods:** No tillage or conventional tillage was used on nine plots each (50 x 6 m plots). A mouldboard plough was used for conventional tillage (25–30 cm depth, 100% incorporation of crop residues). A seed drill and herbicide were used for no tillage. Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Carbon dioxide was measured with an open chamber (21 cm diameter, 900 mL airflow/minute, 2 samples/plot/day, every 7–14 days, in 2006–2009).

A meta-analysis in 2013 of studies from multiple Mediterranean countries (25) found a higher percentage of organic matter in soils with no tillage, compared to conventional tillage. **Organic matter:** A higher percentage of organic carbon was found in soils with no tillage, compared to conventional tillage (in herbaceous crops: 18% higher). **Methods:** No tillage included herbicide use. The Web of Knowledge database was searched, using the keywords, "Mediterranean", "soil", and "conventional", and 33 data sets from 21 studies of no tillage were found and meta-analysed. The most recent studies included in this meta-analysis were published in 2011.

A replicated, randomized, controlled study in 1996–2008 in a rainfed barley field in the Ebro river Valley, Spain (26) (same study as (4,17,23,24,26)), found more organic matter and more soil organisms in soils with no tillage, compared to conventional tillage. **Organic matter:** More organic carbon was found in soils with no tillage, compared to conventional tillage (9.25 vs 7.39 g C/kg dry soil). **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with no tillage, compared to conventional tillage (295 vs 231 mg C/kg dry soil). **Methods:** There were nine plots (50 x 6 m) for each of two tillage treatments (no tillage: pre-emergence herbicide; conventional tillage: mouldboard plough, 25–30 cm depth). Plots were tilled in October or November. Soils samples were collected in October 2008 (before tillage, three soil cores/plot, 4 cm diameter, 0–50 cm depth).

A replicated, randomized, controlled study in 1986–2010 in a rainfed wheat field in southern Spain (27) (same study as (21)) found less nitrate in soils with no tillage, compared to conventional tillage. **Nutrients**: Less nitrate was found in plots with no tillage, compared to conventional tillage (104 vs 112 kg NO_3-N/ha). **Methods:** No tillage or conventional tillage was used on three plots each (10 x 5 m plots). A mouldboard plough, a disk harrow, and/or a vibrating tine cultivator were used for conventional tillage (depth not reported). A seed drill and pre-emergence herbicide was used for no tillage. Post-emergence herbicide was used on some subplots (which had different wheat rotations), and some subplots were fertilized (0–150 kg N/ha/year). Soil samples were collected before sowing (Eijkelkamp auger, three samples/plot, 0–90 cm depth), in 1993–2010.

A replicated, randomized, controlled study in 2008–2010 in a rainfed wheat-vetch field in southwest Spain (28) (same study as (22)) found more organic matter, soil organisms, and aggregation in soils with no tillage, compared to conventional tillage. **Organic matter:** More organic carbon was found in soils with no tillage, compared to conventional tillage, in three of five comparisons (soil aggregates <1 mm in diameter: 18–22 vs 13–15 g C/kg soil). **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with no tillage, compared to conventional tillage, in three of five comparisons (in smaller soil aggregates with diameters of 1–2, 0.25–0.5, or <0.5 mm: 504–549 vs 341–346 mg C/kg soil). **Soil erosion and aggregation:** More large aggregates were found in soils with no tillage, compared to conventional tillage (2–5 mm macroaggregates: 31% vs 24% of soil weight), and fewer smaller aggregates were found, in two of four comparisons (0.5–1 mm aggregates: 21% vs 26% of soil weight). **Methods:** No tillage or conventional tillage was used on three plots each (300 m^2 plots), in 2008–2009. In 1999–2008, no tillage was used on all plots. A mouldboard plough (25 cm depth, in 2008), or a chisel plough (10–15 cm depth, in 2009), and a disk harrow were used for conventional tillage, and crop residues were removed (in 2008 and 2010). A seed drill and herbicide were used for no tillage, and crop residues were retained. Soil samples were collected in October 2010 (0–10 cm depth, five samples/plot). It was not clear whether these results were a direct effect of tillage or residue removal.

A replicated, randomized, controlled study in 1990–2010 in a winter cereal field in the Ebro river valley, Spain (29), found more organic matter and greater stability in soils with no tillage, compared to conventional tillage. The most organic matter and the greatest stability were found in soils with 11–20 years of no tillage. **Organic matter:** More organic carbon was found in soils with no tillage, compared to conventional tillage, in three of sixteen comparisons (0–5 cm depth: 17–24 vs 12 g C/kg soil). **Soil erosion and aggregation:** More water-stable macroaggregates (0.25–8 mm diameter) and fewer water-stable microaggregates (0.053–0.25 mm diameter) were found in soils with no tillage, compared to conventional tillage (macroaggregates, in eight of 32 comparisons, 0–10 cm depth: 0.12–0.32 vs 0.02–0.04 g aggregate/g dry soil; microaggregates, in six of 16 comparisons, 0–10 cm depth: 0.25–0.41 vs 0.44–0.50). More large, dry macroaggregates (2–8 mm diameter) were found in soils with no tillage, compared to conventional tillage, in three of 16 comparisons (10–20 cm depth: 0.52–0.56 vs 0.38–0.40 g aggregate/g dry soil). Fewer small, dry macroaggregates (0.25–2 mm) were found in soils with no tillage, compared to conventional tillage, in four of 16 comparisons (10 –30 cm depth: 0.27 – 0.32 vs 0.36–0.41 g aggregate/g dry soil). **Implementation options:** More organic carbon was found in soils with 11–20 years of no tillage, compared to 1–4 years, at one of four depths (0–5 cm depth: 24 vs 11–17 g C/kg soil). More large, water-stable macroaggregates (2–8 mm diameter) were found in soils with 11–20 years of no tillage, compared to 1–4 years, at one of four depths (0–5 cm depth: 0.30–0.32 vs 0.02–0.12 g aggregate/g dry soil). More small, water-stable macroaggregates were found in soils with 4–20 years of no tillage, compared to one year, at one of four depths (0–5 cm depth: 0.13–0.16 vs 0.04 g aggregate/g dry soil). More large, dry macroaggregates (2–8 mm diameter) and fewer small macroaggregates (0.25–2 mm diameter) were found in soils with 4–20 years of no tillage, compared to 0–1 year, at one of four depths (10–20 cm depth: large: 0.52–0.56 vs 0.38–0.40 g aggregate/g dry soil; small: 0.30–0.32 vs 0.39–0.41). **Methods:** No tillage was used on four plots for 1–20 years (beginning in 1990, 1999, 2006, and 2009). Conventional tillage was used on the same four plots, before no tillage began, and also on one control plot for 20 years (1990–2010). Plots were 1,500 m^2. Soil samples were collected in July 2010 with a flat spade (0–30 cm depth).

A replicated, randomized, controlled study in 2009–2012 in two irrigated vegetable fields in central Italy (30) found more nitrogen in soils with no tillage, compared to conventional tillage. **Nutrients:** More nitrate was found in soils with no tillage, compared to conventional tillage, in three of 12 comparisons (in plots with hairy vetch as a winter cover crop: 10–16 vs 6–12 mg NO_3-N/kg dry soil), and more ammonium was found in one of 12 comparisons (in plots with hairy vetch as a winter cover crop: 9 vs 4 mg NH_4-N/kg dry soil). **Methods:** No tillage or conventional tillage was used on nine plots each (6 x 4 m plots). Each plot had a winter cover crop (hairy vetch, oats, or oilseed rape). Cover crops were sown in September 2009–2010 and suppressed in May 2010–2011. A mouldboard plough and a disk harrow (two passes) were used for conventional tillage (incorporating the cover crop residues to 30 cm depth). The cover crop residues were gathered into strips of mulch (50 cm wide, along crop rows) in plots with no tillage. Pepper seedlings were transplanted into these plots in May 2010–2011 and were last harvested in October 2010 and September 2011. After the pepper harvest, endive and savoy cabbage seedlings were transplanted into these plots, and they were harvested in December 2010 and November 2011 (endive) or March 2011 and February 2012 (cabbage). No fertilizer was added while the crops were growing, but the plots were irrigated. Nutrients were measured in soil samples (10 samples/plot, 0–30 cm depth, when these crops were harvested). It was not clear whether these results were a direct effect of tillage or mulch.

A replicated, controlled study in 1991–2010 in a rainfed durum wheat field in Sicily, Italy (31), found more microbial biomass and carbon dioxide in soils with no tillage, compared to conventional tillage. **Organic matter:** Similar amounts of organic carbon were found in soils with no tillage or conventional tillage (20–21 vs 19–21 g C/kg soil). **Nutrients:** Similar amounts of nitrogen were found in soils with no tillage or conventional tillage (1.1–1.3 vs 1–1.4 g total N/kg soil). **Soil microbial biomass:** More microbial biomass (measured as carbon) was found in soils with no tillage, compared to conventional tillage (330–509 vs 208–293 mg C/kg soil). **Greenhouse gases:** More carbon dioxide was found in soils with no tillage, compared to conventional tillage (19–22 vs 14–17 mg C/kg soil/day). **Methods:** No tillage or conventional tillage was used on four plots each (18.5 × 20 m plots), with either wheat-faba bean or wheat-wheat rotations. Fertilizer and herbicide were used on all plots. Ploughing (30 cm depth) and harrowing (1–2 passes, 10–15 cm depth) were used for conventional tillage. Soil samples were collected after the harvest, in June 2009 (three samples/plot, 0–15 cm depth). Carbon dioxide was measured on 36 days in April 2008–April 2009 (closed chambers, 12 measurements/plot, 9–11 am).

A replicated, randomized, controlled study in 2008–2013 in a rainfed wheat-sunflower-pea field near Seville, Spain (32), found more organic matter and more nitrogen in soils with no tillage, compared to conventional tillage, in some comparisons. **Organic matter:** More organic carbon was found in soils with no tillage, compared to conventional tillage, at one of three depths (0–5 cm: 11 vs 9 g C/kg soil). **Nutrients:** More nitrogen was found in soils with no tillage, compared to conventional tillage, at one of three depths (0–5 cm: 1.06 vs 0.91 g N/kg soil), but no differences were found in other nutrients (0–25 cm: 14.5–25.6 vs 22.2–26.1 g phosphorus/kg soil; 290–508 vs 367–428 g potassium/kg soil). **Methods:** No tillage or conventional tillage was used on three plots each (6 x 33.5 m plots). A mouldboard plough (25–30 cm depth), a chisel plough (25 cm depth, twice/year), and a disk harrow (12 cm depth) were used for conventional tillage. A seed drill and herbicide were used for no tillage. Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. Soil samples were collected in October 2012 (0–25 cm depth).

A replicated, randomized, controlled study in 2004–2011 in rainfed wheat-sunflower-pea fields near Seville, Spain (33) (same study as (13,38)), found more organic matter in soils with no tillage, compared to conventional tillage. **Organic matter:** More organic carbon was found in soils with no tillage, compared to conventional tillage, in one of three comparisons, in medium-term plots (2004–2011, 0–5 cm depth: 11 vs 9 g C/kg soil), but no differences were found in short-term plots (2008–2011: 7–10 vs 7–9 g C/kg soil). **Soil organisms:** Similar amounts of microbial biomass (measured as carbon) were found in soils with no tillage or conventional tillage (581–746 vs 604–858 mg C/kg soil). **Methods:** No tillage or conventional tillage was used on three plots each (20 x 9 m plots), in each of two experiments: a short-term experiment (2008–2011), and a medium-term experiment (2004–2011). A mouldboard plough (25–30 cm depth), a cultivator (15–20 cm depth, two passes), and a disk harrow (15 cm depth) were used for conventional tillage. A seed drill was used for no tillage, and crop residues were retained (>60% cover). Soil samples were collected in January 2011 (0–25 cm depth, five samples/plot).

A replicated, randomized, controlled study in 2010–2012 in a rainfed barley field in northeast Spain (34) found less nitrate and greater stability in soils with no tillage, compared to conventional tillage. More greenhouse gas was absorbed by soils with no tillage. **Organic matter:** Similar amounts of organic matter were found in soils with no tillage or conventional tillage (6 g C/kg dry macroaggregates). **Nutrients:** Less nitrate was found in soils with no tillage, compared to conventional tillage (93 vs 110 mg NO_3-N/kg dry macroaggregates), but there were similar amounts of ammonium (13 vs 20 mg NH_4-N/kg dry macroaggregates). **Soil organisms:** Similar amounts of microbial biomass (measured as carbon and nitrogen) were found in soils with no tillage or conventional tillage (954 vs 866 mg C/kg soil; 237 vs 228 mg N/kg soil). **Soil erosion and aggregation:** More water-stable aggregates were found in soils with no tillage, compared to conventional tillage, in one of three comparisons (0.2 vs 0.1 g). **Greenhouse gases:** More methane was absorbed by soils with no tillage, compared to conventional tillage (–0.2 vs 0.07 μg/kg macroaggregates/h). Similar carbon-dioxide emissions (1,406 vs 1,334 μg/kg macroaggregates/h) and nitrous-oxide emissions (0.92 vs 0.75 μg/kg macroaggregates/h) were found in soils with no tillage or conventional tillage. **Methods:** No tillage or conventional tillage was used on three plots each (plot size not clearly reported). Some plots were fertilized (0–150 kg N/ha). A disk plough (20 cm depth) was used for conventional tillage, in October. Pre-emergence herbicide was used for no tillage. Soil samples (0–5 cm depth) were collected in March 2012 (greenhouse gases were measured in soil samples).

A replicated, randomized, controlled study in 1996–2013 in two rainfed barley fields in northeast Spain (35) (same study as (36)) found that tillage had inconsistent effects on greenhouse gases. **Organic matter:** Similar amounts of organic carbon were found in soils with no tillage or conventional tillage (short-term field: 96 vs 99 Mg/ha). **Greenhouse gases:** More methane was absorbed by soils with no tillage, compared to conventional tillage, in one of two comparisons (long-term experiment: –2.4 vs –1.1 kg C/ha), but less was absorbed in one of two comparisons (short-term experiment: –1.1 vs

–2.7 kg C/ha). More carbon dioxide was emitted from soils with no tillage, compared to conventional tillage (3,985–4,480 vs 2,611–3,313 kg C/ha). **Methods:** No tillage or conventional tillage was used on three plots each, in each of two fields (2010–2013 in the short-term field, and 1996–2013 in the long-term field; plots size not clearly reported). A mouldboard plough (25 cm depth) and a cultivator (15 cm depth) were used for conventional tillage in the long-term field, and a chisel plough was used in the short-term field (depth not reported), in September–October. For no tillage, the residues were chopped and spread, and pre-emergence herbicide was used. Some plots were fertilized (0–150 kg N/ha). Soil samples were collected in June 2013 in the short-term field (0–75 cm depth). Greenhouse-gas samples were collected every 2–3 weeks in 2011–2013, in the long-term field, and 2011–2012 in the short-term field (closed chambers, 15 mL samples, 0, 30, and 60 minutes after closing).

A replicated, randomized, controlled study in 1996–2013 in two rainfed barley fields in northeast Spain (36) (same study as (35)) found less nitrate in soils with no tillage, compared to conventional tillage. Tillage had inconsistent effects on greenhouse gases. **Nutrients:** Less nitrate was found in soils with no tillage, compared to conventional tillage, in one of two comparisons (long-term experiment: 36 vs 56 kg/ha), but similar amounts of ammonium were found (10–11 vs 9–11 kg/ha). **Greenhouse gases:** More nitrous oxide was emitted from soils with no tillage, compared to conventional tillage, in one of two comparisons (short-term experiment: 0.20 vs 0.14 mg N_2O-N/m^2/day). Less greenhouse gas was emitted, per kilo of barley, in plots with no tillage, compared to conventional tillage (0.05 vs 0.10 kg CO_2 equivalent/kg barley). **Methods:** No tillage or conventional tillage was used on three plots each, in each of two fields (2010–2013 in the short-term field, and 1996–2013 in the long-term field; plots size not clearly reported). A mouldboard plough (25 cm depth) and a cultivator (15 cm depth) were used for conventional tillage. For no tillage, the residues were chopped and spread, and pre-emergence herbicide was used. Some plots were fertilized (0–150 kg N/ha). Soil samples (0–5 cm depth) and greenhouse-gas samples (closed chambers, 15 mL samples, 0, 30, and 60 minutes after closing), were collected every 2–3 weeks in 2011–2013.

A replicated, randomized, controlled study in 1994–2013 in a rainfed wheat field near Madrid, Spain (37) (same study as (6,19,39)), found that tillage had inconsistent effects on organic matter, soil organisms, and greenhouse gases. **Organic matter:** More organic carbon was found in soils with no tillage, compared to conventional tillage, in seven of 12 comparisons (9–13 vs 6 g organic C/kg soil), but less was found in one of 12 comparisons (6 vs 5 g). **Soil organisms**: More microbial biomass (measured as carbon) was found in soils with no tillage, compared to conventional tillage, in six of 12 comparisons (390–750 vs 200–300 mg C/kg soil), but less was found in one of 12 comparisons (200 vs 300 mg). **Greenhouse gases:** More carbon dioxide was found in soils with no tillage, compared to conventional tillage, in six of 12 comparisons (40–60 vs 20–30 mg CO_2–C/kg soil/d), but less was found in one of 12 comparisons (18 vs 22 mg). **Methods:** No tillage or conventional tillage was used on four plots each (in which a total of 24 subplots, 10 x 25 m each, were used for this study). A mouldboard plough was used for conventional tillage (25 cm depth). Pre-emergence herbicide was used for no tillage. The subplots had wheat monocultures or fallow-wheat-vetch-barley rotations. The cereals were fertilized (NPK, 200 kg/ha, twice/year, in October and March). The crop residues were shredded and retained. Soil samples were collected in October 2010, April 2011, November 2011, May 2012, October 2012 and April 2013 (50 mm diameter, 0–15 cm depth).

A replicated, randomized, controlled study in 2004–2010 in rainfed wheat-sunflower-pea fields near Seville, Spain (38) (same study as (13,33)), found more organic matter and more soil aggregation in soils with no tillage, compared to conventional tillage. **Organic matter:** More organic carbon was found in soils with no tillage, compared to conventional tillage, in four of ten comparisons (6–10 vs 5–6 g C/kg soil). **Soil organisms:** Similar amounts of microbial biomass (measured as carbon) were found in soils with no tillage or conventional tillage (20–75 vs 27–87 g microbial C/kg organic C). **Soil erosion and aggregation:** More large aggregates were found in soils with no tillage, compared to conventional tillage, in autumn, in one of two comparisons (1–2 mm aggregates: 20 vs 17% of soil weight), and fewer small aggregates were found in autumn, in one of three comparisons (<0.25 mm aggregates: 15 vs 21% of soil weight). However, no differences in aggregate distributions were found in spring (data reported for five aggregate sizes). **Methods:** No tillage or conventional tillage was used on three plots each (200 m^2 plots). A mouldboard plough (25–30 cm depth), a cultivator (15–20 cm depth, two passes), and a disk harrow (15 cm depth) were used for conventional tillage. A seed drill and pre-emergence herbicide were used for no tillage, and crop residues were retained (>60% cover). Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. Soil samples were collected in spring and autumn 2010 (0–10 cm depth, five samples/plot).

A replicated, randomized, controlled study in 1994–2011 in a rainfed cereal-legume field near Madrid, Spain (39) (same study as (6,19,37)), found more organic matter and more soil organisms in soils with no tillage, compared to conventional tillage. **Organic matter:** More organic carbon was found in soils with no tillage, compared to conventional tillage (30.2 vs 11.2 mg dissolved organic C/kg soil). **Nutrients:** Similar amounts of nitrate and ammonium were found in soils with no tillage, compared to conventional tillage (1–18 mg NO_3-N/ha; 0.2–3.5 mg NH_4-N/kg). **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with no tillage, compared to conventional tillage (304 vs 94 mg C/kg soil), but there were similar amounts of bacteria (denitrifying bacteria: 10^6 gene copies). **Greenhouse gases:** Similar nitrous-oxide and methane emissions were found in soils with no tillage or conventional tillage (0.05 kg N_2O-N/ha; –137 vs –231 g CH_4-C/ha). **Methods:** No tillage or conventional tillage was used on three plots each (10 x 25 m). A mouldboard plough and a cultivator were used for conventional tillage (20 cm depth) in October. A seed drill and herbicide were used for no tillage. Soil and greenhouse-gas samples were collected 1–12 times/month, in November 2010–October 2011 (soil cores: 0–15 cm depth, 2.5 cm diameter; closed chambers: 19.3 cm height, 35.6 cm diameter, 20 mL gas samples, 0–60 minutes after closing).

A replicated, randomized, controlled study in 2009–2011 in an irrigated eggplant field in central Italy (40) found more nitrogen in soils with no tillage, compared to conventional tillage. **Nutrients:** More nitrogen was found in soils with no tillage, compared to conventional tillage, in one of four comparisons (37 vs 24 mg inorganic N/kg dry soil). **Methods:** A mouldboard plough (30 cm depth) was used on all plots in autumn, before winter cover crops were planted. Cover crops were mown or chopped in spring, before tillage. No tillage or conventional tillage was used on 12 plots each (6 x 4 m plots). A mouldboard plough (30 cm depth) and a disk (two passes) were used for conventional tillage (which incorporated the cover crop residues into the soil). Cover crop residues were mulched and herbicide was used for no tillage. Eggplant seedlings were transplanted into the plots in May, and fruits were harvested four times/year in July–September 2010–2011. Soil samples were collected when the seedlings were transplanted and when the last fruits were harvested each year (0–30 cm depth, six samples/plot). All plots were fertilized before the cover crops were grown, but not after. All plots were irrigated. It was not clear whether these results were a direct effect of cover crops or tillage.

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3.10. Use no tillage instead of reduced tillage: Soil (20 studies)

- **Organic matter (6 studies):** Three replicated, randomized, controlled studies from Spain[12,16,19] found more organic matter in soils with no tillage, compared to reduced tillage, in some comparisons[16] or all comparisons[12,19]. Three replicated, randomized, controlled studies from Spain[9,13,18] found similar amounts of organic matter in soils with no tillage, compared to reduced tillage. No studies found less organic matter in soils with no tillage, compared to reduced tillage.
- **Nutrients (7 studies)**
    - Nitrogen (6 studies): Three replicated, randomized, controlled studies from Italy and Spain[2,15,20] found more nitrogen in soils with no tillage, compared to reduced tillage, in some comparisons. Two of these studies[2,15] also found less nitrogen in some comparisons. One replicated, randomized, controlled study from Spain[11] found less nitrogen in soils with no tillage, compared to reduced tillage, in some comparisons. Two replicated, randomized, controlled studies from Spain[16,19] found similar amounts of nitrogen in soils with no tillage, compared to reduced tillage.
    - Phosphorus (2 studies): One replicated, randomized, controlled study from Spain[4] found more phosphorus in soils with no tillage, compared to reduced tillage. One replicated, randomized, controlled study from Spain[16] found similar amounts of phosphorus in soils with no tillage or reduced tillage. No studies found less phosphorus in soils with no tillage, compared to reduced tillage.
    - Potassium (1 study): One replicated, randomized, controlled study from Spain[16] found similar amounts of potassium in soils with no tillage or reduced tillage. No studies found less potassium in soils with no tillage, compared to reduced tillage.
- **Soil organisms (8 studies)**
    - Microbial biomass (6 studies): Five replicated, randomized, controlled studies from Spain found similar amounts of microbial biomass in soils with no tillage or reduced tillage[10,12,13,18,19]. One replicated, randomized, controlled study from Spain[6] found more microbial biomass in soils with no tillage, compared to reduced tillage, in some comparisons, but found less in some comparisons.
    - Bacteria (1 study): One replicated, randomized, controlled study from Spain[19] found fewer denitrifying bacteria in soils with no tillage, compared to reduced tillage.
    - Other soil organisms (2 studies): One replicated, controlled study from the USA[7] found similar numbers of mites and nematodes, but different communities of mites and nematodes, in soils with no tillage, compared to reduced tillage. One replicated,

randomized, controlled study from Spain[14] found more mites in soils with no tillage, compared to reduced tillage.

- **Soil erosion and aggregation (4 studies):** One replicated, randomized, controlled study from Spain[5] found more large aggregates in soils with no tillage, compared to reduced tillage, in some comparisons. One replicated, randomized, controlled study from Italy[13] found similar aggregates in soils with no tillage or reduced tillage. One replicated, randomized, controlled study from Spain[1] found higher water-stability in soils with no tillage, compared to reduced tillage, in some comparisons, but found lower water-stability in some comparisons. One replicated, randomized, controlled study from Spain[9] found similar water-stability in soils with no tillage or reduced tillage.
- **Greenhouse gases (4 studies):** Two replicated, randomized, controlled studies from Spain[3,19] found less greenhouse gas in soils with no tillage, compared to reduced tillage, in some comparisons. Two replicated, randomized, controlled studies from Australia and Spain[8,17] found similar amounts of greenhouse gas in soils with no tillage or reduced tillage.

A replicated, randomized, controlled study in 1983–1996 in a rainfed wheat field in the Henares river valley, Spain (1), found that tillage had inconsistent effects on soil stability. **Soil erosion and aggregation:** Lower soil stability was found in plots with no tillage, compared to reduced tillage, in one of four comparisons (1–2 mm pre-wetted soil aggregates: 76.3 vs 77.8% water stable), but higher stability was found in two of four comparisons (1–2 mm air-dried soil aggregates: 11.0 vs 3.5% water stable; 4.38 mm air-dried soil aggregates: 12 vs 2%). **Methods:** No tillage or reduced tillage was used on four plots each. Each plot had two subplots (20 x 30 m, with or without crop rotation). A chisel plough (20 cm depth, in autumn) and a tine cultivator (10–15 cm depth, two passes, in spring) were used for reduced tillage. A seed drill and pre-emergence herbicide were used for no tillage. Fertilizer and post-emergence herbicide were used on all plots. Soil samples were collected in June or July 1996 (0–30 cm, four samples/subplot).

A replicated, randomized, controlled study in 1996–1999 in three rainfed barley fields in the Ebro river valley, Spain (2) (same study as (8,11,12)), found that tillage had inconsistent effects on nitrogen in soils. **Nutrients:** Less nitrogen was found in soils with no tillage, compared to reduced tillage, in one of nine comparisons (128 vs 176 kg/ha), but more nitrogen was found in one of nine comparisons (165 vs 125 kg/ha). **Methods:** No tillage or reduced tillage was used on 27 plots each (50 x 6 m plots). A cultivator (10–15 cm depth, 1–2 passes) was used for reduced tillage, in September. Herbicide was used for no tillage. Two-thirds of the plots were fertilized (50–75 or 100–150 kg N/ha). Barley was sown, with a seed drill, in October–November (month of harvest not reported). Soil samples were collected four times/year (0–50 cm in two of three fields, 0–100 cm in one field, two soil cores/plot).

A replicated, randomized, controlled study in 2003–2005 on rainfed farms in the Ebro river valley, Spain (3), found less greenhouse gas in soils with no tillage, compared to reduced tillage. **Greenhouse gases:** Less carbon dioxide was found in soils with no tillage, compared to reduced tillage, in six of 20 comparisons, in the two days after tillage (0.1–0.6 vs 0.1–6.4 g CO_2/m^2/hour). **Methods:** No tillage or reduced tillage was used on seven plots each (33–50 x 7–10 m plots), on a total of two farms, with multiple crops. A cultivator (15 cm depth) or chisel plough (25–30 cm depth) was used for reduced tillage. Herbicide was used for no tillage. Carbon dioxide was measured with a dynamic chamber (21 cm diameter, 900 mL airflow/minute, two samples/plot), 4–6 times in the 48 hours after tillage.

A replicated, randomized, controlled study in 1982–2003 in a rainfed wheat-sunflower-legume field near Seville, Spain (4), found more phosphorus in soils with no tillage, compared to reduced tillage. **Nutrients:** More phosphorus was found in soils with no tillage, compared to reduced tillage (1,528 vs 961 mg phosphorus/kg soil). **Methods:** No tillage or reduced tillage was used on four plots each (180 x 15 m plots), in 1983–2003. A cultivator (15 cm depth, before seeds were sown) was used for reduced tillage. Herbicide and a double-disk planter were used for no tillage. Fertilizer was used on wheat crops. Soil samples were collected in September 2003 (15 subsamples/plot, 5 cm depth).

A replicated, randomized, controlled study in 2003 in rainfed farmland in the Ebro river valley, Spain (5), found greater soil aggregation in plots with no tillage, compared to reduced tillage. **Soil erosion and aggregation:** More large aggregates were found in soils with no tillage, compared to reduced tillage, in four of six comparisons (0–10 cm depth, water-stable aggregates >2000 μm: 0.08–0.15 vs 0.02–0.03 g aggregate/g soil). **Methods:** No tillage or reduced tillage was used on three plots each (10 x 33 m). A chisel plough was used for reduced tillage (25–30 cm depth). Herbicide was used for no tillage. Soil samples were collected with a flat spade (0–20 cm depth) in July 2003.

A replicated, randomized, controlled study in 1990–2006 on two rainfed barley fields in Spain (6) (same study as (18)) found that tillage had inconsistent effects on soil organisms. **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with no tillage, compared to reduced tillage, in one of six comparisons (0–5 cm depth, in Zaragoza: 130 vs 60 mg C/kg dry soil), but less was found in one of six comparisons (0–5 cm depth, in Lleida: 360 vs 480). **Methods:** No tillage or reduced tillage was used on nine plots each in Lleida province (50 x 6 m plots, established in 1996) and six plots each in Zaragoza province (33.5 x 10 m plots, established in 1990). A chisel plough (in Zaragoza but not in Lleida, 25–30 cm depth) and a cultivator (10–15 cm depth, 1–2 passes) were used for reduced tillage. A seed drill and herbicide were used for no tillage. Soil samples were collected in March 2006 (0–25 cm depth).

A replicated, controlled study in 1993–2006 in an irrigated tomato-corn field in Davis, California, USA (7), found similar numbers of soil organisms, but different communities of soil organisms, in soils with no tillage, compared to reduced tillage. **Soil organisms:** Similar numbers of mites and nematodes were found in soils with no tillage or reduced tillage (822 vs 888 individuals/100 g fresh soil). However, the composition of nematode and mite communities differed between soils with no tillage or reduced tillage (reported as distance in multivariate space). **Methods:** No tillage or reduced tillage was used on three plots each (reduced: 0.4 ha plots; no tillage: 3 m^2 microplots). Plots with reduced tillage were tilled about two times/year (depth not reported). Plots with no tillage were hand weeded. All plots were irrigated. Half of the plots were fertilized, and compost was added to the other half. Soil samples were collected eight times in March 2005–November 2006 (three samples/plot). Mites were sampled with soil cores (5 cm diameter, 10 cm depth). Nematodes were sampled in soil cubes (20 x 20 x 20 cm).

A replicated, randomized, controlled study in 1996–2008 in a rainfed barley field in the Ebro river valley, Spain (8) (same study as (2,11,12)), found similar amounts of greenhouse gas in soils with no tillage or reduced tillage. **Greenhouse gases:** Similar amounts of carbon dioxide were found in soils with no tillage or reduced tillage (amounts of carbon dioxide not reported). **Methods:** No tillage or reduced tillage was used on nine plots each (50 x 6 m). A cultivator was used for reduced tillage (10–15 cm depth, 50% incorporation of crop residues). Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Greenhouse gas was sampled with an open chamber (2 samples/plot, 21 cm diameter, 900 mL airflow/minute), in 2005–2008 (several samples within 2 days before and after tillage).

A replicated, randomized, controlled study in 1994–2007 in a rainfed wheat field near Madrid, Spain (9) (same study as (19)), found no differences in organic matter or soil stability in soils with no tillage or reduced tillage. **Organic matter:** Similar amounts of organic carbon were found in soils with no tillage or reduced tillage (7–11 Mg C/ha). **Soil erosion and aggregation:** No differences in soil stability were found in plots with no tillage, compared to reduced tillage (25–65% of aggregates were water-stable). **Methods:** No tillage or reduced tillage was used on eight plots each (10 x 25 m plots), in autumn 1994–2007. A chisel plough (15 cm depth) and a cultivator were used for reduced tillage. Herbicide and direct seeding were used for no tillage. All plots were fertilized. Soil samples were collected after the seedbeds were prepared (three samples/plot, 0–15 cm depth), in November 2006 and October 2007.

A replicated, randomized, controlled study in 2008–2010 in a rainfed wheat-legume field in southwest Spain (10) (same study as (13)) found similar numbers of soil organisms in soils with no tillage or reduced tillage. **Soil organisms:** Similar amounts of microbial biomass (measured as carbon or nitrogen) were found in soils with no tillage or reduced tillage (199–1,612 vs 120–2,363 mg C/kg soil; 9–40 vs 9–69 mg N/kg soil). **Methods:** No tillage or reduced tillage was used on three plots each (30 x 10 m plots). A chisel plough was used for reduced tillage (10–15 cm depth). A seed drill was used for no tillage. All plots were fertilized. Soil samples were collected in January 2009, June 2009, and January 2010 (three samples/plot, nine soil cores/sample, 0–25 cm depth). No tillage was used on all plots in 1999–2008.

A replicated, randomized, controlled study in 1996–2009 in a rainfed barley field in the Ebro river valley, Spain (11) (same study as (2,8,12)), found less nitrate in soils with no tillage, compared to reduced tillage. **Nutrients:** Less nitrate was found in soils with no tillage, compared to reduced tillage (270 vs 461 kg N–NO_3/ha), but no differences in ammonium were found (amounts of ammonium not reported). **Methods:** No tillage or reduced tillage was used on nine plots each (50 x 6 m plots). A cultivator was used for reduced tillage (10–15 cm depth, 50% incorporation of crop residues), in October or November. A seed drill and herbicide were used for no tillage. Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Soil samples were collected when sowing the crop in November 2005–2008 (two samples/plot, 4 cm diameter soil auger, 0–100 cm depth).

A replicated, randomized, controlled study in 1996–2008 in a rainfed barley field in the Ebro river Valley, Spain (12) (same study as (2,8,11)), found more organic matter, but no difference in soil organisms, in soils with no tillage, compared to reduced tillage. **Organic matter:** More organic carbon was found in soils with no tillage, compared to reduced tillage (9.25 vs 8.65 g C/kg dry soil). **Soil organisms:** No difference in microbial biomass (measured as carbon) was found between soils with no tillage or reduced tillage (295 vs 263 mg C/kg dry soil). **Methods:** There were nine plots (50 x 6 m) for each of two tillage treatments (no tillage: pre-emergence herbicide and seed drill; reduced tillage: cultivator, 10–15 cm depth). Plots were tilled in October or November. Soil samples were collected in October 2008 (before tillage, three soil cores/plot, 4 cm diameter, 0–50 cm depth).

A replicated, randomized, controlled study in 2008–2010 in a rainfed wheat-vetch field in southwest Spain (13) (same study as (10)) found similar amounts of organic matter, soil organisms, and aggregation in soils with no tillage or reduced tillage. **Organic matter:** Similar amounts of organic carbon were found in soils with no tillage or reduced tillage (14–22 vs 17–23 g C/kg soil). **Soil organisms:** Similar amounts of microbial biomass (measured as carbon) were found in soils with no tillage or reduced tillage (452–549 vs 373–646 g C/kg soil). **Soil erosion and aggregation:** Similar amounts of soil aggregation were found in soils with no tillage or reduced tillage (data reported for five soil fractions). **Methods:** No tillage or reduced tillage was used on three plots each (300 m^2 plots), in 2008–2009. From 1999–2008, no tillage was used on all plots. Herbicide was used for no tillage. A chisel plough (10–15 cm depth) and herbicide were used for reduced tillage. Soil samples were collected in October 2010 (0–10 cm depth, five samples/plot).

A replicated, randomized, controlled study in 2002–2012 in a rainfed cereal field in Spain (14) found more mites in soils with no tillage, compared to reduced tillage. **Organic matter:** Similar amounts of organic matter were found in plots with no tillage or reduced tillage (data not reported). **Nutrients:** Similar amounts of nitrogen were found in plots with no tillage or reduced tillage (data not reported). **Soil organisms:** More oribatid mites were found in plots with no tillage, compared to reduced tillage (5,162 vs 3,121 individuals/m^2). **Methods:** Plots (11 x 12.5 m or 7 x 12.5 m) had reduced tillage (disc-harrowing, 15 cm depth) or no tillage (with herbicide). Straw was removed from all plots. Soil samples were collected in October 2011, February 2012, and May 2012 from plots without fertilizer and plots with 25 t/ha/year (three cores/plot, 0–5 cm depth). The other plots were sampled in May 2012.

A replicated, randomized, controlled study in 2009–2012 in two irrigated vegetable fields in central Italy (15) found that tillage had inconsistent effects on nutrients in soils. **Nutrients:** More nitrate was found in soils with no tillage, compared to reduced tillage, in one of 12 comparisons (in plots with hairy vetch as a winter cover crop: 10 vs 6 mg NO_3-N/kg dry soil), but less nitrate was found in one of 12 comparisons (in plots with oats as the winter cover crop: 3 vs 6). More ammonium was found in soils with no tillage, compared to reduced tillage, in one of 12 comparisons (in plots with hairy vetch as a winter cover crop: 9 vs 5 mg NH_4-N/kg dry soil), but less ammonium was found in one of 12 comparisons (in plots with oilseed rape as the winter cover crop: 4 vs 11). **Methods:** Reduced tillage or no tillage was used on nine plots each (6 x 4 m plots). Each plot had a winter cover crop (hairy vetch, oats, or oilseed rape). Cover crops were sown in September 2009–2010 and suppressed in May 2010–2011. A rotary hoe was used for reduced tillage (incorporating the cover crop residues to 10 cm depth). The cover crop residues were gathered into strips of mulch (50 cm wide, along crop rows) in plots with no tillage. Pepper seedlings were transplanted into these plots in May 2010–2011 and were last harvested in October 2010 and September 2011. After the pepper harvest, endive and savoy cabbage seedlings were transplanted into these plots, and they were harvested in December 2010 and November 2011 (endive) or March 2011 and February 2012 (cabbage). No fertilizer was added while the crops were growing, but the plots were irrigated. Nutrients were measured in soil samples (10 samples/plot, 0–30 cm depth, when these crops were harvested). It was not clear whether these results were a direct effect of tillage or mulch.

A replicated, randomized, controlled study in 2008–2013 in a rainfed wheat-sunflower-pea field near Seville, Spain (16), found more organic matter (in one of three comparisons), but found similar amounts of nutrients, in soils with no tillage, compared to reduced tillage. **Organic matter:** More organic carbon was found in soils with no tillage, compared to reduced tillage, at one of three depths (0–5 cm: 11 vs 9 g C/kg soil). **Nutrients:** Similar amounts of nitrogen, phosphorus, and potassium were found in soils with no tillage or reduced tillage (0.76–1.06 vs 0.92–0.99 g N/kg soil; 14.5–25.6 vs 17.8–25.7 g phosphorus/kg soil; 290–508 vs 307–419 g potassium/kg soil). **Methods:** No tillage or reduced tillage was used on three plots each (6 x 33.5 m plots). A chisel plough

(25 cm depth), a disc harrow (5 cm depth), and herbicide were used for reduced tillage. A seed drill and herbicide were used for no tillage. Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. Soil samples were collected in October 2012 (0–25 cm depth).

A replicated, randomized, controlled study in 2010–2011 in an irrigated wheat field in Western Australia (17) found similar greenhouse-gas emissions in soils with no tillage or reduced tillage. **Greenhouse gases:** Similar nitrous oxide emissions were found in soils with no tillage or reduced tillage (0.04 g ha/hour). **Methods:** No tillage or reduced tillage was used on three plots each (1.4 x 40 m plots) in 2010, when the plots were fallow. A rotary hoe (12 cm depth) was used for reduced tillage. Herbicide was used for no tillage. Wheat was grown on all plots in 2011. Fertilizer (150 kg/ha) and herbicides were used on all plots in 2011. Nitrous oxide was sampled in closed chambers (two chambers/plot; one hour/sample; five sample dates/plot).

A replicated, randomized, controlled study in 2008–2011 in a rainfed wheat-sunflower-pea field near Seville, Spain (18) (same study as (6)), found similar amounts of organic matter and soil organisms in soils with no tillage or reduced tillage. **Organic matter:** Similar amounts of organic carbon were found in soils with no tillage or reduced tillage (7–10 vs 6–9 g C/kg soil). **Soil organisms:** Similar amounts of microbial biomass (measured as carbon) were found in soils with no tillage or reduced tillage (581–746 vs 740–958 mg C/kg soil). **Methods:** No tillage or reduced tillage was used on three plots each (20 x 9 m plots). A chisel plough (15–20 cm depth, every other year) and a disc harrow (5–7 cm depth) were used for reduced tillage. A seed drill was used for no tillage. More than 60% of crop residues were retained in all plots. Soil samples were collected in January 2011 (0–25 cm depth, five samples/plot).

A replicated, randomized, controlled study in 1994–2011 in a rainfed cereal-legume field near Madrid, Spain (19) (same study as (9)), found more organic matter, but fewer soil organisms and lower greenhouse-gas emissions, in soils with no tillage, compared to reduced tillage. **Organic matter:** More organic carbon was found in soils with no tillage, compared to reduced tillage (29.7% more dissolved organic carbon). **Nutrients:** Similar amounts of nitrate and ammonium were found in soils with no tillage, compared to reduced tillage (1–18 mg NO_3–N/ha; 0.2–3.5 mg NH_4–N/kg). **Soil organisms:** Fewer bacteria were found in soils with no tillage, compared to reduced tillage (denitrifying bacteria: 10^6 vs 10^8 gene copies), but no difference in microbial biomass (measured as carbon) was found (304 vs 186 mg C/kg soil). **Greenhouse gases:** Lower nitrous oxide emissions were found in soils with no tillage, compared to reduced tillage (0.05 vs 0.12 kg N_2O–N/ha), but no difference in methane emissions was found (–137 vs –473 g CH_4–C/ha). **Methods:** No tillage or reduced tillage was used on three plots each (10 x 25 m). A chisel plough and a cultivator were used for reduced tillage (15 cm depth) in October. A seed drill and herbicide were used for no tillage. Soil and greenhouse-gas samples were collected 1–12 times/month, in November 2010–October 2011 (soil cores: 0–15 cm depth, 2.5 cm diameter; closed chambers: 19.3 cm height, 35.6 cm diameter, 20 mL gas samples, 0–60 minutes after closing).

A replicated, randomized, controlled study in 2009–2011 in an irrigated eggplant field in central Italy (20) found more nitrogen in soils with no tillage, compared to reduced tillage. **Nutrients:** More nitrogen was found in soils with no tillage, compared to reduced tillage, in one of four comparisons (37 vs 30 mg inorganic N/kg dry soil). **Methods:** A mouldboard plough (30 cm depth) was used on all plots in autumn, before winter cover crops were planted. Cover crops were mown or chopped in spring, before tillage. No tillage or reduced tillage was used on 12 plots each (6 x 4 m plots). A rotary hoe (10 cm depth) was used for reduced tillage (which incorporated some of the cover crop residues into the soil). Cover crop residues were mulched and herbicide was used for no tillage. Eggplant seedlings were transplanted into the plots in May, and fruits were harvested four times/year in July–September 2010–2011. Soil samples were collected when the seedlings were transplanted and when the last fruits were harvested each year (0–30 cm depth, six samples/plot). All plots were fertilized before the cover crops were grown, but not after. All plots were irrigated.

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3.11. Use reduced tillage in arable fields: Soil (40 studies)

- **Organic matter (14 studies):** One meta-analysis from multiple Mediterranean countries[29] found more organic matter in soils with reduced tillage, compared to conventional tillage. Eleven replicated studies (ten randomized and controlled, one site comparison) from Italy, Spain, Syria, and the USA[13,22,23,27,28,30,31,34,35,37,39] found more organic matter in soils with reduced tillage, compared to conventional tillage, in some comparisons[23,27,28,34,35,37] or all comparisons[13,22,30,31,39]. Two replicated, randomized, controlled studies from Spain and the USA[33,36] found similar amounts of organic matter in soils with reduced tillage or conventional tillage, in all comparisons. No studies found less organic matter in soils with reduced tillage, compared to conventional tillage.
- **Nutrients (15 studies)**
  - Nitrogen (14 studies): Seven replicated studies (five randomized and controlled, one site comparison) from Italy, Spain, and the USA[2,5,8,13,22,32,40] found more nitrogen in soils with reduced tillage, compared to conventional tillage, in some comparisons. Three of these studies[2,5,8] also found less nitrogen in some comparisons. Two replicated, randomized, controlled studies from Spain[3,26] found less nitrogen in soils with reduced tillage, compared to conventional tillage, in some comparisons[3] or all comparisons[26]. Five replicated, randomized, controlled studies from Spain, Syria, and the USA[14,26,27,33,39] found similar amounts of nitrogen in soils with reduced tillage or conventional tillage, in all comparisons.
  - Phosphorus (6 studies): Five replicated, randomized, controlled studies from Italy, Spain, and the USA[4,5,8,9,22] found more phosphorus in soils with reduced tillage, compared to conventional tillage, in some comparisons[4,8,22] or all comparisons[5,9]. One replicated, randomized, controlled study from Spain[33] found similar amounts of phosphorus in soils with reduced tillage, compared to conventional tillage, in all comparisons.
  - Potassium (3 studies): Two replicated, randomized, controlled studies from Spain[4,8] found more potassium in soils with reduced tillage, compared to conventional tillage, in some comparisons. One replicated, randomized, controlled study from Spain[33] found similar amounts of potassium in soils with reduced tillage, compared to conventional tillage, in all comparisons.
  - pH (1 study): One replicated, randomized, controlled study from Spain[8] found similar pH levels in soils with reduced tillage or conventional tillage.

- **Soil organisms (16 studies)**
    - Microbial biomass (15 studies): Eleven replicated, randomized, controlled studies from Italy, Spain, and the USA[2,7,16-18,22,24,28,31,34,35] found more microbial biomass in soils with reduced tillage, compared to conventional tillage, in some comparisons. Two replicated, randomized, controlled studies from Spain and Syria[27,37] found less microbial biomass in soils with reduced tillage, compared to conventional tillage, in some comparisons. Two replicated, randomized, controlled studies from Spain[30,39] found similar amounts of microbial biomass in soils with reduced tillage or conventional tillage, in all comparisons.
    - Bacteria (1 study): One replicated, randomized, controlled study from Spain[39] found more denitrifying bacteria in soils with reduced tillage, compared to conventional tillage.
    - Other soil organisms (2 studies): One replicated, controlled study from the USA[19] found similar numbers of mites and nematodes, but differences in mite and nematode communities, in soils with reduced tillage, compared to conventional tillage. One replicated site comparison from the USA[13] found more earthworms in fields with fewer passes of the plough, in one of three comparisons.
- **Soil erosion and aggregation (9 studies)**
    - Soil aggregation (8 studies): Three replicated, randomized, controlled studies from Spain[11,23,28] found that soil aggregates had higher water-stability in plots with reduced tillage, compared to conventional tillage, in some comparisons. One of these studies[28] also found that soil aggregates had lower water-stability in some comparisons. One replicated, randomized, controlled study from Spain[1] found that water-stability was similar in plots with reduced tillage or conventional tillage. One replicated, randomized, controlled study from Spain[37] found more large aggregates in soils with reduced tillage, compared to conventional tillage, in one of two comparisons. One replicated, randomized, controlled study from Spain[11] found smaller aggregates in soils with reduced tillage, compared to conventional tillage. Three replicated, randomized, controlled studies from Spain and the USA[12,14,31] found similar amounts of aggregation in soils with reduced tillage or conventional tillage.
    - Soil erosion (1 study): One replicated, randomized, controlled study from Egypt[38] found less erosion with less tillage (one pass with the tractor, compared to two), but found more erosion with shallower tillage, compared to deeper.
- **Greenhouse gases (11 studies)**
    - Carbon dioxide (9 studies): Three replicated, randomized, controlled studies from Spain[20,25,35] found more carbon dioxide in soils with reduced tillage, compared to conventional tillage, in some comparisons[25,35] or all comparisons[20]. Three replicated, randomized, controlled studies from Spain and the USA[6,21,28] found less carbon dioxide in soils with reduced tillage, compared to conventional tillage, in some comparisons[6,21] or all comparisons[28]. Three controlled studies from Italy, Spain, and the USA[10,15,22] found similar amounts of carbon dioxide in soils with reduced tillage or conventional tillage, in all comparisons.
    - Nitrous oxide (3 studies): Two replicated, randomized, controlled studies from Spain and the USA[14,39] found more nitrous oxide in soils with reduced tillage, compared to conventional tillage, in some comparisons[14] or all comparisons[39]. One controlled study from the USA[15] found similar amounts of nitrous oxide in soils with reduced tillage or conventional tillage, in all comparisons.

- Methane (1 study): One replicated, randomized, controlled study from Spain[39] found similar amounts of methane in soils with reduced tillage or conventional tillage.

- **Implementation options (1 study):** One replicated, randomized, controlled study from Egypt[38] found that less soil was lost in runoff water from plots that were tilled at slower tractor speeds.

A replicated, randomized, controlled study in 1983–1996 in a rainfed wheat field in the Henares river valley, Spain (1), found no differences in soil stability between plots with reduced tillage or conventional tillage. **Soil erosion and aggregation:** No differences in soil stability were found between plots with reduced tillage or conventional tillage (pre-wetted soil aggregates: 78–89% were water-stable; air-dried soil aggregates: 1–4% were water-stable). **Methods:** Conventional tillage or reduced tillage was used on four plots each. Each plot had two subplots (20 x 30 m, with or without crop rotations). A mouldboard plough (30 cm depth) was used for conventional tillage, in autumn. A chisel plough (20 cm depth) was used for reduced tillage, in autumn. A tine cultivator (10–15 cm depth, two passes) was used for both conventional and reduced tillage, in spring. Fertilizer and post-emergence herbicide were used on all plots. Soil samples were collected in June or July 1996 (0–30 cm, four samples/subplot).

A replicated, randomized, controlled study in 1998–2000 in an irrigated vegetable field in the Salinas Valley, California, USA (2), found more microbial biomass in soils with reduced tillage, compared to conventional tillage. Tillage had inconsistent effects on nutrients. **Nutrients:** Similar amounts of nitrogen were found in soils with reduced tillage, compared to conventional tillage (1.5–1.6 g total N/kg soil; 0–15 cm depth). At depths of 0–90 cm, less nitrate was found in soils with reduced tillage, compared to conventional tillage, in 12 of 14 comparisons (4–61 vs 5–64 g NO_3-N/g soil), but more nitrate was found in one of 14 comparisons (34 vs 29). At depths of 0–15 cm, tillage had inconsistent effects on nitrate (0–64 vs 0–53 µg NO_3-N/g soil) and ammonium (0–9 vs 0–6 µg NH_4-N/g soil). **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with reduced tillage, compared to conventional tillage, in two of 16 comparisons (120–130 vs 90–100 µg C/g soil). More microbial biomass (measured as nitrogen) was found in soils with reduced tillage, compared to conventional tillage, in three of 16 comparisons (12–15 vs 5–8 µg N/g soil). **Methods:** There were four plots (0.52 ha), for each of four treatments (reduced tillage or conventional tillage, with or without added organic matter). In plots with added organic matter, compost was added two times/year, and a cover crop (Merced rye) was grown every autumn or winter. Lettuce or broccoli crops were grown in raised beds. Sprinklers and drip irrigation were used in all plots. Soils were disturbed to different depths (conventional tillage: disking to 50 cm depth, cultivating, sub-soiling, bed re-making, and bed-shaping; reduced tillage: cultivating to 20 cm depth, rolling, and bed-shaping). Soils were collected, along the planting line, with 6 cm soil cores.

A replicated, randomized, controlled study in 1996–1999 in three rainfed barley fields in the Ebro river valley, Spain (3) (same study as (20,25,26,30)), found less nitrogen in soils with reduced tillage, compared to conventional tillage. **Nutrients:** Less nitrogen was found in soils with reduced tillage, compared to conventional tillage, in two of nine comparisons (125–176 vs 219–247 kg/ha). **Methods:** Reduced tillage or conventional tillage was used on 27 plots each (50 x 6 m plots). A mouldboard plough (25–30 cm depth) and a cultivator (15 cm depth, 1–2 passes) were used for conventional tillage, in August–September. A cultivator (10–15 cm depth, 1–2 passes) was used for reduced tillage, in September. Two-thirds of the plots were fertilized (50–75 or 100–150 kg N/ha).

Barley was sown, with a seed drill, in October–November. Soil samples were collected four times/year (0–50 cm in two of three fields, 0–100 cm in one field, two soil cores/plot).

A replicated, randomized, controlled study in 2000–2002 in a rainfed sunflower-wheat field near Seville, Spain (4), found more phosphorus and potassium in soils with reduced tillage, compared to conventional tillage. **Nutrients:** More phosphorus and potassium were found in soils with reduced tillage, compared to conventional tillage, in three of 10 comparisons (26–29 vs 20–24 mg phosphorus/kg soil; 313–403 vs 261–313 mg potassium/kg soil). **Methods:** Reduced tillage or conventional tillage was used on three plots each (22 x 14 m plots). A mouldboard plough (25–30 cm depth, in 2000–2001), a cultivator (15–20 cm depth), and a disc harrow (15 cm depth) were used for conventional tillage, and crop residues were burned. A chisel plough (25–30 cm depth, in 2000), a disc harrow, and pre-emergence herbicide were used for reduced tillage, and crop residues were retained. Soil samples were collected in November 2001, January 2002, and December 2002 (six samples/tillage treatment, 0–40 cm depth). Sunflower was grown in 2001 and it was not fertilized. Wheat was grown in 2001–2002 and it was fertilized.

A replicated, randomized, controlled, before-and-after study in 1999–2004 in an irrigated tomato-cotton field in the San Joaquin Valley, California, USA (5) (same study as (36)), found that tillage had inconsistent effects on nitrogen in soils. Phosphorus in soils increased after reduced tillage, but it did not change after conventional tillage. **Nutrients:** After four years, nitrogen increased in soils with conventional tillage (before: 1,300 lb/acre; after: 1,400–1,600), but decreased in soils with reduced tillage, in one of two comparisons (before: 1,400; after: 1,200), and increased in soils with reduced tillage, in one of two comparisons (before: 1,300; after: 1,600). After four years, nitrate increased in soils with reduced tillage, in one of two comparisons (before: 18 ppm; after: 25), but did not change in soils with conventional tillage (before: 16–17; after: 10–19). After four years, phosphorus increased in soils with reduced tillage (before: 7–8 ppm; after: 15–17), but did not change in soils with conventional tillage (before: 8; after: 7–9). **Methods:** Reduced tillage or conventional tillage was used on 16 plots each, in 1999–2009. The plots (9 x 82 m) had six raised beds each. Rainfed winter cover crops (triticale, rye, and vetch) were planted on half of the plots, in October 1999–2003, and crop residues were chopped in March. Different numbers of tillage practices were used (conventional tillage: 18–21 tractor passes, including disc and chisel ploughing; reduced tillage: 12–13 tractor passes, not including disc and chisel ploughing). Tomatoes and cotton were grown in rotation. Fertilizer and herbicide was used in all plots. Soil samples were collected in spring (before planting) and in autumn (after harvest), in 2000–2004 (0–30 cm depth; number and volume of samples not reported).

A replicated, randomized, controlled study in 2003–2005 on rainfed farms in the Ebro river valley, Spain (6), found less greenhouse gas in soils with reduced tillage, compared to conventional tillage. **Greenhouse gases:** Less carbon dioxide was found in soils with reduced tillage, compared to conventional tillage, in 12 of 30 comparisons, in the two days after tillage (0.1–6.4 vs 0.1–13.3 g CO_2/m^2/hour). **Methods:** Reduced tillage or conventional tillage was used on seven plots each (33–50 x 7–10 m plots), on a total of two farms, with multiple crops. A mouldboard or subsoil plough was used for conventional tillage (25–40 cm depth). A cultivator (15 cm depth) or chisel plough (25–30 cm depth) was used for reduced tillage. Carbon dioxide was measured with a dynamic chamber (21 cm diameter, 900 mL airflow/minute, two samples/plot), 4–6 times in the 48 hours after tillage.

A replicated, randomized, controlled study in 1992–2005 in a rainfed wheat-sunflower-pea field near Seville, Spain (7) (same study as (28,33)), found more soil organisms in soils with reduced tillage, compared to conventional tillage. **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with reduced tillage, compared to conventional tillage, in one of six comparisons (0–5 cm depth, November 2004: 316 vs 183 mg C/kg soil). **Methods:** Conventional tillage or reduced tillage was used on three plots each (22 x 14 m plots). A mouldboard plough (25–30 cm depth), a cultivator (12–15 cm depth, 1–3 times/year), a disc harrow (5–15 cm depth, 1–2 times/year), and herbicide were used for conventional tillage. A chisel plough (25–30 cm depth), a disc harrow (5–7 cm depth), and herbicide were used for reduced tillage. Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. Soil samples were collected in November 2004 and December 2005 (0–25 cm depth, two samples/plot).

A replicated, randomized, controlled study in 1993–2000 in a rainfed field near Madrid, Spain (8), found more phosphorus and potassium in soils with reduced tillage, compared to conventional tillage, but tillage had inconsistent effects on nitrogen. **Nutrients:** More nitrogen was found in soils with reduced tillage, compared to conventional tillage, in six of eight comparisons (0.7–1.3 vs 0.4–0.9 mg/ha), but less was found in one of eight comparisons (0.5 vs 0.6 mg/ha). More phosphorus was found in soils with reduced tillage, compared to conventional tillage, in two of four comparisons in 1997 (12–13 vs 7–8 kg/ha). More potassium was found in soils with reduced tillage, compared to conventional tillage, in two of four comparisons in 1997 (230–260 vs 150–190 kg/ha). Similar pH was found in soils with reduced tillage or conventional tillage (pH 7.8). **Methods:** Conventional tillage or reduced tillage was used on 20 subplots each (10 x 25 m subplots). Barley-barley, barley-vetch, or barley-fallow rotations were used on the subplots. A mouldboard plough (30 cm depth) was used for conventional tillage. A chisel plough (20 cm depth) was used for reduced tillage. Barley was fertilized, but vetch and fallows were not. Herbicide was used when needed. Soil samples were collected after harvest (0–90 cm depth; nitrogen was measured at 0–30 cm depth; phosphorus and potassium at 0–80 cm depth).

A replicated, randomized, controlled study in 1982–2003 in a rainfed wheat-sunflower-legume field near Seville, Spain (9), found more phosphorus in soils with reduced tillage, compared to conventional tillage. **Nutrients:** More phosphorus was found in soils with reduced tillage, compared to conventional tillage (961 vs 776 mg phosphorus/kg soil). **Methods:** Reduced tillage or conventional tillage was used on four plots each (180 x 15 m plots), in 1983–2003. Crop residues were burned, and a mouldboard plough (50 cm depth, once every three years, in summer) and a cultivator (15 cm depth, before seeds were sown) were used, for conventional tillage. A cultivator (15 cm depth, before seeds were sown) was used for reduced tillage. Fertilizer was used on wheat crops. Soil samples were collected in September 2003 (15 subsamples/plot, 5 cm depth).

A replicated, randomized, controlled study in 2002–2005 on three rainfed farms in the Ebro river valley, Spain (10), found similar amounts of greenhouse gas in soils with reduced tillage or conventional tillage. **Greenhouse gases:** Similar amounts of carbon dioxide were found in soils with reduced tillage or conventional tillage (0.11–1.65 vs 0.12–1.76 g CO_2/m^2/hour). **Methods:** Reduced tillage or conventional tillage was used on ten plots each (Peñaflor: three plots each, 33 x 10 m plots; Agramunt: four plots each, 9 x 50 m plots; Selvanera: three plots each, 7 x 50 m plots). In Peñaflor, a mouldboard plough (30–40 cm depth) and a cultivator (10–15 cm depth) were used for conventional tillage.

In Agramunt, a mouldboard plough (25–30 cm depth) and a cultivator (15 cm depth) were used for conventional tillage. In Selvanera, a subsoil plough (40 cm depth) and a cultivator (15 cm depth) were used for conventional tillage. A cultivator (Agramunt and Selvanera: 15 cm) or chisel plough (Peñaflor: 25–30 cm depth) was used for reduced tillage. Carbon dioxide samples were collected from December 2002 (Peñaflor, twice/month) or December 2003 (Agramunt and Selvanera, once/month) to June 2005, with an open chamber (900 mL airflow/minute, 21 cm diameter).

A replicated, randomized, controlled, before-and-after study in 2004 in a barley field in the Ebro river valley, Spain (11), found that tillage had inconsistent effects on soil aggregation. **Soil erosion and aggregation:** Soil aggregates were smaller immediately after reduced tillage, compared to conventional tillage, in two of five comparisons (1.8–1.9 vs 2.3 mm dry mean weight diameter; 29–35 vs 2–16% reduction in dry mean weight diameter). Soil aggregates were smaller after 15 years of reduced tillage, compared to conventional tillage, in three of ten comparisons (1.8–2.2 vs 2.3–2.6 mm dry mean weight diameter). Soil aggregates were more stable after 15 years of reduced tillage, compared to conventional tillage, in four of ten comparisons (16–20 vs 12–15% water stability). **Methods:** Reduced tillage or conventional tillage was used on three plots each (33.5 x 10 m plots), in 1989–2004. A chisel plough was used for reduced tillage (20–25 cm depth). A mouldboard plough was used for conventional tillage (30–35 cm depth). Soil samples were collected before (8 November) and after (15 November) the soils were tilled (flat spade, 0–40 cm depth, two subsamples/plot).

A replicated, randomized, controlled study in 2003 in rainfed farmland in the Ebro river valley, Spain (12), found similar amounts of soil aggregation in plots with reduced tillage, compared to conventional tillage. **Soil erosion and aggregation:** Similar amounts of large aggregates were found in soils with reduced tillage or conventional tillage (0–20 cm depth: water-stable aggregates >2,000 μm: 0.01–0.03 g aggregate/g soil). **Methods:** Conventional tillage or reduced tillage was used on three plots each (10 x 33 m). A mouldboard plough was used for conventional tillage (30–35 cm depth). A chisel plough was used for reduced tillage (25–30 cm depth). Soil samples were collected with a flat spade (0–20 cm depth) in July 2003.

A replicated site comparison in 2004–2005 in 16 irrigated tomato fields in the Sacramento Valley, California, USA (13), found more earthworms in fields with fewer passes of the plough. **Organic matter:** More carbon was found in fields with fewer passes of the plough in the year before they were sampled (total carbon; data reported as model results). **Nutrients:** More nitrogen was found in fields with fewer passes of the plough in the year before they were sampled (total nitrogen; data reported as model results). **Soil organisms:** More earthworms were found in fields with fewer passes of the plough in the year before they were sampled, in one of three comparisons (individual earthworm biomass; data reported as model results). **Methods:** Earthworms were collected from 16 tomato fields, in February–April 2005. In 2004, these fields had different numbers of tillage operations (3–10 passes of the plough). Five fields were cover cropped, and seven were mulched with crop residues. All fields were fertilized and irrigated.

A replicated, randomized, controlled study in 2003–2004 in three irrigated maize-tomato fields near Davis, California, USA (14), found higher greenhouse-gas emissions in soils with reduced tillage, compared to conventional tillage. **Nutrients:** Similar amounts of nitrogen were found in soils with reduced tillage or conventional tillage (1.8–2.6 vs 1.9–2.7 Mg N/ha). **Soil erosion and aggregation:** Similar amounts of soil aggregation were found in soils with reduced tillage or conventional tillage (1.2–1.7 vs 1.2–1.8 mm mean weight diameter). **Greenhouse gases:** Higher nitrous oxide emissions were found in soils with reduced tillage, compared to conventional tillage, in two of seven comparisons (emissions not reported for all of these comparisons, but the highest emissions were found in plots with reduced tillage: 29–40 g N_2O-N/ha/day). **Methods:** Reduced tillage or conventional tillage was used on nine plots each (1.5 x 1.0 m plots). Nine tillage practices, in 12–15 tractor passes, were used for conventional tillage. Five tillage practices, in 5–10 tractor passes, were used for reduced tillage. Soil samples were collected with soil cores (two cores/plot, 4 cm diameter, 0–15 cm depth), when the maize was harvested (September). Greenhouse-gas emissions were measured with closed chambers (March–September, every three weeks, from each plot).

A controlled study in 2003–2006 in an irrigated wheat-sunflower-chickpea field in Yolo County, California, USA (15), found similar amounts of greenhouse gas in soils with reduced tillage, compared to conventional tillage. **Greenhouse gases:** Similar amounts of greenhouse gas (carbon dioxide and nitrous oxide) were found in soils with reduced tillage, compared to conventional tillage (3–14 vs 3–15 Mg C/ha/year; 2–9 vs 1–4 kg N/ha/year). **Methods:** Conventional tillage was used on one half of a field, and reduced tillage was used on the other half, in 2003–2006. Different crops were planted in different years (2003: fallow; April 2004: maize; May 2005: sunflower; November 2005: chickpea). Ripping (45 cm depth), disking (15 cm depth), grading, listing beds were used for conventional tillage. Herbicide, stubble chopping, mulching, and disking were used for both conventional tillage and reduced tillage. Both treatments were fertilized and irrigated. Greenhouse gases were measured with closed chambers, in several places (crop row, crop bed, bottom of the furrow, and side of the furrow), 1–2 times/month, in 2003–2006 (nine samples/treatment).

A replicated, randomized, controlled study in 1990–2006 on three rainfed farms in Spain (16) found more soil organisms in plots with reduced tillage, compared to conventional tillage. **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with reduced tillage, compared to conventional tillage, in two of nine comparisons (0–10 cm depth, in Lleida: 420–490 vs 170–230 mg C/kg dry soil). **Methods:** Reduced tillage or conventional tillage was used on nine plots each in Lleida province (50 x 6 m plots, established in 1996), six plots each in Zaragoza province (33.5 x 10 m plots, established in 1990), and three plots each in Sevilla province (22 x 14 m plots). A mouldboard plough (25–40 cm depth, in Zaragoza and Sevilla), a cultivator (10–15 cm depth, 1–3 times/year), a disc harrow (5–15 cm depth, 1–2 times/year, in Sevilla), and herbicide (in Sevilla) were used for conventional tillage. A chisel plough (in Zaragoza but not in Lleida, 25–30 cm depth), a cultivator (10–15 cm depth, 1–2 passes), a disc harrow (5–7 cm depth, in Sevilla), and herbicide (in Sevilla) were used for reduced tillage. Soil samples were collected in March 2006 (0–25 cm depth).

A replicated, randomized, controlled study in 1991–2008 on a rainfed wheat-sunflower-pea field near Seville, Spain (17) (same study as (18)), found more soil organisms in plots with reduced tillage, compared to conventional tillage. **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with reduced tillage, compared to conventional tillage, in two of three comparisons (0–10 cm depth: 978–1,058 vs 806–814 mg C/kg soil). **Methods:** Reduced tillage or conventional tillage was used on three plots each (22 x 14 m), in 1991–2008. A chisel plough (25–30 cm depth, every two years) and a disc harrow (5–7 cm depth, every year) were used for reduced tillage. A mouldboard plough (25–30 cm depth), a cultivator (15–20 cm, 2–3 passes), and a disc harrow (15 cm) were used for conventional tillage (every year). Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. In 1991–2003, crop residues were burned on plots with conventional tillage. Crop residues were retained and herbicides were used on plots with reduced tillage. Soil samples were collected in March 2008 (three samples/plot, 400 g/soil core, 0–20 cm depth).

A replicated, randomized, controlled study in 1991–2008 on a rainfed wheat-sunflower-pea field near Seville, Spain (18) (same study as (17)), found more soil organisms in plots with reduced tillage, compared to conventional tillage. **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with reduced tillage, compared to conventional tillage, in three of six comparisons (654–1,058 vs 806–814 mg C/kg soil). **Methods:** Reduced tillage or conventional tillage was used on three plots each (22 x 14 m), in 1991–2008. A chisel plough (25–30 cm depth, every two years) and a disc harrow (5–7 cm depth, every year) were used for reduced tillage. A mouldboard plough (25–30 cm depth), a cultivator (15–20 cm, 2–3 passes), and a disc harrow (15 cm) were used for conventional tillage (every year). Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. In 1991–2003, crop residues were burned on plots with conventional tillage. Crop residues were retained and herbicides were used on plots with reduced tillage. Soil samples were collected in March and July 2008 (three samples/plot, 0–20 cm depth).

A replicated, controlled study in 1993–2006 in an irrigated tomato-corn field in Davis, California, USA (19), found similar numbers of soil organisms, but different communities of soil organisms, in plots with reduced tillage, compared to conventional tillage. **Soil organisms:** Similar numbers of mites and nematodes were found in soils with reduced tillage or conventional tillage (596–888 vs 527–797 individuals/100 g fresh soil). However, the composition of nematode and mite communities differed between soils with reduced tillage or conventional tillage (reported as distance in multivariate space). **Methods:** Conventional tillage or reduced tillage was used on six plots each (0.4 ha plots). Plots were tilled about five times/year (conventional) or two times/year (reduced; depth not reported). All plots were irrigated. Half of the plots were fertilized, and compost was added to the other half. Soil samples were collected eight times in March 2005–November 2006 (three samples/plot). Mites were sampled with soil cores (5 cm diameter, 10 cm depth). Nematodes were sampled in soil cubes (20 x 20 x 20 cm).

A replicated, randomized, controlled study in 1996–2008 in a rainfed barley field in the Ebro river valley, Spain (20) (same study as (3,25,26,30)), found more greenhouse gas in soils with reduced tillage, compared to conventional tillage. **Greenhouse gases:** More carbon dioxide was found in soils with reduced tillage, compared to conventional tillage (amount of carbon dioxide not reported). **Methods:** Reduced tillage or conventional tillage was used on nine plots each (50 x 6 m). A mouldboard plough or a disc plough was used for conventional tillage (25–30 cm depth, 100% incorporation of crop residues). A cultivator was used for reduced tillage (10–15 cm depth, 50% incorporation of crop residues). Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Greenhouse gas was sampled with an open chamber (2 samples/plot, 21 cm diameter, 900 mL airflow/minute), in 2005–2008 (several samples within 2 days before and after tillage).

A replicated, randomized, controlled study in 2003–2005 in a vineyard in Napa Valley, California, USA (21), found less carbon dioxide in soils with reduced tillage, compared to conventional tillage. **Greenhouse gases:** Less carbon dioxide was found in soils with reduced tillage, compared to conventional tillage, in one of two years (8.57 vs 10.11 Mg CO_2-C/ha). **Methods:** Three plots (518 m^2 each, four vine alleys each) were disked in spring (conventional tillage: 30 cm depth), and three plots were not disked (reduced tillage). Short stature barley was grown as a winter cover crop on all plots.

Cover crops were mown in spring, before disking. All plots were disked in autumn (5 cm depth), before the cover crops were planted.

A replicated, randomized, controlled study in 2000–2009 on a farm in Sicily, Italy (22), found more organic matter, nitrogen, phosphorus, and soil organisms in soils with reduced tillage, compared to conventional tillage. **Organic matter:** More organic carbon was found in soils with reduced tillage, compared to conventional tillage (8–16 vs 6–11 g C/kg soil). **Nutrients:** More nitrogen or phosphorus was found in soils with reduced tillage, compared to conventional tillage, in one of two comparisons (2.2 vs 1.7 g N/kg soil; 20 vs 11 mg phosphorus/kg soil). **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with reduced tillage, compared to conventional tillage (334–680 vs 241–464 mg C/kg soil), and more microbial biomass (measured as nitrogen) was found in one of two comparisons (102 vs 78 mg N/kg soil). **Greenhouse gases:** Similar amounts of carbon dioxide were found in soils with reduced tillage, compared to conventional tillage (69–71 vs 109–111 mg C-CO_2/kg soil). **Methods:** Conventional tillage or reduced tillage was used on eight plots each (20 x 15 m plots), in 2000–2009. A mouldboard plough (20 cm depth) was used for both conventional tillage (6–8 ploughings/year) and reduced tillage (one ploughing/year, plus hoeing to control weeds). Compost was added to all plots (15–30 t/ha/year). Soil samples were collected in May 2009 (five sub-samples/plot, 0–20 cm depth).

A replicated, randomized, controlled study in 1994–2007 in a rainfed wheat field near Madrid, Spain (23) (same study as (35,39)), found more organic matter and higher stability in soils with reduced tillage, compared to conventional tillage. **Organic matter:** More organic carbon was found in soils with reduced tillage, compared to conventional tillage, in two of four comparisons (0–7.5 cm depth: 8–9 vs 6–8 Mg C/ha). **Soil erosion and aggregation:** Higher stability was found in soils with reduced tillage, compared to conventional tillage, in one of four comparisons (0–7.5 cm depth, October 2007: 51 vs 38% of aggregates were water-stable). **Methods:** Reduced tillage or conventional tillage was used on eight plots each (10 x 25 m plots), in autumn 1994–2007. A mouldboard plough (20 cm depth) and a cultivator were used for conventional tillage. A chisel plough (15 cm depth) and a cultivator were used for reduced tillage. All plots were fertilized. Soil samples were collected after the seedbeds were prepared (three samples/plot, 0–15 cm depth), in November 2006 and October 2007.

A replicated, randomized, controlled study in 2008–2010 in a wheat-legume field in southwest Spain (24) (same study as (31)) found more soil organisms in soils with reduced tillage, compared to conventional tillage. **Soil organisms:** More microbial biomass (measured as carbon or nitrogen) was found in soils with reduced tillage, compared to conventional tillage, in four of 18 comparisons (0–5 cm depth, in June 2009 or January 2010: 458–2,363 vs 263–957 mg C/kg soil; 37–69 vs 17–25 mg N/kg soil). **Methods:** Conventional tillage or reduced tillage was used on three plots each (30 x 10 m plots). A mouldboard plough was used for conventional tillage (25 cm depth). Herbicides and a chisel plough were used for reduced tillage (10–15 cm depth). All plots were fertilized. Soil samples were collected in January 2009, June 2009, and January 2010 (three samples/plot, nine soil cores/sample, 0–25 cm depth). No tillage was used on all plots in 1999–2008.

A replicated, randomized, controlled study in 1996–2009 in a rainfed barley field in the Ebro river valley, Spain (25) (same study as (3,20,26,30)), found higher greenhouse-gas emissions in soils with reduced tillage, compared to conventional tillage. **Greenhouse gases:** Higher carbon dioxide emissions were found in soils with reduced tillage, compared to conventional tillage, in three of four comparisons (amounts of carbon dioxide not clearly reported). **Methods:** Reduced tillage or conventional tillage was used on nine plots each (50 x 6 m plots). A mouldboard plough was used for conventional tillage (25–30 cm depth, 100% incorporation of crop residues). A cultivator was used for reduced tillage (10–15 cm depth, 50% incorporation of crop residues). Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Carbon dioxide was measured with an open chamber (21 cm diameter, 900 mL airflow/minute, 2 samples/plot/day, every 7–14 days, in 2006–2009).

A replicated, randomized, controlled study in 1996–2009 in a rainfed barley field in the Ebro river valley, Spain (26) (same study as (3,20,25,30)), found less nitrate in soils with reduced tillage, compared to conventional tillage. **Nutrients:** Less nitrate was found in soils with reduced tillage, compared to conventional tillage (461 vs 852 kg $N-NO_3$/ha), but no differences in ammonium were found (amounts of ammonium not reported). **Methods:** Reduced tillage or conventional tillage was used on nine plots each (50 x 6 m plots) in October or November. A mouldboard plough was used for conventional tillage (25–30 cm depth, 100% incorporation of crop residues). A cultivator was used for reduced tillage (10–15 cm depth, 50% incorporation of crop residues). Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Soil samples were collected when sowing the crop in November 2005–2008 (two samples/plot, 4 cm diameter soil auger, 0–100 cm depth).

A replicated, randomized, controlled study in 1996–2008 in a rainfed legume-cereal field near Aleppo, Syria (27), found more organic matter and fewer soil organisms in soils with reduced tillage, compared to conventional tillage. **Organic matter:** More organic matter was found in soils with reduced tillage, compared to conventional tillage, in four of 10 comparisons (2003: 12–17 vs 10–13 g/kg). **Nutrients:** Similar amounts of nitrogen were found in soils with reduced tillage or conventional tillage (0.76 g/kg soil). **Soil organisms:** Less microbial biomass (measured as carbon and nitrogen) was found in soils with reduced tillage, compared to conventional tillage, in four of eight comparisons (carbon, 5–20 cm depth: 13–38 vs 90–91 mg/kg soil; nitrogen, 10–30 cm depth: 5–10 vs 19–28 mg/kg soil). **Methods:** The crop rotations were vetch–barley (two-course) or vetch–barley–vetch–wheat (four-course). Reduced tillage or conventional tillage was used on twenty plots each (25 x 25 m plots). A mouldboard plough (30 cm depth, after cereal crops) was used for conventional tillage. A cultivator (12 cm depth, after vetch) was used for both conventional and reduced tillage. All plots were fertilized in November. Soils were sampled in 2003 (0–30 cm depth) and 2008 (0–20 cm depth).

A replicated, randomized, controlled study in 1991–2008 in a rainfed wheat-sunflower-pea field near Seville, Spain (28), found more organic matter, more soil organisms, and lower greenhouse-gas emissions in soils with reduced tillage, compared to conventional tillage. Tillage had inconsistent effects on soil stability. **Organic matter:** More organic carbon was found in soils with reduced tillage, compared to conventional tillage, in one of three comparisons (0–5 cm depth: 11 vs 10 g total organic C/kg soil). **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with reduced tillage, compared to conventional tillage, in one of three comparisons (0–5 cm depth: 885 vs 620 mg C/kg soil). **Soil erosion and aggregation:** More stable soils were found in plots with reduced tillage, compared to conventional tillage, in one of nine comparisons (5–10 cm depth: 49 vs 39% water-stable aggregates), but less stable soils were found in one of nine comparisons (data reported as aggregation index). **Greenhouse gases:** Lower carbon dioxide emissions were found in soils with reduced tillage, compared to conventional tillage (0.31 vs 0.40 g CO_2/m^2/hour). **Methods:** Reduced tillage or conventional tillage was used on three plots each (22 x 14 m plots). A mouldboard plough and a chisel plough were used for conventional tillage (25–30 cm depth), and crop residues were burned (1992–2003, but not 2004–2008). A chisel plough and herbicide were used for reduced tillage (25–30 cm depth), and crop residues were retained. Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. Soil samples were collected in 2008 (0–25 cm depth, four samples/plot).

A replicated meta-analysis from 2013 of multiple Mediterranean countries (29) found a higher percentage of organic matter in soils with reduced tillage, compared to conventional tillage. **Organic matter:** A higher percentage of organic carbon was found in soils with reduced tillage, compared to conventional tillage (15% higher). **Methods:** The Web of Knowledge database was searched, using the keywords, "Mediterranean", "soil", and "conventional", and 17 data sets from 12 studies of reduced tillage were found and meta-analysed. The most recent studies included in this meta-analysis were published in 2011.

A replicated, randomized, controlled study in 1996–2008 in a rainfed barley field in the Ebro river valley, Spain (30) (same study as (3,20,25,26)), found more organic matter, but similar amounts of soil organisms, in soils with reduced tillage, compared to conventional tillage. **Organic matter:** More organic carbon was found in soils with reduced tillage, compared to conventional tillage (8.65 vs 7.39 g C/kg dry soil). **Soil organisms:** Similar amounts of microbial biomass (measured as carbon) were found in soils with reduced tillage or conventional tillage (263 vs 231 mg C/kg dry soil). **Methods:** There were nine plots (50 x 6 m) for each of two tillage treatments (reduced tillage: cultivator, 10–15 cm depth; conventional tillage: mouldboard plough, 25–30 cm depth). Plots were tilled in October or November. Soil samples were collected in October 2008 (before tillage, three soil cores/plot, 4 cm diameter, 0–50 cm depth).

A replicated, randomized, controlled study in 2008–2010 in a rainfed wheat-vetch field in southwest Spain (31) (same study as (24)) found more organic matter and soil organisms in soils with reduced tillage, compared to conventional tillage. **Organic matter:** More organic carbon was found in soils with reduced tillage, compared to conventional tillage (17–23 vs 12–15 g C/kg soil). **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with reduced tillage, compared to conventional tillage, in four of five comparisons (in soil aggregates <2 mm in diameter: 526–646 vs 339–346 g C/kg soil). **Soil erosion and aggregation:** Similar amounts of soil aggregation were found in soils with reduced tillage or conventional tillage (data reported for five soil fractions). **Methods:** Conventional tillage or reduced tillage was used on three plots each (300 m^2 plots), in 2008–2009. From 1999–2008, no tillage was used on all plots. A mouldboard plough (25 cm depth, in 2008), or a chisel plough (10–15 cm depth, in 2009), and a disk harrow were used for conventional tillage, and crop residues were removed (in 2008 and 2010). A chisel plough (10–15 cm depth) and herbicide were used for reduced tillage, and crop residues were retained. Soil samples were collected in October 2010 (0–10 cm depth, five samples/plot).

A replicated, randomized, controlled study in 2009–2012 in two irrigated vegetable fields in central Italy (32) found more nitrate and ammonium in soils with reduced tillage, compared to conventional tillage. **Nutrients:** More nitrate was found in soils with reduced tillage, compared to conventional tillage, in two of 12 comparisons (in plots with oats or oilseed rape as the winter cover crop: 6 vs 2 mg NO_3-N/kg dry soil), and more ammonium was found in one of 12 comparisons (11 vs 2 mg NH_4-N/kg dry soil). **Methods:** Reduced tillage or conventional tillage was used on nine plots each (6 x 4 m plots). Each plot had a winter cover crop (hairy vetch, oats, or oilseed rape). Cover crops were sown in September 2009–2010 and suppressed in May 2010–2011. A mouldboard plough and a disk harrow (two passes) were used for conventional tillage (incorporating the cover crop residues to 30 cm depth). A rotary hoe was used for reduced tillage (incorporating the cover crop residues to 10 cm depth). Pepper seedlings were transplanted into these plots in May 2010–2011 and were last harvested in October 2010 and September 2011. After the pepper harvest, endive and savoy cabbage seedlings were transplanted into these plots, and they were harvested in December 2010 and November 2011 (endive) or March 2011 and February 2012 (cabbage). No fertilizer was added while the crops were growing, but the plots were irrigated. Nutrients were measured in soil samples (10 samples/plot, 0–30 cm depth, when these crops were harvested).

A replicated, randomized, controlled study in 2008–2013 in a rainfed wheat-sunflower-pea field near Seville, Spain (33), found similar amounts of organic matter and nutrients in soils with reduced tillage or conventional tillage. **Organic matter:** Similar amounts of organic carbon were found in soils with reduced tillage or conventional tillage (9 g C/kg soil). **Nutrients:** Similar amounts of nitrogen, phosphorus, and potassium were found in soils with reduced tillage or conventional tillage (0.92–0.99 vs 0.91–0.97 g N/kg soil; 17.8–25.7 vs 22.2–26.1 g phosphorus/kg soil; 307–419 vs 367–428 g potassium/kg soil). **Methods:** Reduced tillage or conventional tillage was used on three plots each (6 x 33.5 m plots). A mouldboard plough (25–30 cm depth), a chisel plough (25 cm depth, twice/year), and a disc harrow (12 cm depth) were used for conventional tillage. A chisel plough (25 cm depth, once/year), a disc harrow (5 cm depth), and herbicide were used for reduced tillage. Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. Soil samples were collected in October 2012 (0–25 cm depth).

A replicated, randomized, controlled study in 1991–2011 in rainfed wheat-sunflower-pea fields near Seville, Spain (34) (same study as (16,37)), found more organic matter and more soil organisms in soils with twenty years of reduced tillage, compared to conventional tillage. **Organic matter:** More organic carbon was found in soils with reduced tillage, compared to conventional tillage, in two of three comparisons, in long-term plots (1991–2011, 0–10 cm depth: 13–14 vs 10–11 g C/kg soil), but no differences were found in short-term plots (2008–2011: 6–9 vs 7–9 g C/kg soil). **Soil organisms:** More microbial biomass (measured as carbon) was found in soils with reduced tillage, compared to conventional tillage, in one of three comparisons, in long-term plots (1991–2011, 0–5 cm depth: 580 vs 474 mg C/kg soil), but no differences were found in short-term plots (2008–2011: 740–958 vs 689–868 mg C/kg soil). **Methods:** Reduced tillage or conventional tillage was used on three plots each, in each of two experiments: a short-term experiment (2008–2011, 20 x 9 m plots), and a long-term experiment (1991–2011, 20 x 14 m plots). A mouldboard plough (25–30 cm depth), a cultivator (15–20 cm depth, two passes), and a disc harrow (15 cm depth) were used for conventional tillage. A chisel plough (15–20 cm depth, every other year) and a disc harrow (5–7 cm depth) were used for reduced tillage, and crop residues were retained (>60% cover). Soil samples were collected in January 2011 (0–25 cm depth, five samples/plot).

A replicated, randomized, controlled study in 1994–2013 in a rainfed field near Madrid, Spain (35) (same study as (23,39)), found more organic matter, soil organisms, and greenhouse gas in soils with reduced tillage, compared to conventional tillage. **Organic matter:** More organic carbon was found in plots with reduced tillage, compared to conventional tillage, in two of 12 comparisons (8 vs 6 g C/kg soil). **Soil organisms:** More microbial biomass (measured as carbon) was found in plots with reduced tillage, compared to conventional tillage, in three of 12 comparisons (380–400 vs 200–250 mg

C/kg soil). **Greenhouse gases**: More carbon dioxide was found in plots with reduced tillage, compared to conventional tillage, in two of 12 comparisons (30–40 vs 20–28 mg CO_2-C/kg soil/d). **Methods:** Conventional tillage or reduced tillage was used on eight plots each (10 x 25 m plots). A mouldboard plough was used for both conventional tillage (25 cm depth) and reduced tillage (20 cm depth). Wheat was grown on half of the plots, whereas wheat, vetch, and barley were grown in rotation on the other half. Wheat and barley were fertilized. Crop residues were shredded and retained. Soil sam ples were collected six times in October 2010–April 2013 (soil cores, 0–15 cm depth, 5 cm diameter).

A replicated, randomized, controlled study in 1999–2009 in an irrigated tomato-cotton field in the San Joaquin Valley, California, USA (36) (same study as (5)), found similar amounts of organic matter in soils with reduced tillage or conventional tillage. **Organic matter:** Similar amounts of carbon were found in soils with reduced tillage or conventional tillage (24–29 vs 23–26 t total C/ha). **Methods:** Reduced tillage or conventional tillage was used on 16 plots each, in 1999–2009. The plots (9 x 82 m) had six raised beds each. Rainfed winter cover crops (triticale, rye, and vetch) were planted on half of the plots, in October 1999–2008, and crop residues were chopped in March. Different numbers of tillage practices were used for conventional tillage (19–23 tractor passes, including disc and chisel ploughing) and reduced tillage (11–12 tractor passes, not including disc and chisel ploughing). Tomatoes and cotton were grown in rotation. Fertilizer and herbicide were used in all plots. Soil samples were collected in autumn 2007 (0–30 cm depth, 7.6 diameter soil cores, 6–8 subsamples/plot).

A replicated, randomized, controlled study in 1991–2010 in rainfed wheat-sunflower-pea fields near Seville, Spain (37) (same study as (16,34)), found more organic matter, fewer soil organisms, and more aggregation in soils with reduced tillage, compared to conventional tillage. **Organic matter:** More organic carbon was found in soils with reduced tillage, compared to conventional tillage, in four of ten comparisons (6–9 vs 5–7 g C/kg soil). **Soil organisms:** Less microbial biomass (measured as carbon) was found in soils with reduced tillage, compared to conventional tillage, in one of ten comparisons (in autumn, 1–2 mm aggregates: 67 vs 107 g microbial C/kg organic C). **Soil erosion and aggregation:** More large aggregates were found in soils with reduced tillage, compared to conventional tillage, in autumn (1–2 mm aggregates: 18 vs 16% of soil weight; 2–5 mm: 35 vs 31%), and fewer small aggregates were found in one of three comparisons, in autumn (0.25–0.5 mm aggregates: 14 vs 19% of soil weight). However, no differences in aggregate distributions were found in spring (data reported for five aggregate sizes). **Methods:** Reduced tillage or conventional tillage was used on three plots each (300 m^2 plots). A mouldboard plough (25–30 cm depth), a cultivator (15–20 cm depth, two passes), and a disc harrow (5–7 cm depth) were used for conventional tillage. A chisel plough (15–20 cm depth, every other year) and a disc harrow (5–7 cm depth) were used for reduced tillage, and crop residues were retained (>60% cover). Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. Soil samples were collected in spring and autumn 2010 (0–10 cm depth, five samples/plot).

A replicated, randomized, controlled study in 2012–2013 in a rainfed wheat field in Wadi Madwar, northwestern Egypt (38), found less erosion of soils with less frequent tillage, compared to more frequent, more erosion of soils with shallower tillage, compared to deeper, and less erosion of soils that were tilled at slower speeds, compared to faster. **Soil erosion and aggregation:** Less soil was lost in runoff water from plots with reduced tillage, compared to conventional tillage (1.44 vs 1.66 t/ha). More soil was lost in runoff water from plots that were tilled to 15 cm depth, compared to 20–25 cm depth (1.31 vs 1.20–1.22 t/ha). **Implementation options:** Less soil was lost in runoff water from plots that were tilled at slower tractor speeds (0.69–1 m/s: 1.21–1.22 t/ha), compared to faster speeds (1.25–1.53 t/ha: 1.26–1.29 t/ha). **Methods:** Reduced tillage or conventional tillage was used on three plots each (0.45 ha plots). A chisel plough was used for both reduced tillage (one pass) and conventional tillage (two passes). Each plot had three subplots (0.15 ha subplots, tilled to 15, 20, or 25 cm depth). Each subplot had four sub-subplots (size not reported; tilled at 0.69, 1, 1.25, or 1.53 m/s). Runoff water was collected in buried containers, downhill from each sub-subplot, after each storm.

A replicated, randomized, controlled study in 1994–2011 in a rainfed cereal-legume field near Madrid, Spain (39) (same study as (23,35)), found higher greenhouse-gas emissions, more soil organisms, and more organic matter in soils with reduced tillage, compared to conventional tillage. **Organic matter:** More organic carbon was found in soils with reduced tillage, compared to conventional tillage (27.1 vs 11.2 mg dissolved organic C/kg soil). **Nutrients:** Similar amounts of nitrate and ammonium were found in soils with reduced tillage, compared to conventional tillage (1–18 mg NO_3-N/ha; 0.2–3.5 mg NH_4-N/kg). **Soil organisms:** More bacteria were found in soils with reduced tillage, compared to conventional tillage (denitrifying bacteria: 10^8 vs 10^6 gene copies), but no difference in microbial biomass (measured as carbon) was found (186 vs 94 mg C/kg soil). **Greenhouse gases:** Higher nitrous oxide emissions were found in soils with reduced tillage, compared to conventional tillage (0.12 vs 0.05 kg N_2O–N/ha), but no difference in methane emissions was found (–473 vs –231 g CH_4–C/ha). **Methods:** No tillage or reduced tillage was used on three plots each (10 x 25 m), in October. A chisel plough and a cultivator were used for reduced tillage (15 cm depth). A mouldboard plough and a cultivator were used for conventional tillage (20 cm depth). Soil and greenhouse-gas samples were collected 1–12 times/month, in November 2010–October 2011, in the vetch phase of a fallow-wheat-vetch-barley rotation (soil cores: 0–15 cm depth, 2.5 cm diameter; closed chambers: 19.3 cm height, 35.6 cm diameter, 20 mL gas samples, 0–60 minutes after chamber closure). The vetch was not fertilized.

A replicated, randomized, controlled study in 2009–2011 in an irrigated eggplant field in central Italy (40) found more nitrogen in soils with reduced tillage, compared to conventional tillage. **Nutrients:** More nitrogen was found in soils with reduced tillage, compared to conventional tillage, in one of four comparisons (30 vs 24 mg inorganic N/kg dry soil). **Methods:** A mouldboard plough (30 cm depth) was used on all plots in autumn, before winter cover crops were planted. Cover crops were mown or chopped in spring, before tillage. Reduced tillage or conventional tillage was used on 12 plots each (6 x 4 m plots). A mouldboard plough (30 cm depth) and a disc (two passes) were used for conventional tillage (which incorporated the cover crop residues into the soil). A rotary hoe (10 cm depth) was used for reduced tillage (which incorporated some of the cover crop residues into the soil). Eggplant seedlings were transplanted into the plots in May, and fruits were harvested four times/year in July–September 2010–2011. Soil samples were collected when the seedlings were transplanted and when the last fruits were harvested each year (0–30 cm depth, six samples/plot). All plots were fertilized before the cover crops were grown, but not after. All plots were irrigated.

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Habitat management: Effects on soil

3.12. Plant buffer strips: Soil (1 study)

- **Organic matter (1 study):** One replicated, randomized, controlled study from Italy[1] found more organic matter in plots with buffers.
- **Nutrients (1 study):** One replicated, randomized, controlled study from Italy[1] found more nitrogen in plots with buffers.
- **Soil organisms (1 study):** One replicated, randomized, controlled study from Italy[1] found more microbial biomass in plots with buffers.
- Soil erosion and aggregation (0 studies)
- Greenhouse gases (0 studies)
- **Implementation options (1 study):** One study from Italy[1] found some differences between buffers of different widths, and other differences between buffers with different numbers of trees.

A replicated, randomized, controlled study in (1997–2010) in a maize field in the Po Valley, Italy (1), found more organic matter, nitrogen, and microbial biomass in buffered plots, compared to unbuffered plots. **Organic matter:** More organic matter was found in buffered plots, in seven of eight comparisons (0.25–0.35% vs 0.22%). **Nutrients:** More nitrogen was found in buffered plots, in seven of eight comparisons (0.13–0.14% vs 0.1%). **Soil organisms:** More microbial biomass (measured as carbon) was found in buffered plots, in six of eight comparisons (316–566 vs 257 mg/kg dry soil), and more microbial biomass (measured as nitrogen) was found in two of eight comparisons (40–47 vs 27 mg/kg dry soil). **Implementation options:** More organic matter was found in plots with 3 m buffers, compared to 6 m buffers (0.30–0.34% vs 0.25–0.27%). Similar soil nitrogen was found in plots with 3 m buffers and 6 m buffers (1%). Less microbial biomass (measured as carbon) was found in plots with 3 m buffers, compared to 6 m buffers, in one of two comparisons (450 vs 541 mg/kg dry soil), but more was found in one of two comparisons (391 vs 327 mg). Less microbial biomass (measured as nitrogen) was found in plots with 3 m buffers, in one of two comparisons (33 vs 40 mg/kg dry soil). Similar amounts of organic matter were found in plots that had buffers with one or two tree rows (0.20–0.28%). More nitrogen was found in plots that had buffers with one tree row, compared to two, in one of two comparisons (0.14% vs 0.12%). Similar amounts of microbial biomass (measured as carbon) were found in plots that had buffers with one or two tree rows (316–565 mg/kg dry soil). More microbial biomass (measured as nitrogen) was found in plots that had buffers with one tree row, compared to two, in one of two comparisons (40 vs 34 mg/kg dry soil). **Methods:** Maize plots had grass buffers (3 m grass: tall fescue *Festuca arudinacea*), grass and woody buffers (3 m grass with one tree row; 6 m grass with one tree row; 6 m grass with two tree rows), or no buffers (two replicates of each plot). Trees included guelder-rose *Viburnum opulus* and London sycamore *Platanus hybrida*. Plots were ploughed (35–40 cm depth) and harrowed before sowing crops. Fertilizers were applied (April: 400 kg/ha of NPK; May: 450 kg/ha of urea). Grass buffers were mown twice a year in growing season (residues were not removed) and tree offshoots were removed. Trees were coppiced in 2003 and 2010. Soil samples were taken (0–15 cm) in April and October 2010.

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3.13. Plant hedgerows: Soil (1 study)

- Organic matter (0 studies)
- Nutrients (0 studies)
- Soil organisms (0 studies)
- **Soil erosion and aggregation (1 study):** One replicated site comparison from the USA[1] found similar particle sizes in soils with or without planted hedgerows.
- Greenhouse gases (0 studies)

A replicated site comparison in farmland in the Central Valley, California, USA (1) (years of study not reported), found similar soil structure in field edges with or without planted hedgerows. **Soil erosion and aggregation:** Similar particle sizes were found in soils with or without planted hedgerows (data reported as statistical results). **Methods:** Eight fields with planted hedgerows (mostly Californian native shrubs and forbs, at least five years after planting) were compared with eight field edges without planted hedgerows. Two soil samples were collected from each site (0–10 cm depth).

(1) Sardiñas, H.S., Ponisio, L.C. & Kremen, C. (2016) Hedgerow presence does not enhance indicators of nest-site habitat quality or nesting rates of ground-nesting bees. *Restoration Ecology*, 24, 499-505.

3.14. Restore habitat along watercourses: Soil (2 studies)

- **Organic matter (1 study):** One replicated site comparison from the USA[1] found less carbon in soils at restored sites, compared to natural sites.
- **Nutrients (1 study):** One replicated site comparison from the USA[1] found less nitrogen, phosphorus, and potassium in soils at restored sites, compared to natural sites.
- **Soil organisms (1 study):** One controlled study from the USA[2] found different nematode communities in restored and unrestored areas.
- Soil erosion and aggregation (0 studies)

- Greenhouse gases (0 studies)
- **Implementation options (1 study)**: One replicated site comparison from the USA[1] found less carbon, nitrogen, and phosphorous in soils at older restored sites compared to younger restored sites.

A replicated site comparison in 2005–2006 in 46 riparian sites in the Central Valley, California, USA (1), found less carbon, nitrogen, phosphorus, and potassium in soils at restored sites, compared to natural sites. **Organic matter:** Less carbon was found in soils at restored sites, compared to natural sites (1.1% vs 1.8%). **Nutrients:** Less phosphorus (13 vs 41 ppm), potassium (181 vs 380), total nitrogen (0.09 vs 0.14%), and nitrate (5 vs 12 ppm) was found in soils at restored sites, compared to natural sites. **Implementation options:** Older restored sites had less total nitrogen, carbon, and phosphorous than younger restored sites (data not provided). **Methods:** Thirty restored sites (urban: 19; agricultural: 11; all with <30 planted elderberry plants; 2–15 years old) and 16 natural sites (within 20 km of restored sites) were compared. Restored sites were surveyed in July–early November 2005 and August–October 2006 and natural sites in April–September 2006. Restored sites were 24% of the size of natural sites. Soil samples (5–30 cm depth) were collected under three or more shrubs at each site.

A controlled study in 2000–2008 along a stream on a farm in the Central Valley, California, USA (2), found different nematode communities in a restored area, compared to an unrestored area. **Soil organisms:** Different nematode communities were found in the restored and unrestored areas (data reported as ordination results: restoration explained 3% of the variation in nematode communities). **Methods:** Part of the streambank was restored: graded to create a floodplain (4 m width) and planted with native perennial grasses, sedges, forbs, shrubs, and trees. Soil samples were collected from the restored area and the unrestored area in December 2007 and March–April 2008 (0–30 cm depth).

(1) Koch-Munz, M. & Holyoak, M. (2008) An evaluation of the effects of soil characteristics on mitigation and restoration involving blue elderberry, Sambucus mexicana. *Environmental Management*, 42, 49-65.

(2) Briar, S.S., Culman, S.W., Young-Mathews, A., Jackson, L.E. & Ferris, H. (2012) Nematode community responses to a moisture gradient and grazing along a restored riparian corridor. *European Journal of Soil Biology*, 50, 32-38.

Livestock management: Effects on soil

3.15. Exclude grazers: Soil (6 studies)

- **Organic matter (1 study):** One replicated site comparison in shrublands in Spain[6] found less carbon in soils at ungrazed sites, compared to cow-and-sheep-grazed sites.
- **Nutrients (3 studies):** Three replicated studies (one controlled, two site comparisons) from the USA[1,5] and Spain[6] found less nitrogen in soils in ungrazed areas, compared to sheep- or cattle-

grazed areas, in some or all comparisons. One of these studies[1] found more phosphorus in soils at ungrazed sites, compared to grazed sites.

- **Soil organisms (1 study):** One controlled study on a streambank in the USA[3] found more nematodes and more diverse nematode communities in an area with goats and sheep excluded.
- Soil erosion and aggregation (0 studies)
- **Greenhouse gases (3 studies):** One replicated site comparison in shrublands in Spain[6] found more carbon dioxide in soils (soil respiration) in ungrazed plots, compared to sheep- or cattle-grazed plots. One replicated, randomized, controlled study in grassland in the USA[4] found similar amounts of carbon dioxide in soils (soil respiration) in ungrazed and cattle-grazed sites. One replicated, randomized, controlled study in wet grasslands in the USA[2] found less methane in soils in ungrazed plots, compared to cattle-grazed plots.
- **Implementation options (1 study):** One replicated site comparison in shrubland in Spain[6] found less carbon and nitrogen in untilled soils that were grazed, compared to ungrazed, but found no differences in tilled soils that were grazed or ungrazed.

A site comparison in 1991 in annual grasslands on the Central Coast, California, USA (1), found less nitrogen but more phosphorus in ungrazed sites, compared to grazed sites. **Nutrients:** Less nitrogen was found in ungrazed sites, compared to grazed sites (0.09% vs 0.11% total Kjeldahl N), but more phosphorus was found in ungrazed sites (18 vs 11 mg P/kg soil). **Methods:** European domestic cattle were introduced to Monterey County in 1770. In 1937, grazers were excluded from one landscape (the Hastings Natural History Reservation), but not from an adjacent landscape. In 1991, 43 sites in the ungrazed grassland and 37 sites in the grazed grassland were sampled (methods not clearly reported, but soil samples were collected at 5–10 cm depth in a different part of this study).

A replicated, randomized, controlled study in 1999–2001 in grazed wetlands in northern California, USA (2), found lower methane production in plots from which grazers were excluded, compared to cattle-grazed plots. **Greenhouse gases:** Methane production was lower in ungrazed plots, compared to grazed plots (2.6 vs 8.5 mg CH_4–C/m^2/hr). **Methods:** Experimental plots were established in four grazed wetlands in 1999, with cattle excluded from one plot, but not from another plot, in each wetland. Methane emissions were measured monthly in March–September 2002.

A controlled study in 2005–2008 in restored riparian habitat on a farm in the Central Valley, California, USA (3), found more nematodes overall, more bacteria-feeding nematodes, and more diverse communities of nematodes, in plots without grazers, compared to plots grazed by goats and sheep. **Soil organisms:** More nematode biomass and higher nematode diversity were found in plots without grazers, compared to plots with grazers (831 vs 557 µg/100 g soil; diversity reported as Shannon diversity index). More bacteria-feeding nematodes were found in plots without grazers, compared to plots with grazers (178 vs 86 nematodes/100 g soil), but similar numbers of fungus-feeding (168 vs 194), omnivorous and predatory (29 vs 21), and plant-feeding (180 vs 176) nematodes were found in plots with or without grazers. **Methods:** Grazers were introduced to half of a streambank in 2005 (14 animals/ha), but they were excluded by a fence from the other half. Soil samples were collected from the grazed area and the ungrazed area in December 2007 and March–April 2008 (0–30 cm depth).

A replicated, randomized, controlled study in 2008–2010 in grasslands in central California, USA (4), found no differences in soil respiration between plots with or without cattle excluded. **Greenhouse gases:** Potential microbial respiration rates did not differ between plots with or without cattle excluded (9–12 µg CO_2/g/day). **Methods:** Ten sets of plots were established in grassland that had been grazed for decades: five plots in 2008 and five plots in 2009. Half of the plots were fenced to exclude cattle and half were left open and typically grazed in winter (approximately 0.25 cow-calf pairs/ha).

A replicated, controlled study in 2012–2013 in grasslands in central California, USA (5), found less soil nitrogen in plots with cattle excluded, compared to grazed plots. **Nutrients:** Less soil nitrogen was found in ungrazed plots, compared to grazed plots (14–16 vs 17–24 mg NH_4 and NO_3 combined). **Methods:** Sixty 1 x 1 m plots were established in summer 2012: half in an area grazed at 0.25 cow-calf pairs/ha, and half in an area fenced in 2012 to exclude cattle. Soil cores (5 cm diameter, 0–10 cm depth) were collected in April 2013.

A replicated site comparison in 2008–2010 in shrubland in central Spain (6) found less carbon and nitrogen, and higher carbon dioxide emissions, in soils in ungrazed sites, compared to sheep-and-cattle-grazed sites. **Organic matter:** There was less carbon in soils in ungrazed sites, compared to grazed sites, in one of two comparisons (in untilled soils: 3.8–9.6 vs 6.5–15.8 Mg C/ha). **Nutrients:** There was less nitrogen in soils in ungrazed sites, compared to grazed sites, in one of two comparisons (in untilled soils: 0.3–0.7 vs 0.8–1.3 Mg N/ha). **Greenhouse gases:** More carbon dioxide was lost through soil respiration in ungrazed plots, compared to grazed plots (720–740 vs 640–655 g C/m^2/year). **Implementation options:** Differences in carbon and nitrogen, due to grazing, were found in untilled soils, but not in tilled soils (see above for data on tilled soils). **Methods:** Eight holm oak *Quercus ilex* trees were selected in each of two areas grazed by sheep and cattle and in two ungrazed areas. Soils surrounding four trees in each area were tilled in April 2008. Soil respiration was measured nine times in July 2008–February 2010. Soil samples were collected in February 2010 (to measure carbon and nitrogen).

(1) Stromberg, M.R. & Griffin, J.R. (1996) Long-Term Patterns in Coastal California Grasslands in Relation to Cultivation, Gophers, and Grazing. *Ecological Applications*, 6, 1189-1211.

(2) Allen-Diaz, B., Jackson, R.D., Bartolome, J.W., Tate, K.W. & Oates, L.G. (2004) Long-term grazing study in spring-fed wetlands reveals management tradeoffs. *California Agriculture*, 58.

(3) Briar, S.S., Culman, S.W., Young-Mathews, A., Jackson, L.E. & Ferris, H. (2012) Nematode community responses to a moisture gradient and grazing along a restored riparian corridor. *European Journal of Soil Biology*, 50, 32-38.

(4) Esch, E.H., Hernández, D.L., Pasari, J.R., Kantor, R.S.G. & Selmants, P.C. (2012) Response of soil microbial activity to grazing, nitrogen deposition, and exotic cover in a serpentine grassland. *Plant and Soil*, 366, 671-682.

(5) Funk, J.L., Hoffacker, M.K. & Matzek, V. (2015) Summer irrigation, grazing and seed addition differentially influence community composition in an invaded serpentine grassland. *Restoration Ecology*, 23, 122-130.

(6) Uribe, C., Inclán, R., Hernando, L., Román, M., Clavero, M.A., Roig, S. & Miegroet, H.V. (2015) Grazing, tilling and canopy effects on carbon dioxide fluxes in a Spanish dehesa. *Agroforestry Systems*, 89, 305-318.

3.16. Use fewer grazers: Soil (2 studies)

- Organic matter (0 studies)

- **Nutrients (2 studies):** One controlled study in wood pasture in Chile[1] found more nitrogen and phosphorus in paddocks grazed at lower intensities, in some comparisons. One replicated, randomized, controlled study in grasslands in the USA[2] found no difference in nitrogen between areas with low or high levels of simulated grazing.
- Soil organisms (0 studies)
- Soil erosion and aggregation (0 studies)
- **Greenhouse gases (1 study):** One replicated, randomized, controlled study in grasslands in the USA[2] found no differences in rates of soil respiration between areas with low or high levels of simulated grazing.

A controlled study in 1976–1983 in wood pasture (Espinal) in central Chile (1) found more nitrogen and phosphorus in paddocks that were grazed by sheep at lower stocking rates. **Nutrients:** More nitrogen and phosphorus were found at lower stocking rates (e.g., with 1 vs 3.5 sheep/ha: 0.3% vs 0.1% N, 6.0 vs 1.5 mg P_2O_5/kg soil). **Methods:** The study area (32 ha) was grazed with 1 sheep/ha for at least 20 years before the study began. In 1976, seven paddocks were established with fences (2.5–10 ha/paddock, 10 sheep/paddock), each with a different stocking rate (1, 1.5, 2, 2.5, 3, 3.5, or 4 sheep/ha). In paddocks with 1–3.5 sheep/ha, soil samples were collected in 1983 (0–20 cm depth).

A replicated, randomized, controlled study in 2008–2010 in sown plots in lowland grasslands in northern California, USA (2), found no difference in nitrogen availability or soil respiration between plots grazed at medium intensity, compared to high intensity. **Nutrients:** There was no difference in nitrogen availability between plots grazed at medium or high intensity (0.2–0.3 g N/g soil/day). **Greenhouse gases:** There were no differences in soil respiration between plots grazed at a medium or high intensity (245–315 µmol CO_2/min/g soil). **Methods:** In 2007 four experimental blocks were established across two pastures. Each block was split into eighteen plots and subjected to one of three treatments: no manipulation; mowing and trampling by cattle to simulate medium cattle grazing; mowing and trampling by cattle to simulate heavy cattle grazing. Soil nitrogen availability was measured in December 2009–March 2010 using ion exchange resin bags. Soil respiration was measured in February 2010.

(1) del Pozo, A., Ovalle, C., Casado, M.A., Acosta, B. & de Miguel, J.M. (2006) Effects of grazing intensity in grasslands of the Espinal of central Chile. *Journal of Vegetation Science*, 17, 791-798.

(2) Stein, C., Hallett, L.M., Harpole, W.S. & Suding, K.N. (2014) Evaluating Ecosystem Services Provided by Non-Native Species: An Experimental Test in California Grasslands. *PLOS ONE*, 9, e75396.

4. Water

Crop and soil management: Effects on water

4.1. Add compost to the soil: Water (6 studies)

- Water use (0 studies)
- **Water availability (4 studies):** Two replicated, randomized, controlled studies from Turkey and the USA[3,4] found more water in soil with added compost, compared to soil without added compost, in some comparisons[4], or in all comparisons[3]. One replicated, randomized, controlled study from the USA[1] found similar amounts of water in soil with or without added compost. One replicated, controlled study from Spain[2] found that less water was lost as runoff from soil with added compost, compared to soil without added compost.
- Pathogens and pesticides (0 studies)
- **Nutrients (2 studies):** One replicated, randomized, controlled study from Spain[5] found more nitrogen, phosphorus, and potassium in runoff from plots with added compost, compared to plots without added compost. One replicated, randomized, controlled study from Portugal[6] found that more nitrate was leached from plots with added compost, compared to plots without added compost, in one of four comparisons.
- **Sediments (1 study):** One replicated, randomized, controlled study from Spain[5] found more organic matter in runoff from plots with added compost, compared to plots without added compost.
- **Implementation options (1 study):** One replicated, randomized, controlled study from Portugal[6] found that similar amounts of nitrate were leached from plots with or without added compost, if the compost was split into two small applications, compared to one large application.

A replicated, randomized, controlled study in 1995 in a broccoli field in the Salinas Valley, California, USA (1), found similar amounts of water in soils with added compost, compared to soils without added compost. **Water availability:** Similar amounts of water were found in soils with or without added compost (17–18% vs 17% water by weight). **Methods:** There were four plots for each of three compost treatments (0, 22, or 44 Mg/ha). Fertilizer (165 kg ammonium nitrate/ha) was added to half (6.1 x 7.7 m) of each plot. The compost was made from green wastes (>30%), cow manure (>20%), spoiled hay (>15%), clay soil (>5%), and crop processing residues. Soil samples were collected on 24 October 1995 (0–20 cm depth).

A replicated, controlled study (year not reported) on a slope in Murcia, Spain (2), found less water loss in plots with added compost, compared to plots without added compost. **Water availability:** Less water was lost as runoff from plots with added compost, compared to plots without added compost, after rainfall events (eight initial events: 2.3 vs 6.0 litres water/m^2; later events: 6.2 vs 12.6). **Methods:** Composted municipal waste was added to three treatment plots, but not three control plots (10 x 3 m plots, 15% slope). Runoff water was collected from the lower edge of each plot, after each rainfall event. Enough compost was added to the soil to increase its organic carbon content by 2%. The soil was rotovated to a depth of 20 cm, to incorporate the compost.

A replicated, randomized, controlled study in 1995–1999 in farmland in southern Turkey (3) found more available water in soils with added compost, compared to soils without added compost. **Water availability:** More available water was found in soils with added compost, compared to soils without added compost (0.17 vs 0.09 cm^3 water/cm^3 soil). **Methods:** Compost (25 t/ha) was added to three treatment plots (10 x 20 m), but not three control plots. The compost was made of grass, stubble, and leaves. Wheat, sweet peppers, maize, and wheat were grown in rotation. Soils were sampled in 1999, after harvesting the last wheat crop. The difference between water retention at field capacity (–33 kPa) and at permanent wilting point (–1,500 kPa) was used to determine available water content.

A replicated, randomized, controlled study in 1998–2000 in an irrigated vegetable field in the Salinas Valley, California, USA (4), found more water in soils with added compost, compared to soils without added compost, in six of 16 comparisons. **Water availability:** More water was found in soils with added compost, compared to soils without added compost, in six of 16 comparisons (0.10–0.27 vs 0.07–0.26 g water/g soil, 0–15 cm depth). **Methods:** There were four plots (0.52 ha), for each of four treatments (minimum tillage or conventional tillage, with or without added organic matter). In plots with added organic matter, compost was added two times/year, and a cover crop (Merced rye) was grown every autumn or winter. The compost was made from municipal yard waste, salad packing plant waste, horse manure, clay, straw, and other compost. Lettuce or broccoli crops were grown in raised beds. Sprinklers and drip irrigation were used in all plots. Soils were disturbed to different depths (conventional tillage: 50 cm with disking, cultivating with a liliston, sub-soiling, bed re-making, and bed-shaping; minimum tillage: 20 cm with a liliston, rollers, and bed-shaping). Soils were collected, along the planting line, with 6 cm soil cores. It was not clear whether these results were a direct effect of adding compost or growing cover crops.

A replicated, randomized, controlled study in 2001–2005 in the Guadalquivir Valley, Andalusia, Spain (5), found more nutrients and sediments in runoff water from soils with added compost, compared to soils without added compost, after rainfall. **Nutrients:** More nitrate was found in runoff from soils with added compost, compared to soils without added compost, after rainfall (60 mm rainfall/hour: 0.12–0.35 vs 0.07–0.09 mg/litre water; 140 mm rainfall/hour: 0.31–0.67 vs 0.10–0.19). More ammonium was found in runoff from soils with added compost, compared to soils without added compost, after rainfall (60 mm rainfall/hour: 5–9 vs 1 mg/litre water; 140 mm rainfall/hour: 13–23 vs 2–3). More phosphorus was found in runoff from soils with added compost, compared to soils without added compost, after rainfall (60 mm rainfall/hour: 0.2–0.7 vs 0 mg/litre water; 140 mm rainfall/hour: 0.7–1.3 vs 0). More potassium was found in runoff from soils with added compost, compared to soils without added compost, after rainfall (60 mm rainfall/hour: 3.5–6.8 vs 1–1.4 mg/litre water; 140 mm rainfall/hour: 8.5–16.1 vs 0.9–2.5). **Sediments:** More organic matter was found in runoff from soils with added compost, compared to soils without added compost, after rainfall (60 mm rainfall/hour: 6–9 vs 0 mg C/litre water; 140 mm rainfall/hour: 14–21 vs 0). **Methods:** There were four plots (9 x 9 m) for each of two treatments (10 or 20 t compost/ha) and one control (no compost). The compost was added in October 2001–2004, and soils were ploughed to a depth of 25 cm. Soils were watered to simulate rainfall and runoff water was collected in October 2002–2005 (60 or 140 mm rainfall/hour).

A replicated, randomized, controlled study in 2006–2008 in a cereal field in the Castelo Branco region, Portugal (6), found that more nitrate was leached from soils with added compost, compared to soils without added compost, in one of four comparisons. **Nutrients and Implementation options:** With a single application of compost in the spring, more nitrate was leached from plots with added compost, compared to plots without added compost, in 2006/2007 (111 vs 49 kg NO_3-N/ha), but not in 2007/2008 (32 vs 23 kg). With a split application (some in spring, some in autumn), there were no significant differences between plots with and without added compost (2006/2007: 107 vs 49 kg NO_3-N/ha; 2007/2008: 35 vs 23 kg). **Methods:** Water in the soil was collected in porous ceramic suction cup samplers (four/plot, 0.6–0.7 m depth, 50 kPa for 24 hours), whenever drainage occurred (October–November and April–May; 16 samples in total). There were three plots (5.6 x 8 m) for each of two treatments (single application or split application of compost) and one control (no compost). The compost was made from municipal waste. Maize was grown in spring–summer, and oats were grown in autumn–winter.

(1) Stamatiadis, S., Werner, M. & Buchanan, M. (1999) Field assessment of soil quality as affected by compost and fertilizer application in a broccoli field (San Benito County, California). *Applied Soil Ecology*, 12, 217-225.

(2) Ros, M., Garcia, C. & Hernandez, T. (2001) The use of urban organic wastes in the control of erosion in a semiarid Mediterranean soil. *Soil Use and Management*, 17, 292-293.

(3) Celik, I., Ortas, I. & Kilic, S. (2004) Effects of compost, mycorrhiza, manure and fertilizer on some physical properties of a Chromoxerert soil. *Soil and Tillage Research*, 78, 59-67.

(4) Jackson, L.E., Ramirez, I., Yokota, R., Fennimore, S.A., Koike, S.T., Henderson, D.M., Chaney, W.E., Calderón, F.J. & Klonsky, K. (2004) On-farm assessment of organic matter and tillage management on vegetable yield, soil, weeds, pests, and economics in California. *Agriculture, Ecosystems & Environment*, 103, 443-463.

(5) Tejada, M. & Gonzalez, J.L. (2008) Influence of two organic amendments on the soil physical properties, soil losses, sediments and runoff water quality. *Geoderma*, 145, 325-334.

(6) Carneiro, J.P., Coutinho, J. & Trindade, H. (2012) Nitrate leaching from a maize × oats double-cropping forage system fertilized with organic residues under Mediterranean conditions. *Agriculture, Ecosystems & Environment*, 160, 29-39.

4.2. Add manure to the soil: Water (5 studies)

- Water use (0 studies)
- **Water availability (3 studies):** One replicated, randomized, controlled study from Turkey[2] found more water in soils with added manure, compared to soils without added manure. Two replicated, controlled studies (one randomized) from Greece[5] and the USA[1] found similar amounts of water in soils with or without added manure.
- Pathogens and pesticides (0 studies)
- **Nutrients (2 studies):** One replicated, randomized, controlled study from Spain[4] found more dissolved organic carbon, but similar amounts of nitrate, in runoff from plots with added manure, compared to plots without added manure. One replicated, randomized, controlled study from Spain[3] found that more nitrate, ammonium, phosphorus, potassium, and organic matter was leached from soils with added manure, compared to soils without added manure.

- Sediments (0 studies)

A replicated, controlled study in 1997–1998 in irrigated fallow land in California, USA (1), found similar amounts of water in soils with or without added manure. **Water availability:** Similar moisture content was found in soils with or without added manure (111 vs 101 g/kg). **Methods:** Plots (2 x 2 m) had added poultry manure (25 Mg/ha) or no added fertilizer (five plots for each). Manure was added in April 1987, February 1988, and October 1988 and was immediately incorporated into the soil (15 cm depth). Plots were irrigated weekly (100 mm/day). Five soil samples (25–100 mm depth) were taken from each plot.

A replicated, randomized, controlled study in 1995–1999 in arable farmland in southern Turkey (2) found more available water in soils with added manure, compared to soils without added manure. **Water availability:** More available water was found in soils with added manure, compared to soils without added manure (0.14 vs 0.09 cm^3 water/cm^3 soil). **Methods:** Cattle manure (25 t/ha) was added to three treatment plots (10 x 20 m), but not three control plots. Wheat, sweet peppers, and maize were grown in rotation. Soils were sampled in 1999, after harvesting the last wheat crop (0–30 cm depth). The difference between water retention at field capacity (–33 kPa) and at permanent wilting point (–1,500 kPa) was used to determine available water content.

A replicated, randomized, controlled study in 2001–2005 in the Guadalquivir Valley, Andalusia, Spain (3), found more nutrients and sediments in runoff from soils with added manure, compared to soils without added manure, after rainfall. **Nutrients:** More nitrate, ammonium, phosphorus, and potassium were found in runoff from plots with added manure, compared to plots without added manure, after rainfall (60 mm rainfall/hour, nitrate: 0.15–0.40 vs 0.07–0.09; ammonium: 6–10 vs 1; phosphorus: 0.3–0.7 vs 0; potassium: 4.1–7.9 vs 1–1.4 mg/litre water) (140 mm rainfall/hour, nitrate: 0.42–0.85 vs 0.10–0.19; ammonium: 16–31 vs 2–3; phosphorus: 0.9–1.8 vs 0; potassium: 11.4–22.3 vs 0.9–2.5 mg/litre water). **Sediments:** More organic matter was found in runoff from soils with added manure, compared to soils without added manure, after rainfall (60 mm rainfall/hour: 7–10 vs 0 mg C/litre water; 140 mm rainfall/hour: 16–26 vs 0). **Methods:** There were four plots (9 x 9 m) for each of two treatments (5.8 or 11.6 t poultry manure/ha) and four control plots (no manure). The manure was added in October 2001–2004, and soils were ploughed (25 cm depth). Soils were watered to simulate rainfall in October 2002–2005 (60 or 140 mm rainfall/hour), and soil loss was measured in plots (1 x 1 m) that overlapped the borders of the treatment and control plots by 0.5 m.

A replicated, randomized, controlled study in 2007–2009 in an irrigated onion field near Madrid, Spain (4), found that more dissolved organic carbon was leached from soils with added manure, compared to soils without added manure. **Nutrients:** Similar amounts of nitrate were leached from soils with or without added manure (1 vs 17 kg/ha). More dissolved organic carbon was leached from soils with added manure (5 vs 2 kg/ha). **Methods:** Plots (20 m^2) had manure (a mixture of hen and goat manure) or no fertilizer (three plots each), added in 2007 and 2008 (110 kg N/ha). The manure was immediately incorporated into the soil (10 cm depth), using a rotocultivator. Plots were irrigated 1–2 times/week (608–618 mm/year). Drainage water was collected in ceramic cups (80 cm depth, 40 kPa) thirty times during the experiment.

A replicated, randomized, controlled study in 2009 in an abandoned wheat field in Greece (5) found similar amounts of water in soils with or without added manure. **Water availability:** Similar amounts of water were found in soils with or without added manure

(8–15%). **Methods:** Plots (1 x 1 m) had added manure (4 kg/m²) or no added manure (four plots for each). Manure was added in January and incorporated into the soil with a mattock. Soil samples (three/plot, 3–20 cm depth) were collected in March and June.

(1) Martens, D.A. & Frankenberger, W.T. (1992) Modification of Infiltration Rates in an Organic-Amended Irrigated Soil. *Agronomy Journal*, 84, 707-717.

(2) Celik, I., Ortas, I. & Kilic, S. (2004) Effects of compost, mycorrhiza, manure and fertilizer on some physical properties of a Chromoxerert soil. *Soil and Tillage Research*, 78, 59-67.

(3) Tejada, M. & Gonzalez, J.L. (2008) Influence of two organic amendments on the soil physical properties, soil losses, sediments and runoff water quality. *Geoderma*, 145, 325-334.

(4) Sanchez-Martin, L., Sanz-Cobena, A., Meijide, A., Quemada, M. & Vallejo, A. (2010) The importance of the fallow period for N2O and CH4 fluxes and nitrate leaching in a Mediterranean irrigated agroecosystem. *European Journal of Soil Science*, 61, 710-720.

(5) Papatheodorou, E.M., Kordatos, H., Kouseras, T., Monokrousos, N., Menkissoglu-Spiroudi, U., Diamantopoulos, J., Stamou, G.P. & Argyropoulou, M.D. (2012) Differential responses of structural and functional aspects of soil microbes and nematodes to abiotic and biotic modifications of the soil environment. *Applied Soil Ecology*, 61, 26-33.

4.3. Add sewage sludge to the soil: Water (3 studies)

- Water use (0 studies)
- **Water availability (2 studies):** One replicated, controlled study from Spain[2] found less runoff from plots with added sewage sludge, compared to plots without it, in one of four comparisons. One replicated, controlled study from the USA[1] found similar amounts of water in soils with or without added sewage sludge.
- Pathogens and pesticides (0 studies)
- **Nutrients (1 studies):** One replicated, randomized, controlled study from Portugal[3] found that more nitrate was leached from soils with added sewage sludge, compared to soils without it, in some comparisons.
- Sediments (0 studies)
- **Implementation options (1 study):** One replicated, controlled study from Portugal[3] found that more nitrate was leached from plots with a split application of sewage sludge, but not with a single application, compared to plots without added sewage sludge.

A replicated, controlled study in 1997–1998 in irrigated fallow land in California, USA (1), found similar moisture content in plots with or without added sewage sludge. **Water availability:** Similar moisture content was found in plots with or without added sewage sludge (117 vs 108 g/kg). **Methods:** Plots (2 x 2 m) had sewage sludge (25 Mg/ha) or no added fertilizer (five plots each). Sewage sludge was added in April 1987, February 1988, and October 1988 and was immediately incorporated into the soil (15 cm depth). Plots were irrigated weekly (100 mm/day). Five soil samples (25–100 mm depth) were taken from each plot.

A replicated, controlled study (years not reported) on a slope in Murcia, Spain (2), found that less water was lost from plots with added sewage sludge, compared to plots without it. **Water availability:** Less water was lost as runoff from plots with added sewage sludge, compared to plots without it, after rainfall events (eight initial events: 2.1 vs 6.0 litres water/m^2; later events: 5.7 vs 12.6). **Methods:** Sewage sludge was added to three treatment plots, but not three control plots (10 x 3 m plots, 15% slope). Runoff water was collected from the lower edge of each plot, after each rainfall event. Enough sewage sludge was added to the soil to increase its organic carbon content by 2%. The soil was rotovated (20 cm depth), to incorporate the sewage sludge.

A replicated, randomized, controlled study in 2006–2008 in a cereal field in the Castelo Branco region, Portugal (3), found that more nitrate was leached from soils with added sewage sludge, compared to soils without it. **Nutrients:** More nitrate was leached from soils with added sewage sludge, compared to soils without it, in one of four comparisons (145 vs 49 kg NO_3-N/ha). **Implementation options:** With a split application of sewage sludge (some in spring, some in autumn), more nitrate was leached from soils with added sewage sludge, compared to soils without it, in 2006/2007 (145 vs 49 kg NO_3-N/ha). However, with a single application in the spring, there was not a significant difference between soils with or without added sewage sludge (2006/2007: 101 vs 49 kg NO_3-N/ha; 2007/2008: 26 vs 23 kg). **Methods:** Water in the soil was collected in porous ceramic suction cup samplers (four/plot; 0.6–0.7 m depth; 50 kPa for 24 hours), whenever drainage occurred (October–November and April–May; 16 samples in total). There were three plots (5.6 x 8 m) for each of two treatments (single application or split application of sewage sludge) and there were two control plots (no sewage sludge). Maize was grown in spring–summer, and oats were grown in autumn–winter.

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(2) Ros, M., Garcia, C. & Hernandez, T. (2001) The use of urban organic wastes in the control of erosion in a semiarid Mediterranean soil. *Soil Use and Management*, 17, 292-293.

(3) Carneiro, J.P., Coutinho, J. & Trindade, H. (2012) Nitrate leaching from a maize × oats double-cropping forage system fertilized with organic residues under Mediterranean conditions. *Agriculture, Ecosystems & Environment*, 160, 29-39.

4.4. Add slurry to the soil: Water (7 studies)

- Water use (0 studies)
- **Water availability (2 studies):** One replicated, randomized, controlled study from Spain[6] found similar amounts of water in soils with or without added slurry, and another one[2] found similar amounts of water-filled pore space.
- Pathogens and pesticides (0 studies)
- **Nutrients (5 studies):** Two replicated, randomized, controlled studies from Spain[1,7] found that more nitrate was leached from plots with added slurry, compared to plots without it. One of these studies[7] also found that more nitrate was lost in runoff from plots with added slurry, in some comparisons. Two replicated, randomized, controlled studies from Portugal[5] and Spain[3] found that similar amounts of nitrate were leached from plots with or without added slurry. Two replicated, randomized, controlled studies from Spain[3,4] found more dissolved organic matter in soils, or leached from soils, with added slurry.
- Sediments (0 studies)

- **Implementation options (3 studies):** One study from Spain[1] found that less nitrate was leached from plots with surface application, compared to injection, of slurry. One study from Spain[7] found that less nitrate was lost through runoff and leaching from plots with less added slurry, compared to more. One study from Spain[2] found similar amounts of water-filled pore space in soils with digested or untreated pig slurry, and another[6] found similar amounts of water-filled pore space in plots with less or more added slurry.

A replicated, randomized, controlled study in 2002 in irrigated farmland in Spain (1) found that more nitrate was leached from plots with added slurry, compared to plots without it. **Nutrients:** More nitrate was leached from plots with added slurry (0.08–2 vs 0.1 g N/m^2). **Implementation options:** Less nitrate was leached from plots with surface application, compared to injection, of slurry (0.8 vs 2 g N/m^2). **Methods:** Plots (3 x 3 m) growing tall fescue *Festuca arundinacea* had pig slurry (surface application or injection, 200 kg N/ha) or no fertilizer (three plots each). Each plot had a lysimeter (1 x 1 m, 0.75 m depth) to measure leaching. Slurry was injected (5 L/m) or applied with a watering can. Water (5 L/plot) was added to the control plots. All plots were sprinkler-irrigated (June–August: daily; September: twice/week). Soil cores were taken from the centre of the plots (0–10 cm depth).

A replicated, randomized, controlled study in 2009 in a rainfed barley field in Spain (2) found similar amounts of water-filled pore space in soils with or without added slurry. **Water availability:** Similar amounts of water-filled pore space were found in soils with or without added slurry (20–60%). **Implementation options:** Similar amounts of water-filled pore space were found in soils with untreated or digested slurry (20–60%). **Methods:** Plots (30 m^2) had no fertilizer or pig slurry (anaerobically-digested pig slurry or untreated), applied in January 2006 (125 kg N/ha; three plots for each) and incorporated into the soil using a rotocultivator (0–5 cm depth). Phosphate and potassium (75 and 40 kg/ha, respectively) were added to all plots. Soil samples were taken every 1–2 weeks during crop period and three times during fallow period (0–10 cm depth), but no samples were taken in June–October (the soil was too dry).

A replicated, randomized, controlled study in 2007–2009 in an irrigated onion field near Madrid, Spain (3), found that more dissolved organic carbon was leached from plots with added slurry, compared to plots without it. **Nutrients:** Similar amounts of nitrate were leached from plots with or without added slurry (31 vs 17 kg/ha), but more dissolved organic carbon was leached from plots with added slurry (3 vs 2 kg/ha). **Methods:** Plots (20 m^2) had anaerobically-digested pig slurry or no fertilizer (three plots each), added in 2007 and 2008 (110 kg N/ha). The slurry was immediately incorporated into the soil (10 cm depth), using a rotocultivator. Plots were irrigated 1–2 times/week (608–618 mm/year). Drainage water was collected in ceramic cups (80 cm depth, 40 kPa) thirty times during the experiment.

A replicated, randomized, controlled study in 2007 in an irrigated melon field in Spain (4) found more dissolved organic matter in soils with added slurry, compared to soils without it. **Nutrients:** More dissolved organic carbon was found in soils with added slurry (22–34 vs 15–34 mg/kg). **Methods:** Plots (4 x 5 m) growing melon *Cucumis melo* (6,950 plants/ha) had digested pig slurry or no slurry, and were either drip or furrow irrigated (three plots for each). Slurry was applied using a hose pipe (175 kg N/ha). Additional fertilizers were added immediately after (phosphorous: 50 kg/ha; potassium: 150 kg/ha). Slurry and fertilizer were incorporated into the soil (15 cm) using a rotocultivator. For furrow irrigation (2 L/min), there were five furrows/plot (80 cm width, 15 cm depth, 100 cm apart). For drip irrigation (3 L/h), there were two lines/subplot (1.8 m apart). Irrigation was applied 20 times, on a weekly basis. Soil samples were taken (0–10 cm depth; frequency not reported).

A replicated, randomized, controlled study in 2006–2008 in a cereal field in the Castelo Branco region, Portugal (5), found that similar amounts of nitrate were leached from soils with or without added slurry. **Nutrients:** Similar amounts of nitrate were leached from soils with or without added slurry (2006–2007: 78 vs 49 kg NO_3-N/ha; 2007–2008: 28 vs 23). **Methods:** Water in the soil was collected in porous ceramic suction cup samplers (four/plot; 0.6–0.7 m depth; 50 kPa for 24 hours), whenever drainage occurred (October–November and April–May; 16 samples in total). Cattle slurry was added to three treatment plots (5.6 x 8 m), but not three control plots, in spring. Maize was grown in spring–summer, and oats were grown in autumn–winter.

A replicated, randomized, controlled study in 2010–2013 in rainfed barley fields in Spain (6) found similar amounts of water-filled pore space in plots with or without added slurry. **Water availability:** Similar amounts of water-filled pore space were found in plots with or without added slurry (25–26% vs 24%). **Implementation options:** Similar amounts of water-filled pore space were found in plots with less or more slurry (25% vs 26%). **Methods:** Plots (40 x 12 m) had pig slurry (75 or 150 kg N/ha) or no fertilizer (three plots each). Plots had conventional tillage (mouldboard plough: 25 cm depth; cultivator: 15 cm depth) or no tillage. Soil samples (0–5 cm depth) were collected every 2–3 weeks in 2011–2013.

A replicated, randomized, controlled study in 2003–2004 in an irrigated maize field in Spain (7) found that more nitrate was lost through leaching and runoff from plots with added slurry, compared to plots without it. **Nutrients:** More nitrate was lost through leaching (105–208 vs 10 kg/ha) and runoff (in three of four comparisons: 74–81 vs 3 mg/L) from plots with added slurry, compared to plots without it. **Implementation options:** Less nitrate was lost through leaching (208–226 vs 105 kg/ha) and runoff (34 vs 74–81 mg/L) from plots with less slurry, compared to more slurry (30 vs 60–120 Mg slurry/ha). **Methods:** Plots (30 x 40 m) had pig slurry (30, 60, 90, or 120 Mg/ha) or no slurry (three plots for each). Slurry was immediately covered after application. Lysimeters (2.6 x 2 m, 1.5 m depth) were installed in each plot, five years before the study. Each plot was drip-irrigated, simulating flood irrigation (May–September, with 7–12 intervals). Water samples were collected after each irrigation or rainfall event in 50 L containers.

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(2) Meijide, A., García-Torres, L., Arce, A. & Vallejo, A. (2009) Nitrogen oxide emissions affected by organic fertilization in a non-irrigated Mediterranean barley field. *Agriculture, Ecosystems and Environment*, 132, 106-115.

(3) Sanchez-Martin, L., Sanz-Cobena, A., Meijide, A., Quemada, M. & Vallejo, A. (2010) The importance of the fallow period for N2O and CH4 fluxes and nitrate leaching in a Mediterranean irrigated agroecosystem. *European Journal of Soil Science*, 61, 710-720.

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(6) Plaza-Bonilla, D., Cantero-Martínez, C., Bareche, J., Arrúe, J.L. & Álvaro-Fuentes, J. (2014) Soil carbon dioxide and methane fluxes as affected by tillage and N fertilization in dryland conditions. *Plant and Soil*, 381, 111-130.

(7) Yagüe, M.R. & Quílez, D. (2015) Pig slurry residual effects on maize yields and nitrate leaching: A study in lysimeters. *Agronomy Journal*, 107, 278-286.

4.5. Use organic fertilizer instead of inorganic: Water (11 studies)

- Water use (0 studies)
- **Water availability (5 studies):** Two replicated, randomized, controlled studies from Spain[3,8] found similar amounts of water-filled pore space in plots with organic or inorganic fertilizer. Two replicated studies (one randomized and controlled, one site comparison) from France[11] and Turkey[1] found more water in plots with organic fertilizer, compared to inorganic fertilizer. One replicated, randomized, controlled study from Spain[4] found less water in plots with organic fertilizer, compared to inorganic fertilizer, in one of two comparisons.
- Pathogens and pesticides (0 studies)
- **Nutrients (6 studies):** Two replicated, randomized, controlled studies from Italy[10] and Spain[6] found that less nitrate was lost from plots with organic fertilizer, compared to inorganic fertilizer, in some comparisons. One of these studies[6] also found that more dissolved organic matter was lost, in one of two comparisons. One replicated, randomized, controlled study from Spain[9] found more nitrate in runoff from plots with organic fertilizer, compared to inorganic fertilizer. Three replicated, controlled studies (two randomized) from Portugal[7] and Spain[2,5] found that similar amounts of nitrogen were lost from plots with organic or inorganic fertilizer.
- Sediments (0 studies)
- **Implementation options (1 study):** One study from Spain[6] found that less nitrate, but more organic matter, was leached from plots that were fertilized with manure, compared to slurry.

A replicated, randomized, controlled study in 1995–1999 in arable farmland in southern Turkey (1) found more water in soils with organic fertilizer, compared to inorganic fertilizer. **Water availability:** More available water was found in soils with organic fertilizer, compared to inorganic fertilizer (0.14–0.17 vs 0.09 cm^3 water/cm^3 soil). **Methods:** There were three plots (10 x 20 m) for each of three treatments: cattle manure (25 t/ha), compost (25 t/ha), or mineral fertilizer (160 kg N/ha, 26 kg P/ha, 83 kg P/ha). The compost was made of grass, stubble, and leaves. Wheat, sweet peppers, maize, and wheat were grown in rotation. Soils were sampled in 1999, after harvesting the last wheat crop (0–30 cm depth). The difference between water retention capacity at field capacity (–33 kPa) and at permanent wilting point (–1,500 kPa) was used to determine available water content.

A replicated, controlled study in 1998–1999 in an irrigated maize field in Spain (2) found that similar amounts of nitrogen were lost from plots with organic or inorganic fertilizer. **Nutrients:** Similar amounts of nitrogen were lost from plots with organic or inorganic fertilizer added (2.3–2.5 vs 2.5–2.9 g/m^2). **Methods:** Plots (10 × 11 m) had pig slurry (165 kg/ha) or urea (165 kg/ha) (three plots each). Slurry was incorporated into the soil, five days after application, using a rotocultivator (0–5 cm depth). Water samples were taken during the first 15 days after application and every 2 weeks thereafter.

A replicated, randomized, controlled study in 2009 in a rainfed barley field in Spain (3) found similar amounts of water-filled pore space in plots with organic or inorganic fertilizer. **Water availability:** Similar amounts of water-filled pore space were found in plots with organic or inorganic fertilizer (20–60%). **Methods:** Plots (30 m^2) had organic fertilizer (pig slurry, anaerobically-digested pig slurry, municipal solid waste, or composted crop residue with sludge) or inorganic fertilizer (urea), applied in January 2006 (125 kg N/ha; three plots for each fertilizer) and incorporated into the soil using a rotocultivator (0–5 cm depth). Phosphate and potassium (75 and 40 kg/ha, respectively) were added to all plots. Soil samples were taken every 1–2 weeks during crop period and three times during fallow period (0–10 cm depth), but no samples were taken in June–October (the soil was too dry).

A replicated, randomized, controlled study in 2006 in a rainfed almond orchard near Granada, Spain (4), found less water in organically-fertilized soils, compared to inorganically-fertilized soils. **Water availability:** Less water was found in organically-fertilized soils, compared to inorganically-fertilized soils, in one of two comparisons (June: 4.6 vs 5.6 g water/100 g soil). **Methods:** Organic fertilizer (1,500 kg compost/ha, made from sheep manure and turf) or mineral fertilizer (250 kg/ha, 4.6% N, 1.2% P, 1.5% K) was used on 18 plots each (588 m^2). Some organic fertilizer was used on all plots (30 t manure/ha), and one-third of the plots were grazed by sheep (7 kg organic C/ha from excrement). All plots had cover crops. Soil samples were collected on 7 June and 18 July 2006 (0–20 cm depth). It was not clear whether these results were a direct effect of the type or amount of fertilizer.

A replicated, randomized, controlled in 2006–2008 in an irrigated alfalfa field in Spain (5) found that similar amounts of nitrate were lost from plots with organic or inorganic fertilizer. **Nutrients:** Similar amounts of nitrate were lost from plots with organic or inorganic fertilizer (0.2–0.47 mg/L). **Methods:** Lysimeters (5 m^2 and 1.5 m deep) had organic fertilizer (pig slurry: 170 or 340 kg N/ha/year) or inorganic fertilizer (phosphorous-potassium: 200 kg/ha/year; phosphorus pentoxide and potassium oxide: 150 kg/ha/yr). Water samples were collected from lysimeters (100 mL/week).

A replicated, randomized, controlled study in 2007–2009 in an irrigated onion field near Madrid, Spain (6), found that less nitrate, but more organic matter, was leached from plots with organic fertilizer, compared to inorganic fertilizer. **Nutrients:** Less nitrate (1 vs 44 kg/ha), but more dissolved organic carbon (5 vs 3 kg/ha), was leached from plots with organic fertilizer, compared to inorganic fertilizer, in one of two comparisons (manure vs urea). **Implementation options:** More nitrate (31–44 vs 1 kg/ha), but less dissolved organic carbon (3 vs 5 kg/ha), was leached from plots with slurry, compared to manure. **Methods:** Plots (20 m^2) had organic fertilizer (anaerobically digested pig slurry, or hen and goat manure) or inorganic fertilizer (urea), applied in May 2007 and 2008 (110 kg N/ha; three plots for each fertilizer). Fertilizers were immediately incorporated into the soil (10 cm depth), using a rotocultivator. Plots were irrigated 1–2 times/week (608–618 mm/year). Drainage water was collected in ceramic cups (80 cm depth, 40 kPa) thirty times during the experiment.

A replicated, randomized, controlled study in 2006–2008 in a cereal field in the Castelo Branco region, Portugal (7), found that similar amounts of nitrate were leached from soils with organic or inorganic fertilizer. **Nutrients:** Similar amounts of nitrate were leached from soils with organic or inorganic fertilizer (2006–2007: 78–145 kg NO_3-N/ha; 2007–2008: 26–35 kg). **Methods:** Water in the soil was collected in porous ceramic suction cup samplers (four/plot, 0.6–0.7 m depth, 50 kPa for 24 hours), whenever drainage occurred (October–November and April–May; 16 samples in total). There were three plots (5.6 x 8 m) for each of five organic-fertilizer treatments (single application in spring, or split application in spring and autumn, of municipal waste compost or sewage sludge, or split application of cattle slurry) and one mineral-fertilizer treatment. Maize was grown in spring–summer, and oats were grown in autumn–winter.

A replicated, randomized, controlled study in 2010–2013 in a rainfed barley field in Spain (8) found similar amounts of water-filled pore space in plots with organic or inorganic fertilizer. **Water availability:** Similar amounts of water-filled pore space were found in plots with organic or inorganic fertilizer (19–33% vs 16–33%). **Methods:** Plots (inorganic: 50 x 6 m or 40 x 6 m; organic: 40 x 12 m) had inorganic fertilizer (60, 75, 120, or 150 kg N/ha) or organic fertilizer (75 or 150 kg N/ha) (three plots for each). Plots had conventional tillage (mouldboard plough: 25 cm depth; cultivator: 15 cm depth) or no tillage. Soil samples were collected at the end of the experiment (two samples/plot; 0–75 cm depth).

A replicated, randomized, controlled study in 2003–2004 in irrigated arable farmland in Spain (9) found that more nitrate was lost from plots with organic fertilizer, compared to inorganic fertilizer. **Nutrients:** More nitrate was found in runoff from plots with organic fertilizer, compared to inorganic fertilizer, in 12 of 16 comparisons (74–81 vs 3–24 mg/ha). More nitrate was found in leachate from plots with organic fertilizer, compared to inorganic fertilizer, in 14 of 16 comparisons (105–226 vs 10–54 kg/ha). **Methods:** Plots (30 x 40 m) had organic fertilizer (pig slurry: 30, 60, 90, or 120 Mg/ha) or inorganic fertilizer (0, 180, 240, or 300 kg N/ha) (three plots for each). Slurry was immediately covered after application. Lysimeters (2.6 x 2 m; 1.5 m depth), were installed in each plot, five years before the study. Each lysimeter was drip-irrigated, simulating flood irrigation (May to mid-September, with 7–12 intervals). Soil samples were collected after harvest (0–120 cm depth). Water samples were collected after each irrigation or rainfall event in 50 litre containers.

A replicated, randomized, controlled study in 2009–2012 in an irrigated maize-ryegrass field in Italy (10) found less nitrate in runoff from plots with organic fertilizer, compared to inorganic fertilizer. **Nutrients:** Less nitrate was lost in runoff from plots with organic fertilizer, compared to inorganic fertilizer, in one of two comparisons (manure vs inorganic: 42 vs 89 kg N/ha; 8% vs 20%). **Methods:** Plots (12 x 60 m) growing a double-crop rotation of silage maize and Italian ryegrass *Lolium multiflorum* had one of three types of fertilizer: cattle manure, cattle slurry, or inorganic fertilizer (four plots each). Soil samples were taken from each plot (two lysimeters/plot, 10 cm diameter, 50–90 cm depth).

A replicated site comparison in 2009 in rainfed vineyards in southern France (11) found greater water retention in organically-fertilized soils, compared to inorganically-fertilized soils. **Water availability:** Greater water retention was found in organically-fertilized soils, compared to inorganically-fertilized soils, in one of three comparisons (22% vs 14% water content at field capacity, by weight). **Methods:** In 146 plots of three soil types, inorganic fertilizer only (37–69% of plots in each soil type) or at least some organic fertilizer (31–63%) was used for at least five years before soil sampling. Soil samples were collected from the interrows in March–May 2009 (10 homogenized samples/plot, 0–15 cm depth).

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(10) Demurtas, C.E., Seddaiu, G., Ledda, L., Cappai, C., Doro, L., Carletti, A. & Roggero, P.P. (2016) Replacing organic with mineral N fertilization does not reduce nitrate leaching in double crop forage systems under Mediterranean conditions. *Agriculture, Ecosystems and Environment*, 219, 83-92.
(11) Salomé, C., Coll, P., Lardo, E., Metay, A., Villenave, C., Marsden, C., Blanchart, E., Hinsinger, P. & Le Cadre, E. (2016) The soil quality concept as a framework to assess management practices in vulnerable agroecosystems: A case study in Mediterranean vineyards. *Ecological Indicators*, 61, Part 2, 456-465.

4.6. Grow cover crops in arable fields: Water (19 studies)

- **Water use (2 studies):** Of two replicated, randomized, controlled studies from Spain[11,14], one study[14] found that cover crops used more water than bare fallows, and one study[11] found no difference in water use.
- **Water availability (16 studies)**
  - Water content (9 studies): Seven replicated, randomized, controlled studies from the USA[1,3-7,19] found less water in soils with winter cover crops, compared to soils without them, in some comparisons[1,3-5,7,19] or all comparisons[6]. Two replicated, randomized, controlled studies from the USA[9,10] found more water in soils with winter cover crops, compared to soils without them, in some comparisons.
  - Water loss (6 studies): Five controlled studies (four replicated, three randomized) from France[12], Israel[17], Spain[14], and the USA[5,16] found that less water was lost (through drainage, runoff, or evaporation) from plots with cover crops, compared to plots without them, in some comparisons[12,14,16,17] or all comparisons[5]. One replicated, randomized, controlled study from Spain[11] found that more water was lost through drainage from plots with winter cover crops, compared to plots without them, in some comparisons.
  - Water infiltration (3 studies): Of two replicated, controlled studies from the USA[2,15], one[2] found that more water filtered into soils with cover crops, and one[15] found no difference

in infiltration between plots with or without winter cover crops. One controlled study from the USA[16] found that more water percolated deep into the soil in part of a field with a winter cover crop, compared to part with a winter fallow.

- **Pathogens and pesticides (1 study):** One replicated, controlled study from France[13] found that less herbicide was leached from soils with winter cover crops, compared to soils without them.
- **Nutrients (5 studies):** Four replicated, randomized, controlled studies from Spain[11,14] and the USA[3,5] found that less nitrate was leached from soils with winter cover crops, compared to soils without them, in some comparisons[11,14] or all comparisons[3,5]. One controlled study from the USA[16] found that similar amounts of nitrate were leached from part of a field with a winter cover crop and part with a winter fallow. This study[16] also found less ammonium and dissolved carbon, but more phosphorus, in runoff from the part with the winter cover crop, in some comparisons.
- **Sediments (1 study):** One controlled study from the USA[16] found less suspended sediment in runoff from part of a field with a winter cover crop, compared to a winter fallow, in some comparisons.
- **Implementation options (5 studies):** One study from Spain[10] found more water in soils with long-term cover crops, compared to short-term, in some comparisons. Two studies from Spain[14] and the USA[1] found differences in water availability between plots with different cover crops. One study from Spain[11] found differences in nitrate leaching between plots with different cover crops. One replicated, controlled study from the USA[2] found similar infiltration rates under different cover crops.

A replicated, randomized, controlled study in 1986–1988 in an irrigated lettuce field in the Salinas Valley, California, USA (1), found less water in soils with winter cover crops, compared to winter fallows. **Water availability:** Less water was found in soils with cover crops, compared to fallows, in two of five comparisons (75 and 90 cm depth: 14–24 vs 16–20% soil moisture content). **Implementation options:** Less water was found in soils that were cover cropped with *Secale cereale* rye, compared to *Vicia faba* broad beans, in one of five comparisons (90 cm depth: 30% less water). **Methods:** There were six plots (10.7 x 1.1 m raised beds) for each of two winter cover crops (broad beans or rye) and there were six control plots (bare fallow, maintained with herbicide). The cover crops were seeded in November 1986–1987, irrigated until emergence, and chopped, disked, and chisel ploughed in spring (25–30 cm depth). Lettuces were planted in May and July 1987 and March and August 1988, and they were harvested in July and October 1987 and June and October 1988. The lettuces were irrigated (1–2 cm every 2–3 days until emergence, then 2 cm/week). Soil moisture was measured with a hydroprobe at five depths (25, 56, 75, 90, and 106 cm), 13 and 16 weeks after the cover crops were seeded (three measurements/depth).

A replicated, controlled study (years not reported) in a tomato field near Davis, California, USA (2), found that more water filtered into soils with cover crops, compared to bare soils. **Water availability:** More water filtered into soils with cover crops, compared to bare soils (8.0–8.3 vs 7.5 inches in four hours). **Implementation options:** Similar infiltration rates were found under oat-vetch and vetch cover crops (8 vs 8.3 inches in four hours). **Methods:** There were four plots for each of two cover crops (oat-vetch or vetch, planted in winter) and one control (no cover crop). Water infiltration was measured with an infiltrometer in spring, under the tomato crop that followed the cover crops, after three years of cover cropping.

A replicated, randomized, controlled before-and-after study in 1989–1991 in an irrigated lettuce field in Salinas, California, USA (3), found less water, but less nitrate leaching, in soils with cover crops, compared to bare fallows. **Water availability:** At the end of winter, less water was found in soils with winter cover crops, compared to bare fallows, at one of three depths (0–15 cm: 9–10% vs 13% soil moisture content), but similar amounts of water were found earlier in the winter (0–15 cm: 8–13% vs 9–14%), in 1991. **Nutrients:** At the beginning of spring, less nitrate was found in soils with winter cover crops, compared to bare fallows, in some comparisons (all cover crops in 1990: 2–6 vs 18–21 μg NO_3-N/g dry soil; one of two in 1991: 66–79 vs 85–112). After the first rainfall in spring, more nitrate was found in soils with winter cover crops, compared to bare fallows (amounts of nitrate not clearly reported). The inference was that more nitrate was depleted by cover crops over winter, and more nitrate was leached from bare fallows in spring. **Methods:** In 1989–1990, six winter cover crops (*Raphanus sativus* oilseed radish, *Brassica hirta* white senf mustard, *Brassica alba* white mustard, *Lolium multiflorum* annual ryegrass, *Secale cereale* Merced rye, and *Phacelia tanacetifolia*) were grown on three plots each (two 12 m rows/plot), and bare fallows were maintained (with herbicide and hand cultivation) on three plots. In 1990–1991, two winter cover crops (*Secale cereale* Merced rye and *Phacelia tanacetifolia*) were grown on six plots each (two 8 m rows/plot), and bare fallows were maintained on six plots. Cover crops were tilled into the plots (15–20 cm depth in March 1990, depth not reported in February 1991). Lettuce was sown in April 1990–1991. All plots were irrigated and fertilized (56–85 kg N/ha, before sowing lettuce). Soil samples were collected in November 1989–1990, January 1990–1991, February 1991, and March 1990 (0–60 cm depth, 4 cm diameter, two cores/plot), weekly from late March to the end of June 1990 (0–15 cm depth), and every 2–7 days from mid-February to the end of March 1991 (0–15 cm depth).

A replicated, randomized, controlled study in 1991–1992 in an irrigated lettuce field in the Salinas Valley, California, USA (4), found less water in soils with winter cover crops, compared to bare soils. **Water availability:** Less water was found in soils with cover crops, compared to bare soils, in some comparisons (7 and 12 days after cover crops were incorporated into the soil: 7–9% vs 9–11% water; total number of significantly different comparisons not clearly reported). **Methods:** Three plots had winter cover crops (Merced rye *Secale cereale*, sown on 19 December 1991) and three plots had bare soils over winter. The plots (raised beds) were 8 x 4 m each. All plots were disked on 8 April (incorporating the cover crops). Soil samples were collected on 7–9 days between cover-crop incorporation and lettuce harvesting. Lettuce was sown on 8 May and harvested on 8 July 1992.

A replicated, randomized, controlled study in 1992–1993 in an irrigated broccoli field in the Salinas Valley, California, USA (5), found that less nitrate was leached from soils with winter cover crops, compared to bare soils, but cover crops had inconsistent effects on water availability. **Water availability:** Less water was found in soils with cover crops, compared to bare soils, in two of 16 comparisons (in March: 6–7% vs 8% soil moisture). Less water was lost through drainage from soils with cover crops, compared to bare soils (3.6–3.9 vs 6 mm/cm^2). **Nutrients:** Less nitrate was leached from soils with cover crops, compared to bare soils (measured with ion-exchange resin bags or estimated from soil nitrate concentrations and drainage volumes: 7–9 vs 24–28 g NO_3-N/m^2; measured with suction samplers: 155 vs 281 g NO_3-N/m^2). **Methods:** There were three plots for winter cover crops (half *Phacelia tanacetifolia* and half *Secale cereale* Merced rye, sown in November 1992 and mown in March 1993) and three control plots with bare soil in winter. All plots (252 x 24 m) were tilled in March 1993 (15 cm depth), and the cover crops were incorporated into the soil. Two broccoli crops were grown on raised beds (first crop: April–August 1993; second crop: August–November 1993). All plots were irrigated (440–450 mm/crop, subsurface drip irrigation) and fertilized (41–42 g N/m^2/crop). Soil samples were collected 16 times in November 1992–August 1993, including nine samples in March–April, when the cover crops were incorporated (0–75 cm depth, 6 cm diameter, four cores/plot). Leaching was measured with buried ion-exchange resin bags (60 cm depth, 10 g resin, excavated in March 1993) and suction samplers (60 cm depth, measured weekly in December 1992–March 1993).

A replicated, randomized, controlled study in 1994 in an irrigated wheat field in the Sacramento Valley, California, USA (6), found less water in soils with winter cover crops, compared to fallows. **Water availability:** Less water was found in soils with cover crops, compared to fallows (1.2–3.0 cm less water, 0.16–0.25 vs 0.20–0.35 m^3 water/m^3 soil, 0–90 cm depth). **Methods:** Legumes were grown as winter cover crops in some subplots, and other subplots were fallows (the number and size of the subplots was not clearly reported, but the main plots were 64 x 64 m). Half of the main plots were irrigated. In the wheat-growing season, half of the subplots were fertilized, but the cover crops and fallows were not fertilized. Soil samples were collected in August 1994 (0–90 cm depth), and water content was calculated by drying and weighing the soil (assuming a bulk density of 1.68 g/cm^3).

A replicated, randomized, controlled study in 1991–1994 in an irrigated tomato field in the San Joaquin Valley, California, USA (7), found less water in soils with winter cover crops, compared to winter fallows. **Water availability:** Less water was found in soils with cover crops, compared to fallows, in some comparisons (e.g., about 150 days after planting the cover crops: 4.3–9.9 cm increase in soil water content vs 6.8 mm decrease to 4.0 mm increase in soil water content, 0–210 cm depth; number of significantly different comparisons not clearly reported). **Methods:** There were four plots (93 x 7 m) for each of three treatments, and there were four control plots (winter fallow). The treatments were *Hordeum vulgare* barley, *Vicia dasycarpa* Lana woollypod vetch, or barley and vetch as winter cover crops, planted in October 1991–1993 and incorporated into the soil in March 1992–1994. Soil water content was measured about every two weeks after the cover crops were planted (hydroprobe, six samples/plot, 15, 30, 60, 90, 120, 150, 180, and 210 cm depths).

A replicated, controlled study in 1996–1998 in an irrigated tomato field in the San Joaquin Valley, California, USA (8), found that winter cover crops had inconsistent effects on water availability. **Water availability:** In the tomato-growing season, more water was found in plots with winter cover crops (and no tillage in spring), compared to plots with bare soil in winter (and tillage in spring), in some comparisons (when irrigated; data not clearly reported). However, in in winter and spring, less water was found in plots with cover crops, in some comparisons. **Methods:** There were 12 plots (4.5 x 27.5 m plots) for each of two treatments (two grass-legume mixtures as winter cover crops, sown in October 1996–1997, killed and retained as mulch, with no tillage, in March 1997–1998) and there were 12 control plots (bare-soil fallows in winter, with herbicide, and conventional tillage in spring). Soil water was measured throughout the year with hydroprobes (0–6 feet depth until autumn 1997, then 0–7 feet depth). It was not clear whether these results were a direct effect of cover crops or tillage.

A replicated, randomized, controlled study in 1998–2000 in an irrigated vegetable field in the Salinas Valley, California, USA (9), found more water in soils with cover crops, compared to soils without cover crops, in six of 12 comparisons. **Water availability:** More water was found in soils with cover crops, compared to soils without cover crops, in six of 12 comparisons (0.10–0.27 vs 0.07–0.26 g water/g soil; 0–15 cm depth). **Methods:** There were four plots (0.52 ha), for each of four treatments (reduced tillage or conventional tillage, with or without added organic matter). In plots with added organic matter, compost was added two times/year, and a cover crop (Merced rye) was grown every autumn or winter. Lettuce or broccoli were grown on raised beds. Sprinklers and drip irrigation were used in all plots. Soils were disturbed to different depths (conventional tillage: disking to 50 cm depth, cultivating, sub-soiling, bed re-making, and bed-shaping; reduced tillage: cultivating to 20 cm depth, rolling, and bed-shaping). Soils were collected, along the planting line, with 6 cm soil cores. It was not clear whether these results were a direct effect of adding compost or growing cover crops.

A replicated, randomized, controlled study in 2001–2004 in an irrigated maize field in southwest Spain (10) found more water in soils with winter cover crops, compared to soils without winter cover crops. **Water availability:** More water was found in soils with short-term cover crops, compared to soils without cover crops, in one of nine comparisons (5–10 cm depth, in 2002: 0.33 vs 0.24 cm^3 water/cm^3 soil), and more water was also found in soils with long-term cover crops, compared to soils without cover crops, in five of nine comparisons (0.31–0.38 vs 0.24–0.30). **Implementation options:** More water was found in soils with long-term cover crops, compared to short-term cover crops, in six of nine comparisons (0.31–0.38 vs 0.25–0.30 cm^3 water/cm^3 soil). **Methods:** Cover crops (*Avena strigosa* lopsided oats) were sown on eight plots in September 2001–2003. Four of these plots had winter cover crops for six years before this (long-term cover crops), and four plots did not (short-term cover crops). Four other plots did not have winter cover crops from 2001–2004 or before. All plots were 20 x 10 m and were not tilled after 2001. Cover crops were suppressed with herbicide in April 2002–2004.

A replicated, randomized, controlled study in 2006–2008 in an irrigated maize field in the Ebro river valley, Spain (11), found that less nitrate was leached from soils with winter cover crops, compared to bare soils, but more water was lost through drainage. **Water use:** Similar amounts of water were used in plots with cover crops or bare soils (130–200 mm estimated evapotranspiration in the cover-cropping season). **Water availability:** More water was lost tz`hrough drainage from plots with cover crops, compared to bare soils, in three of 10 comparisons (during the cover-cropping season: 4–7 vs 0–3 mm). **Nutrients:** Less nitrate was leached from soils with cover crops, compared to bare soils, in four of nine comparisons (during the maize-growing season: 2 vs 7–10 mg NO_3-N/litre; 4–5 vs 23–27 kg NO_3-N/ha). **Implementation options:** Less nitrate was leached from soils that were cover cropped with barley or winter rape, compared to common vetch, in two of three comparisons (during the maize-growing season: 2 vs 10 mg NO_3-N/litre). Less water was lost through drainage from plots that were cover cropped with barley or winter rape, compared to common vetch, in two of four comparisons (during the cover-cropping season: 0–1 vs 7 mm). **Methods:** There were three plots (5.2 m^2) for each of three winter cover crops (*Hordeum vulgare* barley, *Brassica rapa* winter rape, or *Vicia sativa* common vetch, sown in October 2006–2007), and there were three control plots with bare soil in winter. Similar amounts of nitrogen were added to all plots (300 kg N/ha), but less of it came from mineral fertilizer in plots with cover crops, to compensate for the organic nitrogen that was added to these plots when the cover crop residues were tilled into the soil. All plots were tilled in spring (March 2007–2008) and autumn (October 2006–2007). All plots were irrigated twice/week (drip irrigation, based on evapotranspiration). Maize was planted in April and harvested in October 2007–2008. Soil samples were collected before the cover crops were incorporated and after the maize was harvested (two soil cores/plot, 5 cm diameter, 0–120 cm depth). Drainage volume and nitrate leaching was measured every week (lysimeters, 5.2 m^2 surface area, 1.5 m depth, 50 litre tank).

A replicated, controlled study in 2004–2008 in an irrigated maize field in the Garonne River corridor, southern France (12) (same study as (13)), found that less water was lost through drainage from soils with winter cover crops, compared to bare soils. **Water availability:** Less water was lost through drainage from soils with winter cover crops, compared to bare soils, on 21 of 67 sampling dates (drainage volumes not reported for significant comparisons). **Methods:** Winter cover crops (2006–2007: white mustard; 2004–2006 and 2007–2008: oats) were grown on six plots, and bare soil was maintained in six plots. The plots were 20 x 50 m. Maize was sown in April–May 2005–2008 and harvested in October 2005–2008. Drainage from soils was measured with fiberglass-wick lysimeters (40 cm depth, two lysimeters/plot), on 67 sampling dates. A centre-pivot sprinkler was used for irrigation (857–943 mm water/year, irrigation plus rainfall).

A replicated, controlled study in 2004–2008 in an irrigated maize field in the Garonne River corridor, in southern France (13) (same study as (12)), found that less herbicide was leached from plots with winter cover crops, compared to plots with bare soil. **Pathogens and pesticides:** Less herbicide was leached from plots with winter cover crops, compared to plots with bare soil (9% vs 16% of applied herbicide). **Methods:** Winter cover crops (2006–2007: white mustard; 2004–2006 and 2007–2008: oats) were grown on two plots, and bare soil was maintained in two plots. The plots were 20 x 50 m. The herbicide (75 g/L Isoxaflutole) was sprayed 1–3 days after the maize was sown, in April–May 2005–2008. Herbicide leaching was measured in drainage water, with fiberglass-wick lysimeters (40 cm depth, two lysimeters/plot, 11–21 samples/year, 6–272 days after treatment with herbicide). A centre-pivot sprinkler was used for irrigation (650–736 mm water/year, irrigation plus rainfall).

A replicated, randomized, controlled study in 2006–2009 in an irrigated maize field in the Tajo river basin, near Madrid, Spain (14), found that less nitrate was leached from soils with winter cover crops, compared to fallows. More water was used by cover crops, compared to fallows, but less water was lost through drainage and evaporation. **Water use:** More water was used by cover crops, compared to fallows (transpiration: 31–117 vs 0 mm). **Water availability:** Less water was lost through drainage from plots with cover crops, compared to fallows, in six of eight comparisons (47–301 vs 106–314 mm), and less water was lost through evaporation, in all comparisons (31–79 vs 51–101 mm). Similar amounts of water were lost as runoff from plots with cover crops or fallows (data not reported). **Nutrients:** Less nitrate was leached from soils with cover crops, compared to fallows, in five of eight comparisons during the cover-cropping seasons (13–36 vs 45–147 kg $N\text{-}NO_3$/ha), and two of six comparisons during the maize-growing seasons (12–30 vs 42). **Implementation options:** Less nitrate was leached from soils that were cover cropped with barley, compared to vetch (129 vs 245 kg $N\text{-}NO_3$/ha cumulative, in 2006–2009). Less water was lost through drainage from plots that were cover cropped with barley, compared to vetch, in two of four comparisons (47–234 vs 60–301 mm), but barley used more water than vetch, in three of four comparisons (transpiration: 63–117 vs 31–108 mm). Less water was lost through evaporation from plots that were cover cropped with barley, compared to vetch, in one of four comparisons (60 vs 79 mm). **Methods:** There were four plots (12 x 12 m plots) for each of two treatments (barley or vetch, as winter cover crops) and there were four control plots (fallow). Cover crops were sown in October 2006–2009 and maize was sown in April 2007–2009. The maize was irrigated (sprinklers) and fertilized (210 kg N/ha, split into two applications, 120 kg P/ha, and 120 kg K/ha). Soil water content was measured every hour with capacitance probes

(10–130 cm depth, three probes/plot, after the cover crops and after the harvest), and nitrate in soil water was measured with ceramic suction cups (buried at 122–124 cm depth, 1 μm pore size). Water balance and nitrate leaching were calculated using the WAVE model.

A replicated, controlled study in 2007–2008 in an irrigated tomato field in Davis, California, USA (15), found similar rates of water infiltration into soils with winter cover crops or fallows. **Water availability:** Similar rates of water infiltration were found in soils with cover crops or fallows (6.7–7.6 vs 6.3–7.1 litres/foot/90 minutes). **Methods:** Conventional tillage or reduced tillage was used on four plots each (90 x 220 feet). Broadcast disking, subsoiling, land planing, and rebedding were used for conventional tillage. A Wilcox Performer was used for reduced tillage (two passes; beds were conserved). Winter cover crops (triticale) were grown on half of each plot, and the other half was fallow in winter. Sprinklers, furrow irrigation, and drip-tape (in furrows) were used to irrigate the tomatoes. All plots were fertilized. Water infiltration was measured in 2008 (using the blocked furrow method).

A controlled study in 2005–2006 in an irrigated tomato field in the Sacramento Valley, California, USA (16), found more phosphorus, but less ammonium, dissolved organic carbon, and sediment, in runoff from the part of the field that was cover cropped, compared to the part that was fallow. **Water availability:** Similar amounts of irrigation water were lost through discharge from each part of the field (42% vs 25%). Overall, less water was lost from the cover-cropped part, compared to the fallow part (44% less), and more water percolated deeply into the cover-cropped part (27% vs 15%), but it was not clear whether these differences were statistically significant. **Nutrients:** Similar amounts of nitrate were leached from each part of the field (measured in resin bags: 2.47 kg/ha). Higher phosphorus concentrations were found in runoff from the cover-cropped part of the field, compared to the fallow part, in one of two comparisons (in winter: 0.4 vs 0.2 mg dissolved reactive P/litre), but no differences were found in nitrogen or dissolved organic carbon concentrations (in winter: 0.1 mg NO_3-N/litre; 0.1 mg NH_4-N/litre; 5.8–7.4 mg C/litre; in summer: 1.6–2.2 mg NO_3-N/litre; 0.1–0.2 mg NH_4-N/litre; 3.3–3.9 mg C/litre). Lower loads (amounts/ha/irrigation or rainfall event) of ammonium and dissolved organic carbon were found in runoff from the cover-cropped part, compared to the fallow part (5.6 vs 8.3 g NH_4-N/ha/event; 0.3 vs 0.7 kg C/ha/event), but no differences were found in nitrate or phosphorus loads (in winter: 0.1 kg NO_3-N/ha/event; 20–22 g dissolved reactive P/ha/event; in summer: 0.4–0.9 kg NO_3-N/ha/event; 61–118 g dissolved reactive P/ha/event). **Sediments:** Less sediment was found in runoff from the cover-cropped part of a field, compared to the fallow part, in two of four comparisons (concentrations, in winter: 0.1 vs 0.7 g total suspended solids/litre; loads, in winter: 0.9 vs 5 kg/ha/event). **Methods:** A field was divided into two parts: one part with a winter cover crop (mustard *Brassica nigra*, planted in autumn 2005, and disked into the soil in spring 2006), and one part fallow. Tomatoes were planted in both parts of the field in spring 2006. Runoff water was collected in autosamplers (250 mL samples, every four hours, if there was >5 cm of water in the flow meter). Cumulative nitrate leaching from the soil was measured with anion exchange resin bags (buried at 75 cm depth).

A replicated, randomized, controlled study in 2011–2014 in irrigated potato fields in Israel (17) found less runoff from plots with cover crops, compared to bare soil. **Water availability:** No runoff was measured in some plots with cover crops, but up to 1.5 litres of runoff/second were measured in plots with bare soil (in 2011; no statistical comparisons were made for any years). **Methods:** Different plots were used in different years (2011–2012: 350 m^2 plots, 20 plots with cover crops, eight plots without cover crops; 2012–2013: 695 m^2 plots, 10 with, 10 without; 2013–2014: 1,800 m^2 plots, four with, four without). Different mixtures of cover crops were used in different years, but oats were used in all years, and triticale was used in Years 1 and 2 (2011–2013). Plots without cover crops were weeded (tilled bare; some plots in all years) or weedy (not tilled; some plots in Year 1). Herbicide and fertilizer were used on all plots. Water was measured in runoff channels, after each rainfall event (one HS flume/plot). Plots had a 5–7% slope.

A replicated, randomized, controlled study in 2011–2013 in two irrigated tomato fields in central Italy (18) found that winter cover crops had inconsistent effects on water availability. **Water availability:** More water was found in plots with winter cover crops (mulched in the spring), compared to control plots, in some comparisons in July–August (data on soil water content not clearly reported), but inconsistent differences in soil water content were found in May–June (sometimes more, sometimes less). **Methods:** Three species of winter cover crops (*Vicia villosa* hairy vetch, *Phacelia tanacetifolia* lacy phacelia, or *Sinapis alba* white mustard) were sown on three plots each, in September, and winter weeds were controlled with herbicide on three control plots (18 x 6 m plots). The cover crops were mown and mulched (strips, 80 cm width) in May, and the control plots were tilled (depth not reported). Tomato seedlings were transplanted in May (transplanted into the) and harvested in August. All plots were tilled (30 cm depth) and fertilized (100 kg P_2O_5/ha, harrowed to 10 cm depth) in September. Some plots were also fertilized (100 kg N/ha) in June–July. Plots were irrigated to replace 50–100% of water lost through evapotranspiration. Soil water content (soil moisture meter, 20 cm depth) was measured weekly, or within 48 hours of rainfall, in the tomato-growing season. It was not clear whether these results were a direct effect of cover cropping, mulching, herbicide, or tillage.

A replicated, randomized, controlled study in 2012–2014 in a mostly rainfed field in the Central Valley, California, USA (19), found less water in soils with winter cover crops, compared to winter fallows. **Water availability:** Over the winter, less water was found in soils with cover crops, compared to fallows, in some comparisons (2013: 5.3 cm less water; 2014: 0.67 less; number of comparisons not clearly reported). This was because water was lost from soils with cover crops, but gained in soils with fallows. **Methods:** There were three plots for each of three cover crops (legumes: 45% *Vicia faba*, 35% *Pisum sativum*, and 20% *V. sativa*; legumes and triticale: 40% *P. sativum*, 30% *V. sativa*, and 30% *Tritocosecale*; or brassica: 45% *Brassica juncea*, 40% *Sinapsis alba*, and 15% *Raphanus sativus*) and there were three fallow plots (kept bare with herbicide). Each plot was 10 x 30 m. All plots were irrigated only to establish the cover crop (10 cm/year). Plots with cover crops were fertilized (112 kg N/ha) and seeds were sown in November. Water content was measured twice/week in January–March (0–90 cm depth).

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4.7. Plant or maintain ground cover in orchards or vineyards: Water (21 studies)

- **Water use (3 studies):** Two replicated, controlled studies (one randomized) from the USA[1,3] found that plants used more water in plots with ground cover, compared to plots with bare soil. One replicated, randomized, controlled study from Portugal[8] found inconsistent differences in water use (sometimes less, sometimes more) between plots with ground cover and plots with tilled soil.
  - **Implementation options (2 studies):** Two studies from Portugal and the USA[8,21] found that plants used similar amounts of water in plots with different types of ground cover.
- **Water availability (17 studies)**

- Water content (13 studies): Four studies (three replicated, randomized, and controlled; one site comparison) from Spain[16] and the USA[6,9,10] found less water[10,16], or less available water in some comparisons[6,9], in soils with seeded cover crops, compared to tilled soils. Two replicated, randomized, controlled studies from Portugal and the USA[11,15] found more water[11], or more available water[15], in soils with ground cover, compared to tilled soils, in some comparisons. Two replicated, randomized, controlled studies from France[5] and the USA[12] found inconsistent differences in water content (sometimes less, sometimes more) in soils with seeded cover crops, compared to bare or tilled soils. Three replicated studies (two randomized and controlled, one site comparison) from Chile[18], France[20], and Portugal[15] found similar amounts of water in soils with or without ground cover. Three replicated, controlled studies (two randomized) from Chile[18] and the USA[2,3] found greater water infiltration or soil porosity in plots with seeded cover crops, compared to bare soil, but one replicated, controlled study from France[13] did not.
- Water loss (7 studies): Six replicated, controlled studies (five randomized) from Chile[18], France[13], Italy[17], Spain[4,14], and the USA[10] found that less water was lost as runoff from plots with seeded cover crops, compared to bare or tilled plots, in some comparisons[14] or all comparisons[4,10,13,17,18]. One replicated, randomized, controlled study from Spain[19] found inconsistent differences in runoff between plots with ground cover and plots with tilled soil.
- **Implementation options (5 studies):** Three studies from vineyards in the USA[6,7,10] found different amounts of water in soils with different types of ground cover, but two studies from Portugal[15] and the USA[21] did not.

- Pathogens and pesticides (0 studies)
- **Nutrients (2 studies):** One replicated, randomized, controlled study from Chile[18] found less nitrogen, phosphorus, and dissolved organic carbon in runoff from plots with seeded cover crops, compared to plots with bare soil. One replicated, randomized, controlled study from the USA[10] found similar amounts of nitrate, nitrogen, and phosphorus in runoff from plots with seeded cover crops, compared to bare soils.
- **Sediments (4 studies):** Three replicated, randomized, controlled studies from Chile[18], Spain[19], and the USA[10] found less sediment in runoff from plots with ground cover, compared to bare or tilled soil, in some comparisons[10,19] or all comparisons[18]. One replicated, controlled study from France[13] found similar amounts of sediment in runoff from plots with seeded cover crops or bare soil.

A replicated, controlled study in 1984–1986 in two irrigated almond orchards in California, USA (1), found higher water use in plots with ground cover, compared to plots without ground cover. **Water use:** Higher water use was found in plots with ground cover, compared to control plots, in 10 of 12 comparisons (16–41 vs 14–32 inches of seasonal water use). **Implementation options:** Lower water use was found in plots with bromegrass, compared to clover or resident vegetation, in one of two orchards (27–32 vs 31–41 inches of seasonal water use). **Methods:** In two orchards (one newly planted, and one mature), plots with and without ground cover were compared (number and size of plots not reported). Bromegrass, clover, or resident vegetation were grown as ground cover, and herbicide was used in control plots. Water use (change in water content between irrigations) was measured with neutron probes (9–120 inches depth, five measurements/tree/plot on about 17 days during the growing season: 1984 and 1986 in the new orchard, and 1985–1986 in the mature orchard).

A replicated, controlled study (years not reported) in an almond orchard in the Central Valley, California, USA (2), found that more water filtered into soils with ground cover, compared to bare soils. **Water availability:** More water filtered into soils with ground cover, compared to bare soils (2.2–2.6 vs 1.3 inches in four hours). **Methods:** There were four plots for each of three ground covers (Blando bromegrass, native vegetation, or strawberry clover) and one control (bare soil). Water infiltration was measured under the ground cover and the controls, after five years.

A replicated, randomized, controlled study in 1989–1990 in an irrigated vineyard in the San Joaquin Valley, California, USA (3), found that grape vines used similar amounts of water in plots with or without cover crops between the vine rows, but more water was used in total, and more water filtered into the soil, in plots with cover crops between the vine rows. **Water use:** Grape vines used similar amounts of water in plots with or without cover crops between the vine rows (soil water depletion within the rows: 427–531 mm, 0–180 cm depth), but more water was used in total in plots with cover crops, in one of two comparisons (plots with winter and summer cover crops: 511 vs 351 mm water/year, 0–180 cm depth). **Water availability:** More water filtered into the soil in plots with cover crops (cumulative infiltration after eight hours of opportunity time/irrigation event: 106–182 vs 69–74 mm/year). **Methods:** There were three plots (one vine row and two interrows, 183 m length) for each of two cover crops (*Bromus mollis* bromegrass as a winter cover crop, treated with herbicide and mulched in summer, or followed by resident vegetation as a summer cover crop), and there were three control plots (bare soil, maintained with herbicide throughout the year). The bromegrass was seeded in January and December 1989 (and reseeded in March 1989 because of poor establishment). All plots were furrow irrigated until the water had advanced to the end of the furrow (five times in March–September 1989–1990), and thus more water was given to plots with faster infiltration (plots with cover crops). Soil water was measured with a hydroprobe (23–180 cm depth, two samples/row and two samples/interrow in each plot, before irrigation and 3–5 days after irrigation). Infiltration was calculated from water advance times along the furrow.

A replicated, randomized, controlled study in 2000–2003 in a rainfed olive orchard near Cordoba, Spain (4) (partly the same study as (14)), found less runoff from plots with cover crops, compared to bare fallows or conventional tillage. **Water availability:** Less water was lost as runoff from plots with cover crops (2.5% of rainfall; 1.3 m^3), compared to conventional tillage (7.4% of rainfall; 3.8 m^3) or no tillage (21.5% of rainfall; 10.6 m^3). **Methods:** There were three plots (6 x 12 m plots, with two olive trees each, on a 13% slope) for each of three treatments: cover crops (2 x 12 m barley strips, sown in October), conventional tillage (15 cm depth, 3–4 passes from September), or no tillage (with herbicide, weed-free). Plots with cover crops were tilled before the barley was sown (10 cm depth). Runoff was collected with tipping-bucket gauges, and sediment was collected in barrels, from autumn 2000.

A replicated, randomized, controlled study in 1998–2002 in a rainfed vineyard in southern France (5) found that planting grass between the vine rows had inconsistent effects on water availability. **Water availability:** More water was found in the soil, in plots with grass between the vine rows, compared to bare soil between the vine rows, in eight of 40 comparisons (0.19–0.33 vs 0.14–0.25 m^3 water/m^3 soil), but less water was found in one of 40 comparisons (0.22 vs 0.27). **Methods:** In 1998, grass seeds (*Festuca arudinacea* tall fescue) were sown between the vine rows in four treatment plots, and herbicide was used to control weeds between the vine rows in four control plots (12 x 15 m plots). The grass was mown three times/year, in the summer. Water was measured every three weeks, in mid-March–August 2002, in soil cores (0–150 cm depth; two cores/plot: one under the vines, one between the vines).

A replicated, randomized, controlled study in 1996–2000 in an irrigated vineyard in the Sacramento Valley, California, USA (6), found that less water was available to grape leaves in plots with cover crops, compared to bare soil, between the vine rows. **Water availability:** Less water was available to grape leaves in plots with cover crops, compared to bare soil, between the vine rows, in three of 16 comparisons (midday water potential: –1.22 to –0.91 vs –1.11 to –0.82). **Implementation options:** More water was available to grape leaves in plots that were cover cropped with barley and oats, compared to other cover crops, in three of 12 comparisons (midday water potential: –1.08 to –0.82 vs –1.22 to –0.91). **Methods:** There were four plots for each of four cover crops (1.8 m width, between vine rows of 3.4 m width), and there were four control plots (periodically disked between the vine rows). Each plot was 10 contiguous vines and two adjacent interrows. The cover crops were Californian native grasses (not tilled, mown), annual clover (not tilled, mown), barley and oats (mown and disked), or legumes and barley (mown and disked in spring and used as a green manure). The Californian native grasses were seeded between the vine rows in autumn 1996. The others were seeded in autumn 1997–1999. All plots were drip irrigated, fertigated (20 kg N/ha/year), and the grass cover crops were also fertilized with urea (45 kg N/ha/year). Herbicide was used under the vines. Midday water potential was measured before irrigation in June and July 1998, May 1999, and June 2000 (pump-up pressure chamber, three leaves/plot).

A study in 1998–2002 in an irrigated vineyard in the Sacramento Valley, California, USA (7), found more water in soil that was cover cropped with legumes, compared to grasses, in summer, but found less water in winter. **Implementation options:** More water was found in soil that was cover cropped with legumes, compared to grasses, in the dry season (13% vs 6% water content), but less water was found in the wet season, after a flood (28% vs 33%). **Methods:** A leguminous cover crop (*Trifolium fragiferum* perennial strawberry clover) was planted in the southern half of the vineyard, and three native Californian, perennial, summer-dormant grasses (*Elymus glaucus* blue wildrye, *Hordeum brachyantherum* meadow barley, and *Bromus carinatus* California brome) were planted in the northern half. These cover crops were planted between every other vine row. They were mown 4–5 times/year and their residues were retained. The vineyard was fertigated with drip lines. Soil samples were collected in five sub-plots, in one 10 x 15 m plot, in each cover crop (0–10 cm depth, 3 cm diameter, nine times in July 2001–October 2002).

A replicated, randomized, controlled study in 2002–2004 in a rainfed vineyard in central Portugal (8) found similar amounts of water use in plots with or without cover crops between the vine rows. **Water use:** Similar amounts of water were used by vines and other vegetation in plots with or without cover crops (226–383 vs 222–357 mm/year). More water was used in plots with cover crops in one of three time-periods (budbreak–bloom: 2.1–3.3 vs 1.6–2.9 mm/day), but less was used in one of three time-periods, in one of two years (veraison–harvest: 0.83–0.89 vs 1.2 mm/day). **Implementation options:** Similar amounts of water were used by vines and other vegetation in plots with different types of cover crops (resident vegetation or sown grasses and legumes) between the vine rows (226–372 vs 241–383 mm/year). **Methods:** There were four plots for each of two cover-cropping treatments (resident vegetation or sown cover crops, both without tillage between the vine rows), and there were four control plots (with tillage between the vine rows; depth not reported). The plots were four vine rows each (100 vines/row). The sown cover crops were 60% grasses (*Lolium* and *Festuca* spp.) and 40% legumes (*Trifolium* spp.), sown in March 2002. The interrows of all plots were mown (treatments: twice/year, in February and May–June; controls: once/year, in February, height not reported). All plots were fertilized, and herbicide was used under the vines. Soil water content was measured between budbreak (early February) and harvest (capacitance probes, 10–100 cm depth, three samples/plot). Water use was estimated from water content and rainfall.

A replicated, randomized, controlled study in 2003–2005 in an irrigated vineyard in Lake County, California, USA (9), found that less water was available in plots with cover crops, compared to tilled soil, between the vine rows. **Water availability:** Less water was available in plots with cover crops, compared to tilled soil, in some comparisons, in one of two years (maximum difference in leaf water potential in 2004: –1.27 vs –0.93 mPa). **Methods:** There were 12–22 plots (20 feet length) with cover crops (5 feet width, seeded in October 2003, each with a different species) between the vine rows (8 feet width) and 12–22 plots with tilled soil between the vine rows (2004: 22 plots; 2005: 12 plots). Leaf water potential was measured once or twice a week (11 am–1 pm, pressure bomb, one vine/plot, June–July 2004 and July–August 2005). All plots were drip irrigated (weekly for 10–12 weeks from July, 40–48 gallons/vine/year).

A replicated, randomized, controlled study in 2000–2005 in an irrigated vineyard in the Salinas Valley, California, USA (10), found less water in soils with cover crops compared to bare soils, but also found that less water was lost as runoff, and runoff water had less sediment, in plots with cover crops. **Water availability:** In winter, less water was lost as runoff from plots with cover crops, compared to bare soils (38–96 vs 177 gallons/plot). However, less water was found in plots with cover crops, compared to bare soils, in one of two comparisons (in plots that were cover cropped with rye: 21.5% vs 23.5% soil moisture in mid-February 2003, for example, when measured between vine rows; number of significantly different comparisons not clearly reported). In the growing season, less water was found in soils with cover crops, compared to bare soils (in all years, when measured between vine rows: 17% vs 15% soil moisture in mid-May 2004, for example; or, in two of three years, when measured in vine rows: 19% vs 18% in mid-July 2004, for example; number of significantly different comparisons not clearly reported). **Nutrients:** In winter, similar amounts of nutrients were found in runoff from plots with cover crops or bare soils (nitrate: 1.2–2 vs 1.7 ppm; total nitrogen: 4.5–6.4 vs 5.6 ppm; total phosphorus: 1.6–2.5 vs 2.6 ppm). **Sediments:** In winter, less sediment was found in runoff from plots with cover crops, compared to bare soils, in one of two comparisons (with triticale as the cover crop: 508 vs 1,735 mg/litre). **Implementation options:** In winter, more water was found in plots that were cover cropped with triticale, compared to rye (23% vs 21.5% soil moisture, for example, in mid-February 2003; number of significantly different comparisons not clearly reported). **Methods:** There were nine plots for each of two treatments and one control. The treatments were triticale (X *Triticosecale*) or *Secale cereale* Merced rye, planted in November 2000–2004 as cover crops (32 inches width) between the vine rows (8 feet width), mown in spring, and disked into the soil in the following November. Bare soils were maintained in the controls through disking in spring and summer (depth not reported). Each plot had 100 vines and the adjacent areas between the vine rows. All plots were drip-irrigated in April–October. Runoff was measured with sumps (16 inches diameter, 5 feet depth) at the lower end of each plot. Soil moisture was measured with a neutron probe (3.5 feet depth). It was not clear whether these results were a direct effect of cover crops or tillage.

A replicated, randomized, controlled study in 2001–2006 in a vineyard in the Central Coast, California, USA (11) (same study as (12)), found more water in soils with cover crops between the vine rows, compared to tilled soils without cover crops. **Water availability:** More water was found in soils with cover crops, compared to tilled soils, in some comparisons (e.g., in spring: 19–21% vs 17% water), but similar amounts of water were found in most comparisons. **Methods:** There were six plots (84.3 x 2.4 m interrows between vines) for each of two cover crops, and there were six control plots (cultivated every two months to control weeds). The cover crops (1.8 m width) were *Triticale* x *Triticosecale* Trios or *Secale cereale* rye, seeded in November 2001–2005 (interrows disked before seeding), and mown in April 2002–2006. Soil samples were collected every 2–3 weeks in December 2005–November 2006 (19 samples/plot, two cores/sample, 0–15 cm depth).

A replicated, randomized, controlled study in 2001–2006 in an irrigated vineyard in the Central Coast, California, USA (12) (same study as (11)), found that cover crops had inconsistent effects on soil water content. **Water availability:** More water was found in soils with cover crops, compared to tilled soils, in some comparisons (in early spring: 20–21% vs 17% water), but less water was found in other comparisons (in late spring: vs 8–10% vs 12–14%). **Methods:** There were six plots for each of two cover crops (*Secale cereale* rye or *Triticale x Triosecale* Trios, sown between the vine rows in autumn, mown in spring), and there were six control plots (tilled between the vine rows every two months; depth not reported). All plots were tilled in autumn. The plots were each 84 x 1.8 m, between two vine rows. Soil samples were collected every 2–3 weeks in November 2005–2006 (two samples/plot, 0–15 cm depth).

A replicated, controlled study in 1999 in a vineyard in southern France (13) found less runoff from plots with grass, compared to bare soil, between the vine rows. **Water availability:** Less water was lost as runoff from plots with grass between the vine rows (17–45 vs 26–60 mm runoff/100 mm simulated rainfall). Similar amounts of water infiltration were found in plots with grass or bare soil between the vine rows (9 vs 10 mm). **Sediments:** Similar amounts of sediment were found in runoff from plots with grass or bare soil between the vine rows (2.7–4.9 vs 3.8–5.7 g soil/litre water). **Methods:** One interrow was cultivated (10 cm depth) and planted with grasses (without herbicide), and another interrow was chemically weeded (with herbicide: conventional management), for four months each. Rainfall was simulated in three plots (1 x 1 m plots) in each interrow (1 x 1 m plots, 60 mm water/hour, for 60 minutes). Soil samples were collected in each plot (200 observation points/m^2; 5 topsoil samples/plot, 0–5 cm depth).

A replicated, randomized, controlled study in 2000–2006 in a rainfed olive orchard near Cordoba, Spain (14) (partly the same study as (4)), found less runoff from plots with cover crops, compared to bare fallows or conventional tillage. **Water availability:** Less water was lost as runoff from plots with cover crops, compared to bare fallows, in six of seven years (0.1–6% vs 3–36% of rainfall), and compared to conventional tillage, in three of seven years (0.1–0.2% vs 0.5–2.1%). **Methods:** There were three plots (6 x 12 m plots, with two olive trees each, on a 13% slope) for each of three treatments: cover crops (2 x 12 m barley strips, sown in October), conventional tillage (15 cm depth, 3–4 passes from September), or no tillage (with herbicide, bare fallows). Plots with cover crops were tilled before the barley was sown (10 cm depth). Runoff was collected with tipping-bucket gauges, and sediment was collected in barrels, from autumn 2000.

A replicated, randomized, controlled study in 2001–2006 in a chestnut orchard in northeast Portugal (15) found that more water was available to chestnut trees in plots with ground cover (without tillage), compared to plots with conventional tillage, in the driest year. **Water availability:** More water was available to chestnut trees in plots with ground cover, in one of four years (2005, the driest year: data reported as higher predawn water potential in chestnut leaves). Similar amounts of water were found in soils with or without ground cover (0.1–0.2 cm^3 water/cm^3 soil, at most depths, on most dates). **Implementation options:** Similar amounts of water were available to chestnut trees in plots with seeded cover crops, compared to resident vegetation (data reported as predawn water potential in chestnut leaves). Similar amounts of water were found in soils with seeded cover crops, compared to resident vegetation (0.1–0.2 cm^3 water/cm^3 soil, at most depths, on most dates). **Methods:** There were three plots for each of two treatments (no tillage with resident vegetation or grasses and legumes, sown in 2001), and there were three control plots (conventional tillage, 15–20 cm depth, thrice/year). Each plot (600 m^2) had six chestnut trees (40 years old in 2001) and was fertilized but not irrigated. Soil water content was measured weekly with time-domain reflectometer probes (0–15 and 0–30 cm depth: four samples/plot; 45 and 75 cm: 2 samples/plot), in 2003–2006. Water potential was measured in June–September 2003–2006 (August–September in 2005) with gas exchangers (12 leaves/plot, south facing, up to 3 m high, 7:00–13:00 hours).

A site comparison in 2006 in two rainfed almond orchards near Granada, Spain (16), found less water in soils with cover crops, compared to conventional tillage. **Water availability:** Less water was found in soils with cover crops (2–5 vs 5–9 g water/100 g soil). **Methods:** Conventional tillage (chisel plough, 20–25 cm depth, 3–4 times/year in 2001–2005, October 2005, and April and June 2006) was used in one orchard, and no tillage was used in another orchard with two cover crops (oats and vetch or oats only, sown in January 2006 on one 1 ha plot each). Both orchards were fertilized (30 t compost/ha), but the orchard with cover crops got more fertilizer (1,500 kg organic fertilizer/ha on one-third of each plot, 250 kg mineral fertilizer/ha on one-third). The orchard with cover crops had cereal-fallow rotations before the cover crops, and it was tilled in November. Soil samples were collected on 7 June and 18 July 2006 (0–20 cm depth). It was not clear whether these results were a direct effect of cover crops (and tillage), fertilizer, or site.

A replicated, randomized, controlled study in 2005–2007 in irrigated vineyards in Sicily, Italy (17), found that less water was lost as runoff from plots with cover crops, compared to plots with conventional tillage (without cover crops), between the vine rows. **Water availability:** Less water was lost as runoff from plots with cover crops, compared to plots with conventional tillage (35–48 vs 57 mm). **Methods:** There were three plots (three vine interrows/plot; 2.2 x 3 m interrows) for each of four temporary cover-crop treatments (*V. faba*; *V. faba* and *V. sativa*; *Triticum durum*; or *T. durum* and *V. sativa*), each of two permanent cover-crop treatments (*T. subterraneum*, *F. rubra*, and *Lolium perenne*, or *T. subterraneum*, *F. rubra* and *F. ovina*), and each of three control plots (conventional tillage in the interrows, 3–4 times/year, 15 cm depth). Cover crops were sown in October. Temporary cover crops were tilled into the soil in April, but permanent cover crops were not tilled. The slope of the vineyard was 16%. Runoff was measured after each significant rainfall event (15 events in November 2005–October 2007) with sediment traps (Gerlach traps: 1 m diameter, 40 litres).

A replicated, randomized, controlled study in 2008–2011 in an irrigated avocado orchard in Chile (18) found less runoff, less sediment and nutrient in runoff, and more soil pores in plots with cover crops, compared to bare soil. **Water availability:** Less water was lost as runoff from plots with cover crops, compared to bare soil (0 vs 3–4 mm). No difference in water retention was found between soils with cover crops or bare soils (9–13 vs 8–13 m^3 water/m^3 soil), but soils with cover crops had a higher percentage of large pores (4–6% vs 3–4% macroporosity). **Nutrients:** Less nitrogen (0–5 vs 42–68 g/ha), phosphorus (0 vs 20–24 g/ha), and dissolved organic carbon (0–3 vs 345–637 g/ha) was found in runoff from plots with cover crops, compared to bare soil. **Sediments:** Less sediment was found in runoff from plots with cover crops, compared to bare soil (0 vs 1,000–3,400 kg soil/ha). **Methods:** Cover crops were grown in five treatment plots, and bare soil was maintained with herbicide in five control plots, in an avocado orchard, on a 47% slope (10 x 50 m plots). The groundcover (*Lolium rigidum* ryegrass and a legume, *Medicago polymorpha*) was sown in August 2008 and mown in February 2009–2010 (residues were retained). All plots were fertilized and irrigated. Runoff was collected in buried barrels downslope of each plot.

A replicated, randomized, controlled study in 2003–2005 in eight rainfed olive orchards in southern Spain (19) found that cover crops had inconsistent effects on runoff, but less sediment was found in runoff from plots with cover crops, compared to tilled plots. **Water availability:** Less water was lost as runoff from plots with cover crops, compared to tilled plots, on four of eight farms (19–56% less runoff), but more water was lost on one of eight farms (15% increase in runoff). **Sediments:** Less soil was found in runoff from plots with cover crops, compared to tilled plots, on seven of eight farms (63–89% less sediment). **Methods:** On each of eight farms, cover crops were grown (two of eight farms) or weeds were not controlled (six of eight farms) on three plots, but weeds were controlled by conventional tillage (depths not reported) on three plots (1 m^2 microplots). Plots were surrounded by steel sheets, which routed the runoff into plastic containers. Runoff and sediments were measured after each rainfall event.

A replicated site comparison in 2009 in rainfed vineyards in southern France (20) found similar water retention in soils with or without ground cover. **Water availability:** Similar water retention was found in soils with or without cover crops (data on water content at field capacity not reported). **Methods:** In 146 plots of three soil types, there was permanent vegetation (4–22% of plots in each soil type), temporary vegetation (48–68%), or bare soil (16–42%) between the vine rows, for at least five years before soil sampling. Soil samples were collected from the interrows in March–May 2009 (10 homogenized samples/plot, 0–15 cm depth).

A replicated, randomized, controlled study in 2008–2010 in an irrigated vineyard in the San Joaquin Valley, California, USA (21), found that grape vines used similar amounts of water, and soils had similar water contents, in plots with cover crops or resident vegetation between the vine rows. **Implementation options:** Similar amounts of water were used by grape vines in plots with cover crops or resident vegetation between the vine rows (midday stem water potential: –1.6 to –0.6 MPa). Similar amounts of water were found in soils between the vine rows with cover crops or resident vegetation, in most comparisons (soil water content: 15–34%). **Methods:** Cover crops were grown in the alleys (2.5 m width) between the vine rows (3.1 m width) on 16 plots (two alleys/plot, 190 vines/plot), and resident vegetation was allowed to grow on 8 plots, over the winter. There were two combinations of cover crops (oats only, or oats and legumes, seeded in November, on 8 plots each). All plots were mown in spring and tilled (15–20 cm depth) in spring, summer, and autumn. Herbicide was used to control weeds in the vine rows (50 cm width). Vines were drip-irrigated (60–70% of evapotranspiration). Soil water content was measured every 1–2 weeks, and stem water potential was measured every 2–3 weeks, during the growing season in 2008–2009 (frequency domain reflectometry, 0–110 cm depth).

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4.8. Use crop rotations: Water (4 studies)

- **Water use (2 studies):** One replicated, randomized, controlled study from Turkey[2] found higher water-use efficiency in plots with crop rotations, compared to continuous wheat, in some comparisons. One replicated, randomized, controlled study from Spain[1] found lower water-use efficiency in plots with crop rotations, compared to continuous wheat, in some comparisons.
- **Water availability (3 studies):** Two replicated, randomized, controlled studies from Australia[3,4] found similar amounts of water in soils with crop rotations or continuous crops. One replicated, randomized, controlled study from Turkey[2] found inconsistent differences in water storage in soils with or without crop rotations.
- Pathogens and pesticides (0 studies)
- Nutrients (0 studies)
- Sediments (0 studies)
- **Implementation options (1 study):** One study from Spain[1] found no difference in water-use efficiency between plots with different crop rotations.

A replicated, randomized, controlled study in 1999–2005 in a rainfed cereal field in northeast Spain (1) found that wheat used water less efficiently in plots with crop rotations, compared to continuous wheat. **Water use:** Wheat used water less efficiently in plots with crop rotations, compared to continuous wheat, in two of four comparisons (7–8 vs 9 kg grain/mm water/ha), but there was not a significant difference in water-use efficiency in barley, with or without crop rotations (10–11 vs 9). Similar amounts of water were used by cereals, in plots with or without rotations (wheat phase: 335–345 vs 300 mm; barley phase: 288–297 vs 293 mm). **Implementation options:** There was no difference in the water-use efficiency of cereals between wheat-barley-rapeseed and wheat-barley-vetch rotations (wheat: 7.2 vs 7.5 kg grain/mm water/ha; barley: 10.3 vs 10.9). **Methods:** Continuous wheat (one plot), continuous barley (one plot), a wheat-barley-rapeseed *Brassica napus* rotation (one plot/phase), or a wheat-barley-vetch *Vicia sativa* rotation (one plot/phase) were grown in each of three blocks. Each plot was 50 x 8 m. Wheat and barley were sown in early November (450 seeds/m^2). Vetch and rapeseed were sown in late September to early October (150 and 80 seeds seeds/m^2, respectively). Fertilizer was used on all plots (except vetch phases) in January and February. Herbicide was used in all plots.

A replicated, randomized, controlled study in 2003–2005 in a rainfed winter wheat field in Central Anatolia, Turkey (2), found that wheat used water to produce grain more efficiently in plots with crop rotations, compared to continuous wheat, but there were inconsistent differences in soil water storage between plots with or without crop rotations. **Water use:** Wheat used water more efficiently in plots with crop rotations, compared to continuous wheat (5.4–9.4 vs 2.3 kg/ha/mm). **Water availability:** Less water was found in soils with crop rotations, compared to continuous wheat, in five of 30 comparisons (116–154 vs 150–167 mm), but more water was found in two of 30 comparisons (156–163 vs 125 mm). **Methods:** Wheat was grown continuously (three plots) or in rotation with one of five other phases (three plots each: winter lentil, chickpea, sunflower, spring lentil, or fallow). Each plot was 5 x 15 m. All plots were fertilized. Before the experiment, these rotations had been used for 21 years in this field. The wheat was harvested in July. Soil moisture was measured with a neutron probe (0–90 cm depth) and soil water storage was calculated from the change in soil moisture.

A replicated, randomized, controlled study in 2009–2010 in a rainfed wheat field in the Wongan Hills, Western Australia (3), found similar amounts of water in soils with a lupin-wheat sequence or a wheat-wheat sequence. **Water availability:** Similar amounts of water were found in soils with or without crop rotation (8.1–17% median water-filled pore space). **Methods:** Wheat or lupin *Lupinus angustifolius* was planted on six 150 m^2 plots each, in June 2009. In June 2010, wheat was planted on all plots. Lime was added to half of the plots (3.5 t/ha). Different fertilizers were used on each crop (e.g., no nitrogen was used on lupin). No plots were tilled. Volumetric water content was measured with moisture probes (10 cm depth, in eight of 12 plots, every 30 minutes, for two years). Soil samples were collected every 7–14 days for two years (0–10 cm depth, eight samples/plot).

A replicated, randomized, controlled study in 2010–2011 in a rainfed field in Western Australia (4) found similar amounts of water in soils with a canola-wheat sequence or a wheat-wheat sequence. **Water availability:** Similar amounts of water were found in soils with or without rotations (volumetric soil moisture content: 10–19% at 0–10 cm depth during the growing season in 2011; water content: 156–177 mm in 2011). **Methods:** Wheat or canola was grown on three plots each, in 2010, and wheat was grown on all plots in 2011. Each plot was 1.4 x 40 m. Fertilizer (150 kg/ha/year) and herbicide were used on all plots. Soil water was measured with a neutron moisture meter (10–150 cm depth, calibrated by measurements of gravimetric water content and bulk density at the same depths) in September 2010–December 2011.

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4.9. Use no tillage in arable fields: Water (15 studies)

- **Water use (1 study):** One replicated, randomized, controlled study from Spain[8] found that barley used water more efficiently in plots without tillage, compared to plots with tillage, in some comparisons.
- **Water availability (14 studies):** Nine controlled studies (eight replicated and randomized) from Spain[2,5,6,11-15] and the USA[10] found more water in soils without tillage, compared to soils with

tillage, in some comparisons[5,11,12,14,15] or all comparisons[2,6,10,13]. One replicated, randomized, controlled study from Lebanon[7] found less water in soils without tillage, compared to soils with tillage, in some comparisons. Three replicated, controlled studies (two randomized) from Spain[4,9] and the USA[1] sometimes found more water, and sometimes found less water, in soils without tillage, compared to soils with tillage. One replicated, randomized, controlled study from Spain[3] found lower porosity in soils without tillage, compared to soils with tillage, in some comparisons.

- Pathogens and pesticides (0 studies)
- Nutrients (0 studies)
- Sediments (0 studies)

A replicated, controlled study in 1996–1998 in an irrigated tomato field in the San Joaquin Valley, California, USA (1), found that tillage (and cover crops) had inconsistent effects on water in soil. **Water availability:** In the tomato-growing season, more water was found in plots that had cover crops in winter and no tillage in spring, compared to plots that had bare soil in winter and tillage in spring, in some comparisons (when irrigated, data not clearly reported), but less water was found in winter and spring, in some comparisons. **Methods:** There were 12 plots (4.5 x 27.5 m plots) for each of two treatments (two grass-legume mixtures as winter cover crops, sown in October 1996–1997, killed and retained as mulch, with no tillage, in March 1997–1998) and there were 12 control plots (bare-soil fallow in winter, with herbicide, and conventional tillage in spring). Soil water was measured throughout the year with hydroprobes (0–6 feet depth until autumn 1997, then 0–7 feet depth). It was not clear whether these results were a direct effect of cover crops or tillage.

A controlled study in 1994–1999 in a rainfed legume-cereal field near Barcelona, Spain (2), found more water in soils with no tillage, compared to conventional tillage. **Water availability:** More water was found in soils with no tillage, compared to conventional tillage (33 vs 26 mm mean topsoil water content in February–May). **Methods:** No tillage or conventional tillage was used on one plot each (90 x 30 m plots). A cultivator (August), a mouldboard plough (September), and a harrow and a roller (November) were used for conventional tillage (depth not reported). Herbicide was used for no tillage (August). Herbicide was used in both plots in September and January, and fertilizer was added in October. Seeds were sown with a seed drill in December and crops were harvested in July. Crop residues were removed from all plots before tillage. Water was measured weekly (February–May, two time-domain reflectometer probes/plot, 20 cm depth).

A replicated, randomized, controlled study in 1992–1997 in a rainfed barley field in the Ebro river valley, Spain (3), found lower porosity in soils with no tillage, compared to subsoil tillage. **Water availability:** Lower porosity was found in soils with no tillage, compared to subsoil tillage, in some comparisons (e.g., in subplots with continuous cropping, in one of two years: 5.0 vs 15.5 cm/day, hydraulic conductivity). **Methods:** No tillage or subsoil tillage was used on four plots each (each with 10 m x 6 m subplots, with continuous cropping or fallow). A cultivator and a subsoil plough were used for subsoil tillage (15–40 cm depth), in October. Herbicide was used for no tillage, in October. Crop residues were removed from all plots. Hydraulic conductivity was measured in July 1996 and August 1997 (tension infiltrometer, 250 mm diameter, seven tensions from 0 to 20 cm water, in subplots with continuous cropping).

A replicated, randomized, controlled study in 2003–2005 on rainfed farms in the Ebro river valley, Spain (4), found that tillage had inconsistent effects on water in soils. **Water availability:** More water was found in soils with no tillage, compared to conventional tillage, in 11 of 24 comparisons, in the two days after tillage (0.04–0.26 vs 0.02–0.20 g water/g soil), but less water was found in 3 of 24 comparisons (0.08–0.11 vs 0.09–0.14). **Methods:** No tillage or conventional tillage was used on ten plots each (33–50 x 7–10 m plots), on a total of three farms, with multiple crops. A mouldboard or subsoil plough was used on plots with conventional tillage (25–40 cm depth). Herbicide was used on plots with no tillage. Water was measured in soil samples (5 cm depth), at three times (0, 24, and 48 hours after tillage).

A replicated, randomized, controlled study in 2002–2004 in an irrigated maize field in southwest Spain (5) found more water in soils with no tillage, compared to conventional tillage. **Water availability:** More water was found in soils with no tillage, compared to conventional tillage, in two of nine comparisons (0–10 cm depth, in 2004: 0.23–0.31 vs 0.14–0.19 cm^3 water/cm^3 soil). **Methods:** Conventional tillage or no tillage was used on four plots each (20 x 10 m plots). A mouldboard plough (0–30 cm depth, in October 2001–2003 and March and April 2002–2004) was used for conventional tillage, and maize residues were burned in September–October 2002–2004. Herbicide was used for no tillage (April and May–June 2002–2004), and maize residues were not burned.

A replicated, randomized, controlled study in 1996–2008 in a rainfed barley field in the Ebro river valley, Spain (6) (same study as (8,9)), found more water in soils with no tillage, compared to conventional tillage. **Water availability:** More water was found in soils with no tillage, compared to conventional tillage (0.09–0.25 vs 0.05–0.18 g water/g dry soil). **Methods:** No tillage or conventional tillage was used on nine plots each (50 x 6 m). A mouldboard plough or a disk plough was used for conventional tillage (25–30 cm depth, 100% incorporation of crop residues). Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Water content was measured in soil samples (0–5 cm depth).

A replicated, randomized, controlled study in 2005–2007 in a rainfed field in the central Bekaa Valley, Lebanon (7), found less water in soils with no tillage, compared to conventional tillage, in one of 10 comparisons. **Water availability:** Less water was found in soils with no tillage, compared to conventional tillage, in one of 10 comparisons (water content not reported). **Methods:** No tillage or conventional tillage was used on four plots each (14 x 6 m), in October. Conventional plots were ploughed (25–30 cm depth) and then shallowly disk-cultivated. Barley, chickpeas, and safflower were planted in November. Barley and safflower were fertilized (60–100 kg N/ha). Soil water was measured at two depths (25 and 50 cm), on five dates from 30 March 2005–16 August 2006, with a time-domain reflectometer.

A replicated, randomized, controlled study in 1996–2009 in a rainfed barley field in the Ebro river valley, Spain (8) (same study as (6,9)), found that barley used water more efficiently in plots with no tillage, compared to conventional tillage, in two of three comparisons. **Water use:** Higher water-use efficiency was found in plots with no tillage, compared to conventional tillage, in two of three comparisons (5.7–6.0 vs 1.8–2.1 kg barley grain/mm rainfall). **Methods:** No tillage or conventional tillage was used on nine plots each (50 x 6 m plots). A mouldboard plough was used for conventional tillage (25–30 cm depth, 100% incorporation of crop residues), in October or November. A seed drill and herbicide were used for no tillage. Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Soil samples were collected five times/year (two samples/plot, 4 cm diameter soil auger, 0–100 cm depth) in 2005–2009. Mature barley was harvested in June 2006–2009.

A replicated, randomized, controlled study in 1996–2009 in a rainfed barley field in the Ebro river valley, Spain (9) (same study as (6,8)), found that tillage had inconsistent effects on water in soils. **Water availability:** More water was found in soils with no tillage, compared to conventional tillage, in 11 of 16 comparisons (110–240 vs 90–215 g water/g soil), but less water was found in one of 16 comparisons (100 vs 115). **Methods:** No tillage or conventional tillage was used on nine plots each (50 x 6 m plots). A mouldboard plough was used for conventional tillage (25–30 cm depth, 100% incorporation of crop residues), in October or November. A seed drill and herbicide were used for no tillage. Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Soil samples were collected four times/year in 2005–2009 (0–100 cm depth).

A replicated, randomized, controlled study in 2009–2010 in a wheat-maize field in the San Joaquin Valley, California, USA (10), found more water in soils with no tillage, compared to conventional tillage. **Water availability:** More water was found in soils with no tillage, compared to conventional tillage (20–23% vs 12–14% volumetric water content). **Methods:** No tillage or conventional tillage was used on three plots each (1.5 x 91 m plots). A disk plough and a chisel plough (30 cm depth) were used for conventional tillage, in April 2009–2010 (after harvesting the wheat). In plots with no tillage, soils were not disturbed after harvesting the wheat. Wheat and maize were grown in rotation. Soil water content was measured after tillage (0–20 cm depth, about 12 reflectometer readings/plot and 4–6 soil cores/plot, 7.5 cm diameter).

A replicated, randomized, controlled study in 2008–2013 in a rainfed wheat-sunflower-pea field near Seville, Spain (11), found more water in soils with no tillage, compared to conventional tillage, in one of three comparisons. **Water availability:** More water was found in soils with no tillage, compared to conventional tillage, in one of three comparisons (0–5 cm depth, in early May 2013: 19.1 vs 7.42% soil moisture). **Methods:** No tillage or conventional tillage was used on three plots each (6 x 33.5 m plots). A mouldboard plough (25–30 cm depth), a chisel plough (25 cm depth, twice/year), and a disk harrow (12 cm depth) were used for conventional tillage. A seed drill and herbicide were used for no tillage. Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. Soil moisture was measured in May 2013 (0–5 cm depth, time-domain-reflectrometry probes) and early June (0–10 cm depth, gravimetric).

A replicated, randomized, controlled study in 1987–2010 in rainfed cereal fields in the Ebro river valley, Spain (12), found more water in soils with no tillage, compared to conventional tillage. **Water availability:** More water was found in soils with no tillage, compared to conventional tillage, in three of 15 comparisons (in Agramunt: 140–240 vs 100–210 mm volumetric water content). **Methods:** No tillage or conventional tillage was used on ten plot each (Peñalba: three plots each, 34 x 175 m plots, established in 2005; Agramunt: four plots each, 9 x 50 m plots, established in 1990; Selvanera: three plots each, 7 x 50 m plots, established in 1987). In Peñalba, a disk plough (20 cm depth) and a cultivator (10 cm depth) were used for conventional tillage. In Agramunt, a mouldboard plough (25 cm depth) and a cultivator (15 cm depth) were used for conventional tillage. In Selvanera, a subsoil plough (40 cm depth) and a chisel plough (15 cm depth) were used for conventional tillage. Herbicide was used for no tillage. Barley (Peñalba) or wheat (Agramunt and Selvanera) was planted in November 2009 with a seed drill (2–4 cm depth) and harvested in June–July 2010. Soil samples were collected two times (at tillering and flowering, four samples/plot, 0–90 cm depth).

A replicated, randomized, controlled study in 1996–2013 in two rainfed barley fields in northeast Spain (13) found more water in soils with no tillage, compared to conventional tillage. **Water availability:** More water was found in soils with no tillage, compared to conventional tillage (32–44% vs 18–20% water-filled pore space). **Methods:** No tillage or conventional tillage was used on three plots each, in each of two fields (from 2010–2013 in the short-term field, and from 1996–2013 in the long-term field; plots size not clearly reported). A mouldboard plough (25 cm depth) and a cultivator (15 cm depth) were used for conventional tillage in the long-term field, and a chisel plough was used in the short-term field (depth not reported), in September–October. For no tillage, the residues were chopped and spread, and pre-emergence herbicide was used. Some plots were fertilized (0–150 kg N/ha). Soil samples (0–5 cm depth) were collected every 2–3 weeks in 2011–2013 (2011–2012 in the short-term field).

A replicated, randomized, controlled study in 1994–2013 in a rainfed wheat field near Madrid, Spain (14) (same study as (15)), found more water in soils with no tillage, compared to conventional tillage. **Water availability:** More water was found in soils with no tillage, compared to conventional tillage, in one of six comparisons (November 2011: 180 vs 128 g water/kg soil). **Methods:** No tillage or conventional tillage was used on four plots each (in which a total of 24 subplots, 10 x 25 m each, were used in this study). A mouldboard plough was used for conventional tillage (25 cm depth). Pre-emergence herbicide was used for no tillage. The subplots had wheat monocultures or fallow-wheat-vetch-barley rotations. The cereals were fertilized (NPK, 200 kg/ha, twice/year, in October and March). The crop residues were shredded and retained. Soil samples were collected in October 2010, April 2011, November 2011, May 2012, October 2012 and April 2013 (50 mm diameter, 0–15 cm depth).

A replicated, randomized, controlled study in 1994–2011 in a rainfed cereal-legume field near Madrid, Spain (15) (same study as (14)), found more water in soils with no tillage, compared to conventional tillage. **Water availability:** More water was found in soils with no tillage, compared to conventional tillage, in some comparisons (amounts of water and numbers of comparisons not reported). **Methods:** No tillage or conventional tillage was used on three plots each (10 x 25 m). A mouldboard plough and a cultivator were used for conventional tillage (20 cm depth) in October. A seed drill and herbicide were used for no tillage. Soil samples were collected 1–12 times/month, in November 2010–October 2011 (0–15 cm depth, 2.5 cm diameter).

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4.10. Use no tillage instead of reduced tillage: Water (10 studies)

- **Water use (1 study):** One replicated, randomized, controlled study from Spain[5] found that crops used water more efficiently in plots with no tillage, compared to reduced tillage, in one of four comparisons.
- **Water availability (9 studies):** Six controlled studies from Spain[1-3,6,7,10] (five of which were replicated and randomized[2,3,6,7,10]) found more water in soils with no tillage, compared to reduced tillage, in some comparisons[2,6,7,10] or all comparisons[1,3]. One replicated, randomized, controlled study from Spain[9] found less water in soils with no tillage, compared to reduced tillage, in one of fifteen comparisons. Two replicated, randomized, controlled studies from Australia and Lebanon[4,8] found similar amounts of water in soils with no tillage or reduced tillage.
- Pathogens and pesticides (0 studies)
- Nutrients (0 studies)
- Sediments (0 studies)

A controlled study in 1994–1999 in a rainfed legume-cereal field near Barcelona, Spain (1), found more water in soils with no tillage, compared to reduced tillage. **Water availability:** More water was found in soils with no tillage, compared to reduced tillage (33 vs 29 mm mean topsoil water content in February–May). **Methods:** No tillage or reduced tillage was used on one plot each (90 x 30 m plots). A cultivator (August), a chisel plough (September), and a harrow and roller (November) were used for reduced tillage (depth not reported). Herbicide was used for no tillage (August). Herbicide was used in both plots in September and January, and fertilizer was added in October. Seeds were sown with a seed drill in December and crops were harvested in July. Crop residues were removed from all plots before tillage. Water was measured weekly (February–May, two time-domain reflectometer probes/plot, 20 cm depth).

A replicated, randomized, controlled study in 2003–2005 on rainfed farms in the Ebro river valley, Spain (2), found more water in soils with no tillage, compared to reduced tillage. **Water availability:** More water was found in soils with no tillage, compared to reduced tillage, in 10 of 18 comparisons, in the two days after tillage (0.08–0.26 vs 0.05–0.23 g water/g soil). **Methods:** No tillage or reduced tillage was used on seven plots each (33–50 x 7–10 m plots), on a total of two farms, with multiple crops. A cultivator (15 cm depth) or chisel plough (25–30 cm depth) was used on plots with reduced tillage. Herbicide was used on plots with no tillage. Water was measured in soil samples (5 cm depth), at three times (0, 24, and 48 hours after tillage).

A replicated, randomized, controlled study in 1996–2008 in a rainfed barley field in the Ebro river valley, Spain (3) (same study as (5,6)) found more water in soils with no tillage, compared to reduced tillage. **Water availability:** More water was found in soils with no tillage, compared to reduced tillage (0.09–0.25 vs 0.06–0.21 g water/g dry soil). **Methods:** No tillage or reduced tillage was used on nine plots each (50 x 6 m). A cultivator was used for reduced tillage (10–15 cm depth, 50% incorporation of crop residues). Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Water content was measured in soil samples (0–5 cm depth).

A replicated, randomized, controlled study in 2005–2007 in a rainfed field in the central Bekaa Valley, Lebanon (4), found no difference in water content between soils with no tillage and soils with reduced tillage. **Water availability:** No difference in water content was found in soils with no tillage and soils with reduced tillage (11–32% water). **Methods:** No tillage or reduced tillage (shallow disc cultivation, 10 cm depth) was used in four plots each (14 x 6 m), in October. Barley, chickpeas, and safflower were planted in November. Barley and safflower were fertilized (60–100 kg N/ha). Soil water was measured at two depths (25 and 50 cm), on five dates from 30 March 2005–16 August 2006, with a time domain reflectometer.

A replicated, randomized, controlled study in 1996–2009 in a rainfed barley field in the Ebro river valley, Spain (5) (same study as (3,6)), found higher water-use efficiency in plots with no tillage, compared to reduced tillage, in one of four comparisons. **Water use:** Higher water-use efficiency was found in plots with no tillage, compared to reduced tillage, in one of four comparisons (6.0 vs 4.3 kg barley grain/mm rainfall). **Methods:** No tillage or reduced tillage was used on nine plots each (50 x 6 m plots). A cultivator was used for reduced tillage (10–15 cm depth, 50% incorporation of crop residues), in October or November. A seed drill and herbicide were used for no tillage. Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Soil samples were collected five times/year (two samples/plot, 4 cm diameter soil auger, 0–100 cm depth) in 2005–2009. Mature barley was harvested in June 2006–2009.

A replicated, randomized, controlled study in 1996–2009 in a rainfed barley field in the Ebro river valley, Spain (6) (same study as (3,5)), found more water in soils with no tillage, compared to reduced tillage, in some comparisons. **Water availability:** More water was found in soils with no tillage, compared to reduced tillage, in seven of 16 comparisons (120–215 vs 105–195 g water/g soil). **Methods:** No tillage or reduced tillage was used on nine plots each (50 x 6 m plots). A cultivator was used for reduced tillage (10–15 cm depth, 50% incorporation of crop residues), in October or November. A seed drill and herbicide were used for no tillage. Two-thirds of the plots were fertilized

(60 or 120 kg N/ha). Soil samples were collected four times/year in 2005–2009 (0–100 cm depth).

A replicated, randomized, controlled study in 2008–2013 in a rainfed wheat-sunflower-pea field near Seville, Spain (7), found more water in soils with no tillage, compared to reduced tillage. **Water availability:** More water was found in soils with no tillage, compared to reduced tillage, in one of three comparisons (0–5 cm depth, in early May 2013: 19.1% vs 9.15% soil moisture). **Methods:** No tillage or reduced tillage was used on three plots each (6 x 33.5 m plots). A chisel plough (25 cm depth), a disc harrow (5 cm depth), and herbicide were used for reduced tillage. A seed drill and herbicide were used for no tillage. Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. Soil moisture was measured in May 2013 (0–5 cm depth, time-domain-reflectrometry probes) and early June (0–10 cm depth, gravimetric).

A replicated, randomized, controlled study in 2010–2011 in a rainfed wheat field in Australia (8) found similar amounts of water in soils with no tillage or reduced tillage. **Water availability:** Similar amounts of water were found in soils with no tillage or reduced tillage (161–168 vs 163–179 mm). **Methods:** No tillage or reduced tillage was used on three plots each (1.4 x 40 m plots) in 2010, when the plots were fallow. A rotary hoe (12 cm depth) was used for reduced tillage. Herbicide was used for no tillage. Wheat was grown on all plots in 2011. Fertilizer (150 kg/ha) and herbicides were used on all plots in 2011. Soil water was measured with a neutron moisture meter (1.5 m depth, between September 2010 and December 2011).

A replicated, randomized, controlled study in 1987–2010 in rainfed cereal fields in the Ebro river valley, Spain (9), found less water in soils with no tillage, compared to reduced tillage. **Water availability:** Less water was found in soils with no tillage, compared to reduced tillage, in one of 15 comparisons (in Selvanera: 110 vs 150 mm volumetric water content). **Methods:** No tillage or reduced tillage was used on ten plot each (Peñalba: three plots each, 34 x 175 m plots, established in 2005; Agramunt: four plots each, 9 x 50 m plots, established in 1990; Selvanera: three plots each, 7 x 50 m plots, established in 1987). A cultivator (Peñalba: 10 cm depth; Agramunt: 15 cm) or a chisel plough (Selvanera: 15 cm) was used for reduced tillage. Herbicide was used for no tillage. Barley (Peñalba) or wheat (Agramunt and Selvanera) was planted in November 2009 with a seed drill (2–4 cm depth) and harvested in June–July 2010.

A replicated, randomized, controlled study in 1994–2011 in a rainfed cereal-legume field near Madrid, Spain (10), found more water in soils with no tillage, compared to reduced tillage. **Water availability:** More water was found in soils with no tillage, compared to reduced tillage, in some comparisons (amounts of water and numbers of comparisons not reported). **Methods:** No tillage or reduced tillage was used on three plots each (10 x 25 m). A chisel plough and a cultivator were used for reduced tillage (15 cm depth) in October. A seed drill and herbicide were used for no tillage. Soil samples were collected 1–12 times/month, in November 2010–October 2011 (0–15 cm depth, 2.5 cm diameter).

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4.11. Use reduced tillage in arable fields: Water (17 studies)

- **Water use (3 studies):** Two replicated, randomized, controlled studies from Spain and Turkey[3,8] found that crops used water more efficiently in plots with reduced tillage, compared to conventional tillage, in some comparisons. One replicated, randomized, controlled study from Egypt[17] found that crops used water more efficiently in plots with less-frequent tillage (one pass with a plough, compared to two), but crops used water less efficiently in plots with shallow tillage, compared to deep tillage.
- **Water availability (14 studies)**
    - Water content (12 studies): Six controlled studies (five replicated and randomized) from Egypt and Spain[2,4,5,9,15,17] found more water in soils with reduced tillage, compared to conventional tillage, in some comparisons[4,5,9,15] or all comparisons[2,17]. Two of these studies[4,9] also found less water in soils with reduced tillage, compared to conventional tillage, in some comparisons. Two replicated, randomized, controlled studies from Lebanon and the USA[1,6] found less water in soils with reduced tillage, compared to conventional tillage, in some comparisons. Four controlled studies from Egypt, Italy, and Spain[11,14,16,17] (three of which were replicated and randomized), found similar amounts of water in soils with reduced tillage or conventional tillage, in all comparisons.
    - Water loss (2 studies): One replicated, controlled study from France[7] found that less water was lost through drainage from soils with reduced tillage, compared to conventional tillage, during the growing season, but more water was lost during the fallow season, in some comparisons. One replicated, randomized, controlled study from Egypt[17] found that less water was lost through runoff from soils with less-frequent tillage

(one pass with a plough, compared to two), but more water was lost through runoff from soils with shallow tillage, compared deep tillage.

  - Water infiltration (3 studies): One replicated, randomized, controlled study from Egypt[17] found that water infiltration rates were faster in soils with reduced tillage, compared to conventional tillage, in some comparisons. Two replicated, controlled studies from Spain and the USA[12,13] found that water infiltration rates were similar in soils with reduced tillage or conventional tillage.

- **Pathogens and pesticides (1 study):** One replicated, randomized, controlled study from France[7] found that less herbicide was leached from soils with reduced tillage, compared to conventional tillage.
- Nutrients (0 studies)
- Sediments (0 studies)
- **Implementation options (2 studies):** One replicated, randomized, controlled study from Egypt[17] found more water and faster water infiltration rates in soils that were tilled at slower tractor speeds, but found that water losses and water-use efficiencies were similar in plots that were tilled at different tractor speeds. One replicated, randomized, controlled study from Turkey[3] found that water-use efficiencies were similar in plots with different types of reduced tillage (rototilling and disking, compared to double disking).

A replicated, randomized, controlled study in 1998–2000 in an irrigated vegetable field in the Salinas Valley, California, USA (1), found less water in soils with reduced tillage, compared to conventional tillage. **Water availability:** Less water was found in soils with reduced tillage, compared to conventional tillage, in 12 of 16 comparisons (0.07–0.26 vs 0.08–0.27 g water/g soil; 0–15 cm depth). **Methods:** There were four plots (0.52 ha), for each of four treatments (reduced tillage or conventional tillage, with or without added organic matter). In plots with added organic matter, compost was added two times/year, and a cover crop (Merced rye) was grown every autumn or winter. Lettuce or broccoli crops were grown in raised beds. Sprinklers and drip irrigation were used in all plots. Soils were disturbed to different depths (conventional tillage: disking to 50 cm depth, cultivating, sub-soiling, bed re-making, and bed-shaping; reduced tillage: cultivating to 20 cm depth, rolling, and bed-shaping). Soils were collected, along the planting line, with 6 cm soil cores.

A controlled study in 1994–1999 in a rainfed legume-cereal field near Barcelona, Spain (2), found more water in soils with reduced tillage, compared to conventional tillage. **Water availability:** More water was found in soils with reduced tillage, compared to conventional tillage (29 vs 26 mm mean topsoil water content in February–May). **Methods:** Reduced tillage or conventional tillage was used on one plot each (90 x 30 m plots). A mouldboard plough was used for conventional tillage, and a chisel plough was used for reduced tillage, in September (depths not reported). Herbicide was used in both plots in September and January, and fertilizer was added in October. Seeds were sown with a seed drill in December and crops were harvested in July. Crop residues were removed from all plots before tillage. Water was measured weekly (February–May, two time-domain reflectometer probes/plot, 20 cm depth).

A replicated, randomized, controlled study in 2001–2004 in a rainfed wheat-vetch field in the Marmara region, Turkey (3), found higher water-use efficiencies in plots with reduced tillage, compared to conventional tillage. **Water use:** Higher crop yields (relative to rainfall) were found in plots with reduced tillage, compared to conventional tillage, in one of two comparisons (7.6 vs 7.2 precipitation use efficiency). **Implementation options:** Similar crop yields (relative to rainfall) were found in plots that were rototilled and disked or double disked (7.6 vs 7.4 precipitation use efficiency). **Methods:** Conventional tillage with a mouldboard plough (20–22 cm depth) and a double disc (two passes, 8–10 cm depth), reduced tillage with a rototiller (20–22 cm depth) and a double disc (one pass, 8–10 cm), or reduced tillage with a double disc (two passes, 8–10 cm) was used on three plots each (15 x 75 m plots). Fertilizer and herbicide were used on all plots. Wheat was sown in December 2001, October 2002, and November 2003. Vetch was sown in December 2001, November 2002, and December 2003. Wheat and vetch were harvested in June 2002–2004 (3 m^2 samples, three/plot).

A replicated, randomized, controlled study in 2003–2005 on rainfed farms in the Ebro river valley, Spain (4), found that tillage had inconsistent effects on water in soils. **Water availability:** More water was found in soils with reduced tillage, compared to conventional tillage, in 4 of 18 comparisons, in the two days after tillage (0.10–0.23 vs 0.09–0.20 g water/g soil), but less water was found in 6 of 18 comparisons (0.05–0.11 vs 0.08–0.14). **Methods:** Reduced tillage or conventional tillage was used on seven plots each (33–50 x 7–10 m plots), on a total of two farms, with multiple crops. A mouldboard or subsoil plough was used on plots with conventional tillage (25–40 cm depth). A cultivator (15 cm depth) or chisel plough (25–30 cm depth) was used on plots with reduced tillage. Water was measured in soil samples (5 cm depth), at three times (0, 24, and 48 hours after tillage).

A replicated, randomized, controlled study in 1996–2008 in a rainfed barley field in northeast Spain (5) (same study as (8,9)) found more water in soils with reduced tillage, compared to conventional tillage, in some comparisons. **Water availability:** More water was found in soils with reduced tillage, compared to conventional tillage, in 10 of 16 comparisons (0.07–0.21 vs 0.05–0.18 g water/g dry soil). **Methods:** Reduced tillage or conventional tillage was used on nine plots each (50 x 6 m). A mouldboard plough or a disc plough was used for conventional tillage (25–30 cm depth, 100% incorporation of crop residues). A cultivator was used for reduced tillage (10–15 cm depth, 50% incorporation of crop residues). Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Water content was measured in soil samples (0–5 cm depth).

A replicated, randomized, controlled study in 2005–2007 in a rainfed field in the central Bekaa Valley, Lebanon (6), found less water in soils with reduced tillage, compared to conventional tillage, in one of 10 comparisons. **Water availability:** Less water was found in soils with reduced tillage, compared to conventional tillage, in one of 10 comparisons (water content not reported). **Methods:** Reduced tillage or conventional tillage was used in four plots each (14 x 6 m), in October. Conventional plots were ploughed (25–30 cm depth) and then shallowly disc cultivated. Reduced plots were shallowly disc cultivated (10 cm depth). Barley, chickpeas, and safflower were planted in November. Barley and safflower were fertilized (60–100 kg N/ha). Soil water was measured at two depths (25 and 50 cm), on five dates from 30 March 2005–16 August 2006, with a time domain reflectometer.

A replicated, controlled study in 2004–2008 in an irrigated maize field in the Garonne River corridor, southern France (7) (same study as (10)), found that tillage had inconsistent effects on water loss. **Water availability:** Less water was lost through drainage from soils with reduced tillage, compared to conventional tillage, during three of four growing seasons, but more water was lost during two of four fallow seasons (drainage volumes not reported for significant comparisons). **Methods:** Conventional tillage or reduced tillage was used on six plots each (20 x 50 m plots). Three of these plots had winter cover crops (white mustard or oats) and three had bare soil. A mouldboard plough (28–30 cm depth) and a cultivator (8 cm depth, 1–2 passes) were used for conventional tillage, in April–May. A cultivator (7–9 cm depth) and a disc harrow (8–12 cm depth) were used for reduced tillage, in March–April. Maize was sown in April–May 2005–2008 and harvested in October 2005–2008. Drainage from soils was measured with fiberglass-wick lysimeters (40 cm depth, two lysimeters/plot), on 67 sampling dates. A centre-pivot sprinkler was used for irrigation (857–943 mm water/year, irrigation plus rainfall).

A replicated, randomized, controlled study in 1996–2009 in a rainfed barley field in the Ebro river valley, Spain (8) (same study as (5,9)), found that tillage had inconsistent effects on water in soils. **Water availability:** More water was found in soils with reduced tillage, compared to conventional tillage, in five of 16 comparisons (160–235 vs 135–215 g water/g soil), but less water was found in one of 16 comparisons (100 vs 115). **Methods:** Reduced tillage or conventional tillage was used on nine plots each (50 x 6 m plots), in October or November. A mouldboard plough was used for conventional tillage (25–30 cm depth, 100% incorporation of crop residues). A cultivator was used for reduced tillage (10–15 cm depth, 50% incorporation of crop residues). Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Soil samples were collected four times/year in 2005–2009 (0–100 cm depth).

A replicated, randomized, controlled study in 1996–2009 in a rainfed barley field in the Ebro river valley, Spain (9) (same study as (5,8)), found higher water-use efficiency in plots with reduced tillage, compared to conventional tillage, in two of three comparisons. **Water use:** Higher water-use efficiency was found in plots with reduced tillage, compared to conventional tillage, in two of three comparisons (4.3–5.2 vs 1.8–2.1 kg barley grain/mm rainfall). **Methods:** Reduced tillage or conventional tillage was used on nine plots each (50 x 6 m plots), in October or November. A mouldboard plough was used for conventional tillage (25–30 cm depth, 100% incorporation of crop residues). A cultivator was used for reduced tillage (10–15 cm depth, 50% incorporation of crop residues). Two-thirds of the plots were fertilized (60 or 120 kg N/ha). Soil samples were collected five times/year (two samples/plot, 4 cm diameter soil auger, 0–100 cm depth) in 2005–2009. Mature barley was harvested in June 2006–2009.

A replicated, controlled study in 2004–2008 in an irrigated maize field in the Garonne River corridor, in southern France (10) (same study as (7)) found that less herbicide was leached from soils with reduced tillage, compared to conventional tillage. **Pathogens and pesticides:** Less herbicide was leached from soils with reduced tillage, compared to conventional tillage (10 vs 15% of applied herbicide). **Methods:** Conventional tillage or reduced tillage was used on two plots each (20 x 50 m plots). A mouldboard plough (28–30 cm depth) and a cultivator (8 cm depth, 1–2 passes) were used for conventional tillage, in April–May. A cultivator (7–9 cm depth) and a disc harrow (8–12 cm depth) were used for reduced tillage, in March–April. The herbicide (75 g/L Isoxaflutole) was sprayed 1–3 days after the maize was sown, in April–May 2005–2008. Herbicide leaching was measured in drainage water, with fiberglass-wick lysimeters (40 cm depth, two lysimeters/plot, 11–21 samples/year, 6–272 days after treatment with herbicide). A centre-pivot sprinkler was used for irrigation (650–736 mm water/year, irrigation plus rainfall).

A controlled study in 1990–2007 in a rainfed wheat field in southern Italy (11) found similar amounts of water in soils with reduced tillage or conventional tillage. **Water availability:** Similar amounts of water were found in soils with reduced tillage or conventional tillage (0.19–0.38 vs 0.20–0.36 cm^3 water/cm^3 soil). **Methods:** A mouldboard plough (40–45 cm depth) was used on one plot (conventional tillage), and a disc harrow (20–25 cm depth) was used on another plot (reduced tillage), from 1990–2007. Each plot was 23 x 10 m. Water content was measured in soil samples (5 cm height, 5 cm diameter, six samples/plot), during the growing season (March 2005, June 2006, May 2007).

A replicated, randomized, controlled study in 1991–2008 in a rainfed wheat-sunflower-pea field near Seville, Spain (12), found similar amounts of water infiltration in soils with reduced tillage or conventional tillage. **Water availability:** Similar amounts of water infiltration were found in soils with reduced tillage or conventional tillage (0.28 vs 0.38 mm conductive macro-pore diameter). **Methods:** Reduced tillage or conventional tillage was used on three plots each (22 x 14 m plots). A mouldboard plough and a chisel plough were used for conventional tillage (25–30 cm depth), and crop residues were burned (1992–2003, but not 2004–2008). A chisel plough and herbicide were used for reduced tillage (25–30 cm depth), and crop residues were retained. Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. Water infiltration was measured with an infiltrometer (between –60 and –20 mm tension) in 2008.

A replicated, controlled study in 2007–2008 in an irrigated tomato field in Davis, California, USA (13), found similar rates of water infiltration in soils with reduced tillage or conventional tillage. **Water availability:** Similar rates of water infiltration were found in soils with reduced tillage or conventional tillage (6.5 vs 7.4 litres/foot/90 minutes). **Methods:** Conventional tillage or reduced tillage was used on four plots each (90 x 220 feet). Broadcast disking, subsoiling, land planing, and rebedding were used for conventional tillage. A Wilcox Performer was used for reduced tillage (two passes; beds were conserved). Sprinklers, furrow irrigation, and drip-tape (in furrows) were used to irrigate the tomatoes. All plots were fertilized. Water infiltration was measured in 2008 (using the blocked furrow method). Winter cover crops (triticale) were grown on half of each plot, and the other half was fallow in winter.

A replicated, randomized, controlled study in 2008–2013 in a rainfed wheat-sunflower-pea field near Seville, Spain (14), found similar amounts of water in soils with reduced tillage or conventional tillage. **Water availability**: Similar amounts of water were found in soils with reduced tillage or conventional tillage (7.23–13.4 vs 7.11–14.0% soil moisture). **Methods:** Reduced tillage or conventional tillage was used on three plots each (6 x 33.5 m plots). A mouldboard plough (25–30 cm depth), a chisel plough (25 cm depth, twice/year), and a disc harrow (12 cm depth) were used for conventional tillage. A chisel plough (25 cm depth, once/year), a disc harrow (5 cm depth), and herbicide were used for reduced tillage. Wheat, sunflowers, and peas were grown in rotation. Wheat was fertilized, but sunflowers and peas were not. Soil moisture was measured in May 2013 (0–5 cm depth, time-domain-reflectrometry probes) and early June (0–10 cm depth, gravimetric).

A replicated, randomized, controlled study in 1987–2010 in rainfed cereal fields in the Ebro river valley, Spain (15), found more water in soils with reduced tillage, compared to conventional tillage. **Water availability:** More water was found in soils with reduced tillage, compared to conventional tillage, in one of 15 comparisons (in Selvanera: 150 vs 110 mm volumetric water content). **Methods:** Reduced tillage or conventional tillage was used on ten plot each (Peñalba: three plots each, 34 x 175 m plots, established in 2005; Agramunt: four plots each, 9 x 50 m plots, established in 1990; Selvanera: three plots each, 7 x 50 m plots, established in 1987). In Peñalba, a disk plough (20 cm depth) and a cultivator (10 cm depth) were used for conventional tillage. In Agramunt, a mouldboard plough (25 cm depth) and a cultivator (15 cm depth) were used for conventional tillage. In Selvanera, a subsoil plough (40 cm depth) and a chisel plough (15 cm depth) were used for conventional tillage. A cultivator (Peñalba: 10 cm depth; Agramunt: 15 cm) or a chisel plough (Selvanera: 15 cm) was used for reduced tillage. Barley (Peñalba) or wheat (Agramunt and Selvanera) was planted in November 2009 with a seed drill (2–4 cm depth) and harvested in June–July 2010. Soil samples were collected two times (at tillering and flowering, four samples/plot, 0–90 cm depth).

A replicated, randomized, controlled study in 1994–2013 in a rainfed field near Madrid, Spain (16), found similar amounts of water in soils with reduced tillage or conventional tillage. **Water availability:** Similar amounts of water were found in soils with reduced tillage or conventional tillage (50–151 g water/kg soil). **Methods:** Conventional tillage or reduced tillage was used on eight plots each (10 x 25 m plots). A mouldboard plough was used for both conventional tillage (25 cm depth) and reduced tillage (20 cm depth). Crop residues were shredded and retained. Soil samples were collected six times, in October 2010–April 2013 (soil cores, 0–15 cm depth, 5 cm diameter).

A replicated, randomized, controlled study in 2012–2013 in a rainfed wheat field in Wadi Madwar, northwestern Egypt (17), found more water, more efficient water use, faster infiltration, and less runoff in plots that were tilled less frequently, but found less efficient water use and more runoff in plots with shallower tillage, compared to deeper. More water and faster infiltration were found in soils that were tilled at slower speeds. **Water use:** Crops used water more efficiently in plots with reduced tillage, compared to conventional tillage (7.78 vs 7.14 kg grain/ha/mm rainfall). Crops used water less efficiently in plots that were tilled to 15 cm depth, compared to 20–25 cm depth (8.35 vs 9.22–9.23 kg grain/ha/mm rainfall). **Water availability:** More water was found in soils with reduced tillage, compared to conventional tillage (67 vs 43 mm). Similar amounts of water were found in soils that were tilled to different depths (15–25 cm depth: 66–68 mm water). Less runoff was found in plots with reduced tillage, compared to conventional tillage (10 vs 11 mm runoff). More runoff was found in plots that were tilled to 15 cm depth, compared to 20–25 cm depth (9.4 vs 8.5–8.6 mm runoff). Faster infiltration rates were found in soils with reduced tillage, compared to conventional tillage (7 vs 6 cm/hour). Faster infiltration rates were found in soils that were tilled to 20 cm depth, compared to 25 cm depth (8.2 vs 7.7 cm/hour), but similar infiltration rates were found in soils that were tilled to 15 cm or 25 cm depth (7.9 vs 7.7 cm/hour). **Implementation options:** No differences in water use or runoff water were found in plots that were tilled at different tractor speeds (8.39–9.26 kg grain/ha/mm rainfall, 8.6–9.2 mm runoff). More water was found in soils that were tilled at slower tractor speeds (0.69–1.25 m/s: 67–69 mm water), compared to the fastest speed (1.53 m/s: 65 mm water). Faster infiltration rates were found in soils that were tilled at slower tractor speeds (0.69–1 m/s: 8.5 cm water/hour), compared to faster tractor speeds (1.25 m/s: 7.8 cm; 1.53 m/s: 7 cm). **Methods:** Reduced tillage or conventional tillage was used on three plots each (0.45 ha plots). A chisel plough was used for both reduced tillage (one pass) and conventional tillage (two passes). Each plot had three subplots (0.15 ha subplots, tilled to 15, 20, or 25 cm depth). Each subplot had four sub-subplots (size not reported; tilled at 0.69, 1, 1.25, or 1.53 m/s). Runoff water was collected in buried containers, downhill from each sub-subplot, after each storm. Soil water content was measured in soil cores (5.5 cm diameter, 0–60 cm length, three samples/sub-subplot, once before tillage and thrice in the dry season). Infiltration was measured with a double-ring infiltrometer (three measurements/sub-subplot, before tillage and three weeks after emergence). Wheat was planted in December 2012, fertilized, and harvested in May 2013.

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Habitat management: Effects on water

4.12. Plant buffer strips: Water (5 studies)

- Water use (0 studies)
- **Water availability (2 studies):** One replicated, randomized, controlled study from Italy[5] found more soil moisture in plots with buffers, compared to plots without buffers, in some comparisons. One replicated, randomized, controlled study from the USA[1] found that similar amounts of water were lost as runoff from plots with or without buffers.
- **Pathogens and pesticides (1 study):** One replicated study from the USA[3] found that grass buffer strips decreased the amount of *Cryptosporidium parvum* (a protozoan pathogen) in runoff, after bovine manure was applied to slopes.
- **Nutrients (2 studies):** One replicated, randomized, controlled study from the USA[2] found less nitrate in runoff from irrigated pastures with buffer strips, but another one[1] found no differences in nitrate or phosphorus in runoff from pastures with or without buffer strips.
- **Sediments (2 studies):** Two replicated, controlled studies (one randomized) from the USA[1,4] found less sediment in runoff from irrigated fields or pastures with buffers, compared to those without buffers, in some[1] or all[4] comparisons.
- **Implementation options (3 studies):** One replicated study from the USA[3] found less *C. parvum* (a protozoan pathogen) in runoff from flatter buffer strips, compared to steeper. One replicated, randomized, controlled study from Italy[5] found more soil moisture in plots with narrower buffer strips, in one of two comparisons. One replicated, randomized, controlled study from the USA[2] found that buffers trapped more runoff in the four weeks after fertilizer application, compared to the next 10 weeks.

A replicated, randomized, controlled study in 1997 in irrigated pastures in the foothills of the Sierra Nevadas, California, USA (1), found less sediment in runoff from pastures with buffers. **Water availability:** Similar amounts of water were lost as runoff from plots with or without buffers (118–1,386 vs 121–893 m^3/ha). **Nutrients:** Similar amounts of nitrate and phosphorus were found in runoff from pastures with or without buffers (sprinkler: 1.78 vs 1.76 kg NO_3-N/ha; 0.34 vs 0.38 kg total P/ha; flood: 0.91 vs 1.34 kg NO_3-N/ha; 0.24 vs 0.23 kg total P/ha). **Sediments:** Less sediment was found in runoff from pastures with buffers, compared to pastures without buffers, in two of four comparisons (0.3 vs 0.4–0.16 g total suspended solids/litre). **Methods:** Buffers (10 m width, parallel to the stream channel or runoff ditch in which runoff was measured) were fenced to exclude grazers on 1 May 1997. Pastures and buffers were 40% clover and 60% grass. Four pastures had buffers, and four did not. Half of the pastures (1 ha each) were intensively sprinkler-irrigated and grazed (six cattle, five-day rotation). The other half (3 ha each) were flood-irrigated and grazed (20 cattle, seven-day rotation). The cattle were yearling beef heifers, in rotation from 1 June to 15 October. Runoff was measured during irrigation events (sprinkler: five events, 787 m^3/ha/event; flood: eight events, 1,642

m^3/ha/event) in August, September, and October (volume was measured every 15 minutes in a weir; samples were collected every hour).

A replicated, randomized, controlled study in summer 2000–2001 in montane pasture in California, USA (2), found that grass buffer strips reduced the amount of nitrate in runoff from extensively grazed irrigated pasture. **Nutrients:** Buffer strips reduced the amount of nitrate in runoff (8 m buffers: 28%; 16 m: 42%). Buffers trapped twice the amount of nitrogen, compared to unbuffered plots, in the first four weeks. **Implementation options:** Buffers trapped higher amounts of runoff in the first four weeks, compared to the next 10 weeks. **Methods:** Plots (5 x 48 m) were buffered (8 or 16 m) or unbuffered (three replicates each). Fertilizers were applied to plots (170 kg/ha) in May. Five cattle (per 0.2 ha) grazed for two days (faecal matter: 336 kg/ha/plot) every three weeks. Buffer strips had no grazing or fertilizer application. Plots and buffer strips were irrigated in April–October (167 L/s/ha, 3.5 h). Soil berms separated plots. Water samples were collected for 14 weeks following fertilizer (5 kg/ha, traceable potassium nitrate) and water (20 L/m) application. A trough at the bottom of the buffers collected surface runoff and soil solution samplers (45 cm deep) collected subsurface runoff.

A replicated study in May 2004 on pastureland in California, USA (3), found that vegetated buffer strips decreased the amount of *Cryptosporidium parvum* (a protozoan pathogen) in runoff, after bovine manure application. **Pathogens and pesticides:** Overall, vegetated buffers (1 m wide) with over 95% vegetation cover and slopes of 5–20% decreased the amount of *C. parvum* in runoff (data reported in logarithmic units). **Implementation options:** Overall, reduction of *C. parvum* for every meter of vegetation was higher for 5% slopes, compared to 12% and 20% slopes (data reported in logarithmic units). **Methods:** Soil boxes (0.5 x 1 m, 0.3 m deep) packed with soil from open grassland (Madera County) were planted with grass (150–200 g of seed/box) and had varying slopes (5, 12, and 20%, four replicates each). Bovine faeces (200 g) spiked with *C. parvum* (2×10^8) were applied to the plots. Grass was clipped to 10 cm high, one day before faeces and water was added. Water was added (53 mm/h, 2 h, four times). Surface runoff and subsurface flow were collected separately at 5-min intervals. Total volume was measured for each sample.

A replicated, controlled study in 2006–2007 in two arable fields in California, USA (4), found that planting vegetation in ditches reduced the amount of sediment in runoff from furrow-irrigated fields. **Sediments:** Vegetated ditches reduced the amount of solids in runoff by 62%. Vegetated ditches reduced the amount of soil in runoff (0.1 g/L). **Methods:** Plots (183 m plots; 8–12 plots; number of plots not clearly reported) grew processing tomatoes (in Davis) or lima beans (in Chico). Each plot had 9–10 furrows, spaced 1.5 m apart. Water was added to the plots (12–20 gallons/minute/furrow; 5-6 replicates per growing season). Runoff was collected in a drain at the end of the plots (every 30 mins from beginning of surface runoff until the water was turned off). Flow rate was automatically measured every minute. Runoff was directed into vegetated and non-vegetated ditches. Water samples (500 ml) were taken before and after it passed through the vegetated ditches. Vegetation was planted in ditches (49 x 1.5 m, 0.2 m deep; six replicates: five with tall fescue *Festuca arundinacea* and one with rye grass *Lolium* spp.).

A replicated, randomized, controlled study in 1997–2010 in arable farmland in the Po Valley, Italy (5), found more soil moisture in plots with buffers, compared to plots without buffers. **Water availability:** Soil moisture was higher in buffered plots, compared to unbuffered plots, in two of eight comparisons (20% vs 19%). **Implementation options:** Soil moisture was higher in plots with 3 m buffers, compared to 6 m buffers, in one of two comparisons (20% vs 18%). **Methods:** Maize plots had grass buffers (3 m grass: tall fescue *Festuca arudinacea*), grass and woody buffers (3 m grass with one tree row; 6 m grass with one tree row; 6 m grass with two tree rows), or no buffers (two replicates of each plot). Trees included guelder-rose *Viburnum opulus* and London sycamore *Platanus hybrida*. Plots were ploughed (35–40 cm depth) and harrowed before sowing crops. Fertilizers were applied (April: 400 kg/ha of NPK; May: 450 kg/ha of urea). Grass buffers were mown twice a year in growing season (residues were not removed) and tree offshoots were removed. Trees were coppiced in 2003 and 2010. Soil samples were taken (0–15 cm) in April and October 2010.

(1) Tate, K.W., Nader, G.A., Lewis, D.J., Atwill, E.R. & Connor, J.M. (2000) Evaluation of Buffers to Improve the Quality of Runoff from Irrigated Pastures. *Journal of Soil and Water Conservation*, 55, 473-478.

(2) Bedard-Haughn, A., Tate, K.W. & Van Kessel, C. (2004) Using nitrogen-15 to quantify vegetative buffer effectiveness for sequestering nitrogen in runoff. *Journal of Environmental Quality*, 33, 2252-2262.

(3) Tate, K.W., Pereira, M.D.G.C. & Atwill, E.R. (2004) Efficacy of vegetated buffer strips for retaining Cryptosporidium parvum. *Journal of Environmental Quality*, 33, 2243-2251.

(4) Long, R.F., Hanson, B.R., Fulton, A.E. & Weston, D.P. (2010) Mitigation techniques reduce sediment in runoff from furrow-irrigated cropland. *California Agriculture*, 64, 135-140.

(5) Cardinali, A., Carletti, P., Nardi, S. & Zanin, G. (2014) Design of riparian buffer strips affects soil quality parameters. *Applied Soil Ecology*, 80, 67-76.

4.13. Restore habitat along watercourses: Water (1 study)

- Water use (0 studies)
- **Water availability (1 study):** One replicated site comparison in the USA[1] found similar amounts of water, in soils, in restored and remnant riparian habitats.
- Pathogens and pesticides (0 studies)
- Nutrients (0 studies)
- Sediments (0 studies)

A replicated site comparison in 2005–2006 in 46 riparian sites in the Central Valley, California, USA (1), found similar amounts of water in soils at restored and natural sites. **Water availability:** Similar amounts of water were found in soils at restored and natural sites (amounts not reported). **Methods:** Thirty restored sites (urban: 19; agricultural: 11; all with <30 planted elderberry plants; 2–15 years old) and 16 natural sites (within 20 km of restored sites) were compared. Restored sites were surveyed in July–early November 2005 and August–October 2006 and natural sites in April–September 2006. Restored sites were 24% of the size of natural sites. Soil samples (5–30 cm depth) were collected under three or more shrubs at each site.

(1) Koch-Munz, M. & Holyoak, M. (2008) An evaluation of the effects of soil characteristics on mitigation and restoration involving blue elderberry, Sambucus mexicana. *Environmental Management*, 42, 49-65.

Livestock management: Effects on water

4.14. Exclude grazers: Water (6 studies)

- Water use (0 studies)
- **Water availability (4 studies):** Four studies (three replicated, randomized, and controlled) in grasslands and shrublands in the USA[2,3,5] and Spain[6] found less water in areas with cattle and sheep excluded, compared to grazed areas, in some or all comparisons.
- Pathogens and pesticides (0 studies)
- **Nutrients (2 studies):** Two replicated, randomized, controlled studies in wet grasslands in the USA[1,4] found inconsistent differences in nitrogen, phosphorus, and pH in surface water in areas with cattle excluded, compared to grazed areas. One of these studies[1] found more nitrate in stream water in ungrazed areas, compared to grazed areas, in one of two experiments.
- **Sediments (1 study):** One replicated, randomized, controlled study in wet grasslands in the USA[4] found no difference in surface water turbidity between areas with cattle excluded and grazed areas.

A replicated, randomized, controlled study in 1992–1996 in grazed wetlands in northern California, USA (1), found no differences between ungrazed and cattle-grazed plots in nitrate or pH levels in surface water. A separate three-year experiment (1999–2001) found higher nitrate levels in streams in ungrazed plots, compared to grazed plots. **Nutrients:** A five-year experiment found no differences between ungrazed and grazed plots in nitrate or pH levels in surface water (data not reported). A three-year experiment found higher nitrate levels in streams in ungrazed plots, compared to grazed plots (81–1,200 vs 23–100 micromoles). **Methods:** A five-year experiment from 1992–1996 was established in three meadows. Within each meadow, three watersheds were randomly assigned to one grazing intensity: cattle excluded, light grazing (leaving 800–1,000 pounds of residual dry matter at the end of the season), or moderate grazing (leaving 600–700 pounds). Samples were taken from the spring and along the creek in each watershed. The second experiment was in 1999–2002 in marshy areas in four meadows. Two plots were established in each meadow: one ungrazed and one with moderate grazing. Water samples were taken monthly.

A replicated, randomized, controlled study in 2000–2003 in wet in alpine meadows in central California, USA (2) (same study as (5)), found that pools in plots from which cattle were excluded were wet for less time than those with two of three grazing regimes, and they dried more frequently than those in plots with one of three grazing regimes. **Water availability:** The maximum time that pools were wet was lower in ungrazed plots, compared to grazed plots, for two of three grazing regimes (65 vs 78–115 days), but not compared to plots that were grazed in the wet season. During a particularly dry year, pools in ungrazed plots dried more frequently than those in continuously-grazed plots, but not seasonally-grazed plots (2 vs 1 drying episodes). **Methods:** Eighteen plots were established in 2000, each with three pools (70–1,130 m^2) and nine times more dry land than pool. Areas were grazed continuously or seasonally (dry: October–November; wet: April–June). Before the experiment, the area had been grazed for at least 100 years.

A replicated, randomized, controlled study in rangelands in central California, USA (3), found that temporary pools dried earlier in plots from which grazers were excluded, compared to cattle-grazed plots. **Water availability:** Temporary pools were wet for less time in ungrazed plots, compared to grazed plots (maximum of 65 vs 115 days). **Methods:** Thirty-six pools in 12 groups on a cattle ranch were studied, 18 of which (six groups) were fenced to exclude cattle. The rest of the ranch was grazed at a density of one cow-calf pair/ha. Pools were monitored each week in the rainy season.

A replicated, randomized, controlled study in 2006–2010 in alpine meadows in central California, USA (4), found that most measures of water quality did not change in pools in meadows from which cattle were excluded, compared to pools in grazed meadows. **Nutrients and Sediments**: There was no change over time in ungrazed meadows, compared to grazed meadows, in total nitrogen concentration (0.4–1.5 ppm), nitrate-nitrogen (0.006–0.016 ppm), dissolved organic carbon (4.5–9.2 ppm), turbidity (reported as nephelometric turbidity units), or pH (6.1–6.8) in pools. Ammonium-nitrogen, soluble reactive phosphorus, and total phosphorus differed between meadows with different grazing regimes, in some years, but there was no clear pattern (details not reported). **Methods:** Nine meadows were studied, with cattle completely excluded from three meadows in 2006–2008, excluded from Yosemite toad *Bufo canorus* breeding habitat in three meadows, or not excluded (grazed over summer). All meadows were grazed for at least a decade before the study. Water quality was sampled each summer.

A replicated, randomized, controlled study in 2002–2010 in central California, USA (5) (same study as (2)), found that pools in plots from which cattle were excluded were shallower and wet for less time than those in grazed plots. **Water availability:** Pools were shallower in ungrazed plots, compared to grazed plots (8 vs 12 cm maximum depth), and were wet for fewer days each year (16–178 vs 41–192 wet days/year). Differences were more pronounced in drier years. **Methods:** Eighteen plots were established in 2000, each with three pools (70–1,130 m^2) and nine times more dry land than pool. Areas were grazed continuously or seasonally (dry: October–November; wet: April–June). Before the experiment, the area had been grazed for at least 100 years. Pools were monitored in 2002–2010.

A replicated site comparison in 2008–2010 in shrubland in central Spain (6) found less soil moisture in ungrazed plots, compared to sheep-and-cattle-grazed plots. **Water availability:** Less soil moisture was found in ungrazed plots, compared to grazed plots (4.4–6.5% vs 6.3–7.7%). **Methods:** Eight holm oak *Quercus ilex* trees were selected in each of two grazed and two ungrazed areas. Soils surrounding four trees in each area were tilled in April 2008. Soil moisture at 10 cm depth was measured nine times in July 2008–February 2010.

(1) Allen-Diaz, B., Jackson, R.D., Bartolome, J.W., Tate, K.W. & Oates, L.G. (2004) Long-term grazing study in spring-fed wetlands reveals management tradeoffs. *California Agriculture*, 58.

(2) Marty, J.T. (2005) Effects of Cattle Grazing on Diversity in Ephemeral Wetlands. *Conservation Biology*, 19, 1626-1632.

(3) Pyke, C.R. & Marty, J. (2005) Cattle Grazing Mediates Climate Change Impacts on Ephemeral Wetlands. *Conservation Biology*, 19, 1619-1625.

(4) Roche, L.M., Allen-Diaz, B., Eastburn, D.J. & Tate, K.W. (2012) Cattle Grazing and Yosemite Toad (Bufo canorus Camp) Breeding Habitat in Sierra Nevada Meadows. *Rangeland Ecology & Management*, 65, 56-65.

(5) Marty, J.T. (2015) Loss of biodiversity and hydrologic function in seasonal wetlands persists over 10 years of livestock grazing removal. *Restoration Ecology*, 23, 548-554.
(6) Uribe, C., Inclán, R., Hernando, L., Román, M., Clavero, M.A., Roig, S. & Miegroet, H.V. (2015) Grazing, tilling and canopy effects on carbon dioxide fluxes in a Spanish dehesa. *Agroforestry Systems*, 89, 305-318.

4.15. Use fewer grazers: Water (1 study)

- Water use (0 studies)
- Water availability (0 studies)
- Pathogens and pesticides (0 studies)
- **Nutrients (1 study):** One replicated, randomized, controlled study in wet grasslands in the USA[1] found no differences in nitrate and pH levels in surface water between areas grazed by cattle at low or moderate intensities.
- Sediments (0 studies)

A replicated, randomized, controlled study in 1992–1996 in grazed wetlands in northern California, USA (1), found no differences in nitrate levels or pH between plots grazed by cattle at light or moderate intensities. **Nutrients:** There was no difference in nitrate levels or pH in surface water in lightly grazed plots, compared to moderately grazed plots (data not reported). **Methods:** Three meadows were studied. Three watersheds in each were randomly assigned to a grazing intensity: one with cattle excluded, one with light grazing (leaving 800–1,000 pounds of residual dry matter at the end of the season), and one with moderate grazing (leaving 600–700 pounds). Samples were taken from both the spring and along the creek in each watershed. Water samples were taken monthly.

(1) Allen-Diaz, B., et al. (2004) Long-term grazing study in spring-fed wetlands reveals management tradeoffs. *California Agriculture*, 58.

4.16. Use seasonal grazing: Water (1 study)

- Water use (0 studies)
- **Water availability (1 study):** One replicated, randomized, controlled study in wet grasslands in the USA[1] found that pools were wet for longer in continuously, compared to seasonally, grazed plots.
- Pathogens and pesticides (0 studies)
- Nutrients (0 studies)
- Sediments (0 studies)

A replicated, randomized, controlled study in 2000–2003 in wet alpine meadows in central California, USA (1), found that pools in continuously grazed plots were wet for longer and dried out less frequently than those in seasonally grazed plots. **Water availability:** The maximum time that pools were wet was higher in continuously grazed plots, compared to seasonally grazed plots (115 vs 65–78 days). During a particularly dry year, pools in continuously grazed plots dried less frequently than those in seasonally grazed plots (1 vs 2 drying episodes). **Methods:** Eighteen plots were established in 2000, each with three pools (70–1,130 m^2) and nine times more dry land than pool. Areas were either grazed continuously or seasonally (dry: October–November; wet: April–June). Before the experiment, the area had been grazed for at least 100 years.

(1) Marty, J.T. (2005) Effects of Cattle Grazing on Diversity in Ephemeral Wetlands. *Conservation Biology*, 19, 1626-1632.

5. Pest regulation

Crop and soil management: Effects on pest regulation

5.1. Add compost to the soil: Pest regulation (3 studies)

- **Pest regulation (2 studies):** Of two replicated, randomized, controlled studies from the USA and an unspecified Mediterranean country[1,2], one study[2] found less disease in crops grown in soils with added compost, compared to soils without it, in some comparisons, but one study[1] found no differences in most crop diseases. One replicated, controlled study from the USA[3] found similar amounts of *Escherichia coli* bacteria in plots with or without added compost. This study[3] also found that similar percentages of pests were consumed by natural enemies in plots with or without added compost.
- **Crop damage (1 study):** One replicated, randomized, controlled study[2] found fewer dead tomato plants in soil with added compost, compared to soil without added compost, in some comparisons.
- **Ratio of natural enemies to pests (1 study):** One replicated, controlled study from the USA[3] found similar ratios of natural enemies to pests (mostly aphids) in plots with or without added compost.
- **Pest numbers (1 study):** One replicated, controlled study from the USA[3] found similar pest numbers in plots with or without added compost.
- Natural enemy numbers (0 studies)

A replicated, randomized, controlled study in 1998–2000 in farmland in the Salinas Valley, California, USA (1), found no differences in most crop diseases or crop pests, in plots with or without added compost. **Pest numbers:** Less corky root disease was found in plots with added compost, compared to plots without it, in one of six comparisons (2.2 vs 2.9 disease severity, on a scale from 1 to 12, on which 12 is the highest severity). Similar amounts of *Sclerotina minor* disease, big vein disease, or pea leafminers *Liriomyza huidobrensis* were found in plots with and without added compost (*S. minor*: 0.3–1.9% vs 0.3–1.8% of plants had symptoms; big vein: 3.0–3.6% vs 2.7–3.4% of plants had symptoms; leafminers: 10–81 vs 8–98 insects/sticky card). **Methods:** There were four plots (0.52 ha), for each of four treatments (minimum tillage or conventional tillage, with or without added organic matter). In plots with added organic matter, compost was added two times/year, and a cover crop (Merced rye) was grown every autumn or winter. The compost was made from municipal yard waste, salad packing plant waste, horse manure, clay, straw, and other compost. Lettuce or broccoli crops were grown in raised beds. Soils were disturbed to different depths (conventional tillage: 50 cm with disking, cultivating with a liliston, sub-soiling, bed re-making, and bed-shaping; minimum tillage: 20 cm with a liliston, rollers, and bed-shaping). It was not clear whether these results were a direct effect of adding compost or growing cover crops.

A replicated, randomized, controlled study (year not reported) in a Mediterranean country (possibly Greece, since all of the authors had addresses in Greece) (2) found less disease and fewer dead tomato plants in pots with added compost, compared to pots without added compost, in some comparisons. **Pest regulation:** Less disease was found on tomato leaves taken from pots with added compost, compared to pots without added compost, after the leaves were inoculated with *Septoria lycopersici* (sum of spot diameters: 0.3–4.0 vs 9.0 mm/leaf, in five of nine comparisons; number of spots: 2.5–3.5 vs 10.3 spots/leaf, in three of nine comparisons). **Crop damage:** Fewer dead tomato plants were found in pots with added compost, after the pots were inoculated with *Phytophthora nicotianae* (0–44% vs 96–99% dead plants) or *Fusarium oxysporum* (5–47% vs 39–86%; 18 of 23 comparisons). **Methods:** For each of two pathogens (*P. nicotianae* or *F. oxysporum*), there were nine pots (300 cm^3) for each of nine treatments (types of compost) and one control (no compost). All pots were inoculated with a pathogen when the tomato seeds were planted or one month before. Dead plants were counted daily. For another pathogen (*S. lycopersici*), there were six tomato plants for each of the nine treatments and one control. When these plants were four weeks old, one leaf from each was inoculated with *S. lycopersici*. Disease spots were measured after five days. The composts were made from olive-mill waste (leaves, press cakes, and wastewaters), grape waste, and mushroom waste. Tomatoes were grown in a growth chamber (25°C, 16 hour photoperiod, irrigated daily).

A replicated, controlled study in 2014 in 29 organic vegetable fields on the Central Coast, California, USA (3), found similar numbers of pests, pathogens, and natural enemies, and similar levels of pest regulation, in plots with or without added compost. **Pest regulation:** Similar percentages of pests (*Helicoverpa zea* corn earworm eggs, *Spodoptera exigua* beet armyworm larvae, and *Macrosiphum euphorbiae* potato aphids) were consumed by natural enemies in plots with or without added compost (data reported as model coefficients). **Ratio of natural enemies to pests:** Similar ratios of natural enemies to pests (mostly aphids) were found in plots with or without added compost (data reported as model coefficients). **Pest numbers:** Similar numbers of pests (mostly aphids) and pathogens (*Escherichia coli* bacteria) were found in plots with or without added compost (one sample from each had *E. coli*, but neither had shiga toxins; data on pests reported as model coefficients). **Methods:** In each of 29 vegetable fields, compost was added to one plot, but not to one adjacent plot (5 x 5 m plots), 1–2 months before lettuces were planted (25 t compost/ha, made from cow, chicken, and green manures). Lettuces were planted in spring (5–28 March) and summer (30 May–5 July). Pests and natural enemies were collected in pitfall traps (three/plot, 7.5 cm diameter) and pan traps (two/plot, blue and yellow, 15 cm diameter) after 48 hours of trapping (one sample when lettuces were seedlings and one when mature). Pests were also collected from three mature lettuces/plot. Five *S. exidua* larvae (second or third instar) and 25–70 *H. zea* eggs, glued to paper cards, were used to monitor pest regulation (48 hours/plot when lettuces were seedlings and when lettuces were mature). Regulation of aphids was measured by comparing mature lettuces in field cages (40 x 40 x 40 cm cages, 0.4 x 6 mm mesh, three caged lettuces/plot, two open cages and one closed to excluded natural enemies; all insects were removed and 50 aphids were added to one closed and one open cage/plot; aphids were collected from all three lettuces after two weeks). *E. coli* bacteria were measured in soil samples in spring (1.25 cm diameter, 0–10 cm depth).

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5.2. Use organic fertilizer instead of inorganic: Pest regulation (2 studies)

- Pest regulation (0 studies)
- Crop damage (0 studies)
- Ratio of natural enemies to pests (0 studies)
- **Pest numbers (2 studies):** One replicated, randomized, controlled study from the USA[1] found more aphids in plots with organic fertilizer, compared to inorganic fertilizer, in some comparisons, but another one[2] found similar numbers of aphids in the same study system.
- Natural enemy numbers (0 studies)

A replicated, randomized, controlled study in 1991 in a broccoli field in the Salinas Valley, California, USA (1) (same study as (2)), found more pests in plots with organic fertilizer, compared to inorganic fertilizer. **Pest numbers:** More aphids were found in plots with organic fertilizer, compared to inorganic fertilizer, in one of eight comparisons (in plots with bare soil, on two of four sampling days: data reported as model results). **Methods:** Plots (10 x 10 m) had organic fertilizer (compost) or inorganic fertilizer (amounts not reported; four plots for each). Cabbage aphids *Brevicoryne brassicae* and green peach aphids *Myzus persicae* were sampled in each plot with two yellow pan traps (12 x 8 x 8 cm traps, 12, 22, 43, and 52 days after transplanting). Pests were also sampled by heat extraction from broccoli leaves (22, 32, 42, 52 and 62 days after transplanting).

A replicated, randomized, controlled study in 1991 in a broccoli field in the Salinas Valley, California, USA (2) (same study as (1)), found similar numbers of pests in plots with organic or inorganic fertilizer. **Pest numbers:** Similar numbers of aphids were found in plots with organic or inorganic fertilizer (data not reported). **Methods:** Plots (10 x 10 m) had organic fertilizer (compost) or inorganic fertilizer (amounts not reported; four plots for each). Cabbage aphids *Brevicoryne brassicae* and green peach aphids *Myzus persicae* were sampled on 50 broccoli leaves from 50 plants in each plot (1990: every 2 weeks; 1991: every 10 days).

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5.3. Grow cover crops in arable fields: Pest regulation (19 studies)

- **Pest regulation (1 study):** One replicated, randomized, controlled study from the USA[2] found that fewer aphids were parasitized in plots with cover crops (living mulches) between broccoli plants, compared to plots without cover crops, in some comparisons.
- **Crop damage (6 studies):** Three controlled studies (two replicated and randomized) from the USA[4,14,16] found similar numbers of diseased broccoli seedlings[4] or tomato plants[14,16] in plots with or without winter cover crops. Two replicated, randomized, controlled studies from the USA[1,7] found less-severely diseased lettuces in plots with winter cover crops, compared to winter fallows, in some comparisons. One replicated, randomized, controlled study from the USA[10] found inconsistent differences in tomato damage between plots with cover crops or fallows.
- Ratio of natural enemies to pests (0 studies)
- **Pest numbers (14 studies)**
    - Weeds (8 studies): Four replicated, randomized, controlled studies from Israel[18] and Italy[8,15,17] found fewer weeds in plots with cover crops, compared to plots without them, in some comparisons[8,17,18] or all comparisons[15]. One replicated, randomized, controlled study from the USA[19] found more weeds in plots with winter cover crops, compared to plots without them, in some comparisons. Two replicated, controlled studies (one randomized) from Italy[13] and the USA[6] found that winter cover crops had inconsistent effects on weeds (sometimes more, sometimes fewer, compared to plots without winter cover crops). One controlled study from the USA[16] found similar amounts of weeds in plots with winter cover crops or fallows.
    - Weed species (2 studies): One replicated, randomized, controlled study from Italy[8] found fewer weed species in plots with winter cover crops, compared to plots without them, in one of three comparisons. One replicated, randomized, controlled study from the USA[19] found different weed communities in plots with or without winter cover crops.
    - Other pests (6 studies): Two replicated, randomized, controlled studies from the USA[2,3] found fewer aphids in plots with cover crops (living mulches) between broccoli plants, compared to plots without cover crops, in some comparisons. One replicated, randomized, controlled study from the USA[4] found more mites (in some comparisons), but similar numbers of centipedes and springtails, in plots with winter cover crops, compared to plots without them. One replicated, randomized, controlled study from the USA[7] found similar numbers of leafminers in plots with or without winter cover crops. One replicated, randomized, controlled study from the USA[5] found similar amounts of fungus in soils with or without winter cover crops. One replicated, randomized, controlled study from the USA[10] found inconsistent differences in nematode numbers between soils with cover crops or fallows.
- Natural enemy numbers (0 studies)
- **Implementation options (13 studies):** Nine studies from Israel[18], Italy[8,13,15,17], and the USA[1,6,9,10] found that different cover crops had different effects on crop damage[1] or pest numbers[6,8-10,13,15,17,18]. Two studies from the USA[2,3] found that different cover crops (living mulches) did not have different effects on pest regulation[3] or pest numbers[2]. Two studies from

the USA[11,12] found that different methods of seeding cover crops had different effects on pest numbers.

A replicated, randomized, controlled study in 1986–1988 in an irrigated lettuce field in the Salinas Valley, California, USA (1), found less-severely diseased lettuces in plots with winter cover crops, compared to winter fallows. **Crop damage:** Less-severely diseased lettuces were found in plots with cover crops, compared to fallows, in one of four harvests (autumn 1988: data reported as disease scores, based on taproot damage by corky root disease). **Implementation options:** Less-severely diseased lettuces were found in plots that were cover cropped with *Secale cereale* rye, compared to *Vicia faba* broad beans (data reported as disease scores). **Methods:** There were six plots (10.7 x 1.1 m raised beds) for each of two winter cover crops (broad beans or rye) and six control plots (bare fallow, maintained with herbicide). The cover crops were seeded in November 1986–1987, irrigated until emergence, and chopped, disked, and chisel ploughed in spring (25–30 cm depth). Lettuces were planted in May and July 1987 and March and August 1988, and they were harvested in July and October 1987 and June and October 1988. The lettuces were irrigated (1–2 cm every 2–3 days until emergence, then 2 cm/week). The severity of corky root disease was measured in 10 roots/plot at harvest.

A replicated, randomized, controlled study in 1991 in a broccoli field in the Salinas Valley, California, USA (2) (same study as (3)), found fewer pests and less parasitism of pests in plots with cover crops (living mulches) between broccoli plants, compared to bare soil. **Pest regulation:** Fewer aphids were parasitized in plots with cover crops, compared to bare soils, in 9 of 12 comparisons (0–7% vs 10–18%). **Pest numbers:** Fewer aphids were found in plots with cover crops, compared to bare soil, in 43 of 48 comparisons (0.01–0.52 vs 0.2–1.8 aphids/leaf). **Implementation options:** Similar numbers of aphids were parasitized in plots with different mixtures of cover crops (0–13%). **Methods:** Broccoli plants were transplanted into cover crops or bare soil (four replicates each, 10 x 10 m plots). The cover crops were white clover *Trifolium repens*, strawberry clover *Trifolium fragiferum*, or a mixture of birdsfoot trefoil *Lotus corniculatus* and red clover *Trifolium praetense*. Cabbage aphids *Brevicoryne brassicae* and green peach aphids *Myzus persicae* were sampled by taking 50 broccoli leaves from 50 plants in each plot (1990: every 2 weeks; 1991: every 10 days).

A replicated, randomized, controlled study in 1991 in a broccoli field in the Salinas Valley, California, USA (3) (same study as (2)), found fewer pests in plots with cover crops (living mulches) between broccoli plants, compared to bare soil. **Pest numbers:** Fewer aphids were found in plots with cover crops, compared to bare soil (pan traps: 0.2–2 vs 1–10, in four of 10 comparisons; broccoli leaves: 0.03–0.24 vs 0.25–0.5, in three of 10 comparisons). **Implementation options:** Similar numbers of aphids were found in plots with different mixtures of cover crops (pan traps: 0.04–0.79; broccoli leaves: 0.03–0.63). **Methods:** Plots had cover crops or bare soil (four replicates each). The cover crops were white clover *Trifolium repens*, strawberry clover *Trifolium fragiferum*, or a mixture of birdsfoot trefoil *Lotus corniculatus* and red clover *Trifolium praetense*. Broccoli plants were transplanted into these plots on 18 May 1991. Cabbage aphids *Brevicoryne brassicae* and green peach aphids *Myzus persicae*, were sampled in each plot with two yellow and black pan traps (12 x 8 x 8 cm), on 12, 22, 32, 42, and 52 days after transplanting the broccoli. Pests were also sampled by heat extraction on 22, 32, 42, 52, and 62 days after transplanting.

A replicated, randomized, controlled study in 1992–1993 in an irrigated broccoli field in the Salinas Valley, California, USA (4), found more mites, but similar numbers of other pests and diseases, in soils with winter cover crops, compared to bare soils. **Crop damage:** Similar numbers of diseased seedlings were found in plots with or without cover crops (numbers of seedlings not reported). **Pest numbers:** More mites were found in plots with cover crops, compared to bare soils, in four of 28 comparisons (90–220 vs 30–150 mites/sample), but similar numbers of centipedes and springtails were found (0.3–15 springtails/sample; numbers of centipedes not reported). Similar amounts of disease-causing fungus were found in soils with or without cover crops (numbers of *Sclerotina minor* sclerotia not reported). **Methods:** There were three plots for winter cover crops (half *Phacelia tanacetifolia* and half *Secale cereale* Merced rye, sown in November 1992 and mown in March 1993) and three control plots with bare soil in winter. All plots (252 x 24 m) were tilled in March 1993 (15 cm depth), and the cover crops were incorporated into the soil. Two broccoli crops were grown on raised beds (first crop: April–August 1993; second crop: August–November 1993). All plots were irrigated (440–450 mm/crop, subsurface drip irrigation) and fertilized (41–42 g N/m^2/crop). Pests were measured in soil samples (0–15 cm depth, 14 samples in March–November 1993). Broccoli diseases were measured in ten 2 m^2 areas/plot.

A replicated, randomized, controlled study in 1991–1994 in an irrigated tomato field in the San Joaquin Valley, California, USA (5), found similar amounts of fungus in soils with winter cover crops or winter fallows. **Pest numbers:** Similar amounts of *Rhizoctonia solani* fungus were found in soils with cover crops or fallows (0.3–1.7 vs 1.3 colony forming units/100 g dry soil). **Methods:** There were four plots (93 x 7 m plots) for each of three winter cover crops and one control (winter fallow). The cover crops were *Hordeum vulgare* barley, *Vicia dasycarpa* Lana woollypod vetch, or a barley-vetch mixture, seeded in October 1991–1993 and incorporated into the soil in March 1992–1994 (15–20 cm depth, rotary tiller). Fungus colonies were measured in soil samples, collected in spring 1994 (0–15 cm depth).

A replicated, controlled study in 1996–1998 in an irrigated tomato field in the San Joaquin Valley, California, USA (6), found more weeds in plots with winter cover crops (and no tillage in spring), compared to plots with winter fallows (and tillage in spring), when herbicide was used on the fallows. When herbicide was not used, differences were inconsistent. **Pest numbers:** More weeds were found in plots with cover crops, compared to fallows, in some comparisons (in 9 of 12 comparisons with herbicide-use on fallows, in 1998: 4–12% vs 0–3% weed cover; in two of 12 comparisons without herbicide-use on fallows, in 1998: 5–6% vs 2%), but fewer weeds were found in two of 12 comparisons without herbicide-use on fallows, in 1998 (4–5% vs 11%). In 1997, similar weed cover was found in plots with or without cover crops (1–4%). **Implementation options:** Fewer weeds were found in plots that were cover cropped with grass-legume mixtures, compared to legumes, in two of six comparisons in 1998 (in May: 4–5% vs 11–12% weed cover). **Methods:** There were 12 plots (4.5 x 27.5 m plots) for each of four treatments (two grass-legume mixtures, or two legumes without grasses, as winter cover crops, sown in October 1996–1997, killed and retained as mulch, with no tillage, in March 1997–1998) and each of two controls (bare-soil fallows in winter, with or without herbicide, and conventional tillage in spring). Tomato seedlings were transplanted in April 1997–1998. The tomatoes were irrigated (two inches/week) and fertilized (0, 100, or 200 lb N/acre). All plots were hand weeded in May, June, and July, and control plots were also cultivated in May and June. Weed cover was estimated before cultivation (July 1997 and May, June, and July 1998) or after cultivation (May and June 1997), in three quadrats/plot (1.8 m^2 quadrats).

A replicated, randomized, controlled study in 1998–2000 in an irrigated vegetable field in the Salinas Valley, California, USA (7), found less corky root disease in plots with winter cover crops, compared to plots without cover crops. **Crop damage:** Less corky root disease was found in plots with cover crops, in one of four comparisons (2.2 vs 2.9 disease severity, on a scale from 1 to 12, on which 12 is the highest severity). Similar amounts of *Sclerotina minor* disease and big vein disease were found in plots with or without cover crops (*S. minor*: 0.3–1.9 vs 0.3–1.7% of plants had symptoms; big vein: 3.0–3.6 vs 2.7–3.4% of plants had symptoms). **Pest numbers:** Similar numbers of *Liriomyza huidobrensis* pea leafminers were found in plots with or without cover crops (10–81 vs 8–98 insects/sticky card). **Methods:** There were four plots (0.52 ha), for each of four treatments (reduced tillage or conventional tillage, with or without added organic matter). In plots with added organic matter, compost was added two times/year, and a cover crop (*Secale cereale* Merced rye) was grown every autumn or winter. Lettuce or broccoli crops were grown on raised beds. Sprinklers and drip irrigation were used in all plots. Soils were disturbed to different depths (conventional tillage: disking to 50 cm depth, cultivating, sub-soiling, bed re-making, and bed-shaping; reduced tillage: cultivating to 20 cm depth, rolling, and bed-shaping). It was not clear whether these results were a direct effect of adding compost or growing cover crops.

A replicated, randomized, controlled study in 1993–2001 in a rainfed cereal field in central Italy (8) found fewer weeds and weed species in plots with winter cover crops, compared to plots without cover crops. **Pest numbers:** Fewer weed species were found in plots with cover crops, compared to plots without cover crops, for one of three species of cover crop (rye: 16 vs 18 weed species). Fewer weeds were found in plots with cover crops, compared to plots without cover crops, for one of three species of cover crop (rye, in plots with conventional tillage: 7,000 vs 9,000 weed seedlings/m^2; subterranean clover, in plots with no tillage: 32,000 vs 40,000). **Implementation options:** Fewer weed species were found in plots that were cover cropped with rye, compared to crimson clover (16 vs 18 species), but no differences were found in two of three comparisons between species of cover crops. **Methods:** Winter cover crops (*Secale cereale* rye, *Trifolium subterraneum* subterranean clover, or *T. incarnatum* crimson clover) were grown on 72 treatment plots, but not on 24 control plots on which cereal crop residues were retained over winter (21 x 11 m sub-sub-plots, in a split-split-plot experimental design). In spring, the cover crops were flailed, half of the plots were tilled (30 cm depth), and half were not. Herbicide and fertilizer were used on all plots. Weed seeds were sampled in soil cores in February 2001 (27 cores/plot, 0–15 cm depth, 3.5 cm diameter) and identified after germination in a greenhouse.

A replicated, randomized study in 2001–2003 in an irrigated lettuce field in the Salinas Valley, California, USA (9), found different numbers of weeds in plots with different species of cover crops. **Implementation options:** Fewer weeds were found in plots that were cover cropped with mustard, compared to oats, in two of six comparisons (December 2001 and January 2002: 18–21 vs 65–110 g weeds/m^2), and also compared to a legume-oat mixture, in three of six comparisons (December 2001, January 2002, and January 2003: 11–21 vs 121–188 g weeds/m^2). Fewer weeds were found in plots that were cover cropped with oats, compared to the legume-oat mixture, in two of six comparisons (January 2002 and 2003: 37–65 vs 170–188 g weeds/m^2). Fewer weed seeds (*Urtica urens* burning nettle) were found in plots that were cover cropped with mustard (0–1,300 viable seeds/m^2), compared to oats (1,900–6,000) or the mixture (4,300–13,600), but the difference between plots with oats or the mixture was not significant. After the cover crops were incorporated into the soil, fewer weeds were found in plots that were cover cropped with mustard (113 weed seedlings/m^2), compared to oats (246/m^2) or the mixture (377/m^2), in one of two years (2002), but the difference between plots with oats or the mixture was not significant. **Methods:** One of three cover crops (*Avena sativa* oats; *Brassica hirta* and *B. juncea* mustard; or *Vicia faba, Pisum sativum, Vicia sativa, Vicia villosa,* and *A. sativa* legume-oat mixture) was planted in October (2001: three 2.2 x 30 m plots each; 2002: four 3 x 30 m plots each). Weed biomass was sampled in two 30 x 30 cm quadrats/plot in 2001–2002, and in one 100 x 100 cm quadrat/plot and one 30 x 30 cm quadrat/plot in 2002–2003, in December, January, and February. Weed seeds were collected in January, in vacuum samples (30 x 30 cm/plot). Cover crops were mown and incorporated into the soil (rototilled, 15 cm depth) in March 2002 and February 2003. The soil was then watered (5–10 cm water), and weeds were counted in eight 50 x 50 cm quadrats and five 30 x 30 cm quadrats (2002: 36 days after incorporation; 2003: 48 days).

A replicated, randomized, controlled study in 1997–2001 in irrigated tomato fields at two sites in the Coachella and San Joaquin Valleys, California, USA (10), found more root-knot nematodes *Meloidogyne* spp. and tomato roots with more galling (caused by nematodes) in soils with cover crops, compared to dry fallows, but cover crops had inconsistent effects on nematodes and galling, compared to wet fallows. **Crop damage:** More root galling was found in plots with cover crops, compared to dry fallows (e.g., in Experiment 1: 0.9–2.7 vs 3.2–7.6 root gall index), but inconsistent differences were found between plots with cover crops or wet fallows (sometimes more, sometimes less). **Pest numbers:** More nematodes were found in soils with cover crops, compared to fallows, in most comparisons (e.g., for dry fallows, in Experiment 2: 4–1,005 vs 1). **Implementation options:** For cover crops that were not resistant to nematodes, more nematodes were found in soils with cover crops, compared to fallows, in most comparisons (e.g., in Experiment 1: 9,148–9,803 vs 19–599). However, for cover crops that were resistant to nematodes, fewer nematodes were found in soils with cover crops, compared to wet fallows, in some comparisons (e.g., in Experiment 1, in four of 10 comparisons: 3–72 vs 19–599), and more nematodes were found in other comparisons (e.g., in Experiment 4, without incorporation: 26–35 vs 1). **Methods:** Six experiments compared plots with cover crops (cowpeas *Vigna unguiculata*: several nematode-resistant cultivars and one susceptible cultivar, sometimes incorporated into the soil, and sometimes not) to plots with fallows (dry or wet) between 1997 and 2001 (4–6 replicate plots/treatment/experiment). Some herbicide, but no fertilizer, was used. In the Coachella Valley, cover crops were sown in late July or early August and suppressed after 70–84 days. The following year, tomatoes were planted in late January or early March and harvested in June. In the Central Valley, cover crops were sown in May and suppressed after 83 days. The following year, tomatoes were planted in April and harvested in August. Nematode juveniles and eggs were counted in soils samples (0–30 cm depth). Root galling was measured at harvest (21 tomato root systems/plot).

A replicated, randomized, controlled study in 2003–2005 on an irrigated vegetable farm in Salinas, California, USA (11) (partly the same study as (12)), found fewer weeds in plots that were sown with more cover crop seeds, compared to fewer, and in plots that were planted in a grid of perpendicular rows, compared to parallel rows. **Implementation options:** Fewer weeds were found in plots that were sown with more cover crop seeds, in five of six harvests (270 kg seeds/ha: 0–10 kg weeds/ha; 180 kg seeds/ha: 1–22 kg weeds/ha; 90 kg seeds/ha: 6–47 weeds/ha). Fewer weeds were found in plots that were sown in a grid (two passes of the seed drill, in perpendicular rows, with half as many seeds/pass as conventional passes), compared to conventionally (one pass, in parallel rows), in one of six harvests (1 vs 6 kg weeds/ha). Weeds emerged at similar times in plots planted with different amounts of seed, and in plots planted in a grid or conventionally (data not reported). **Methods:** Twenty-four plots were planted with winter cover crops (*Secale cereale* Merced rye), with 90, 180, or 270 kg seeds/ha, in October 2003–2004 (12 x 12 m plots). Half of these plots were planted in grid, and half were planted conventionally. Weed biomass was measured 18 days after planting (two quadrats/plot, 50 x 50 cm quadrats).

A replicated, randomized, controlled study in 2003–2005 in two irrigated fields in the Salinas and Hollister Valleys, California, USA (12) (partly the same study as (11)), found fewer weeds in plots that were sown with more cover crop seeds, compared to fewer. **Implementation options:** Fewer weeds were found in plots that were sown with more cover crop seeds, compared to fewer, in seven of 12 comparisons (336 kg seeds/ha: 0–2% of dry matter was weeds; 112 kg seeds/ha: 0–10%). Similar numbers of weeds were found in plots that were sown in a grid (two passes of the seed drill, in perpendicular rows, with half as many seeds/pass as conventional passes), compared to conventionally (one pass, in parallel rows) (data not reported). **Methods:** In Hollister, there were twenty-four 12 x 12 m plots. Half were sown in a grid, and half were sown conventionally. In Salinas, there were nine 12 x 15 m plots. All plots were sown with cover crops in November 2003–2004 (112, 224, or 336 kg seeds/ha). The seeds were a mixture of oats and legumes (beans, peas, and vetch). Biomass was measured four times/year in December–April 2004–2005 (one quadrat/plot, 100 x 50 or 50 x 50 cm).

A replicated, randomized, controlled study in 1999–2001 in two irrigated tomato fields in central Italy (13) found that winter cover crops had inconsistent effects on weeds. **Pest numbers:** In spring, fewer weeds were found in plots with winter cover crops, compared to bare soil in winter, in six of 16 comparisons (10–55 vs 62–82 weeds/m^2; 2–10 vs 12–50 g weeds/m^2), but more weeds were found in one of sixteen comparisons (70 vs 50 g weeds/m^2). **Implementation options:** The fewest weeds were found in plots that had been cover cropped with *Avena sativa* oats (10–21 weeds/m^2; 2–10 g weeds/m^2), and the most were found in plots that had been cover cropped with *Vicia villosa* hairy vetch (57–73 weeds/m^2; 13–70 g weeds/m^2). **Methods:** In September–May, cover crops were grown on 12 treatment plots, but not on three control plots, which were weeded with a disk cultivator (6 x 9 m plots). Cover crops were mown in May. All plots were irrigated and fertilized (100 kg P_2O_5/ha in September, 0–100 kg N/ha in June–July). Tomato seedlings were transplanted in May, and weeds were sampled 15 and 30 days later, between the tomato rows.

A replicated, randomized, controlled study in 2005–2006 in an irrigated, organic tomato field in Yolo County, California, USA (14), found that similar numbers of tomato plants were lost to disease in plots with winter cover crops or winter fallows. **Crop damage:** Similar numbers of tomato plants were lost to Southern blight *Sclerotium rolfsii* in plots with cover crops or fallows (83% vs 89% survival). **Methods:** The field was levelled and fertilized (17 Mg compost/ha). Eight plots had winter cover crops (mustard *Brassica nigra*, planted on 3 November 2005) and eight plots had winter fallows. Each plot was 16 x 9 m. Cover crops were mown on 26 April 2006, sprinkler irrigated, and tilled into the soil (10 cm depth) after 19 days, when fallow plots were also tilled. Plots were weeded and sulfur was used against mites and diseases. Tomatoes were furrow irrigated (approximately every 11 days: 88 mm/event). Plants were assessed for Southern blight, 74 days after planting and at harvest (7–8 September 2006).

A replicated, randomized, controlled study in 1993–2008 in a rainfed wheat-maize-wheat-sunflower field in central Italy (15) found fewer weeds in plots with winter cover crops, compared to plots without cover crops. **Pest numbers:** Fewer weeds were found in plots with cover crops (7–18 vs 28 Mg/ha). **Implementation options:** Fewer weeds were found in plots with non-legume cover crops, compared to legumes (14–18 Mg/ha). Fewer weeds were found in plots with high-nitrogen-supply legumes, compared to low-nitrogen supply legumes (14 vs 18 Mg/ha). **Methods:** There were 32 plots (21 x 11 m sub-sub-plots) for each of three treatments (non-legumes, low-nitrogen-supply legumes, or high-nitrogen-supply legumes as winter cover crops) and there were 32 control plots (no cover crops: crop residues and weeds over winter). Different species of cover crops were used in different years. Half of the plots were tilled, and half were not tilled (but pre-emergence herbicide was used). Post-emergence herbicide and fertilizer were used on all plots. Weeds were collected when the crops were harvested or the cover crops were suppressed (2–4 m^2 quadrats), in 1994–2008.

A controlled study in 2005–2006 in an irrigated tomato field in the Sacramento Valley, California, USA (16), found no differences in crop damage or weed biomass between the parts of the field that were cover cropped or fallow over winter. **Crop damage:** Similar numbers of tomatoes were damaged by insects in each part of the field (5–11 Mg fresh weight/ha), and similar numbers had blossom end rot (4 vs 2 Mg fresh weight/ha). **Pest numbers:** Similar amounts of weed biomass were found in each part of the field (2 Mg dry weight/ha). **Methods:** A field was divided into two parts: one part with a winter cover crop (mustard *Brassica nigra*, planted in autumn 2005, and disked into the soil in spring 2006), and one part fallow. Tomatoes were planted in both parts of the field in spring 2006. Tomatoes were sampled on 393 m transects (1 x 3 m quadrats every 30 m).

A replicated, randomized, controlled study in 2009–2011 in two irrigated pepper fields in central Italy (17), found fewer weeds in plots with winter cover crops, compared to plots without cover crops, and oat was a better cover crop than hairy vetch or canola for controlling weeds. **Pest numbers:** Fewer weeds were found in plots with cover crops, compared to plots without cover crops, in 16 of 18 comparisons (0–117 vs 48–152 plants/m^2). **Implementation options:** Fewer weeds were found in plots with oats as the winter cover crop, compared to hairy vetch, in five of six comparisons (0–7 plants/m^2), and compared to canola, in all comparisons (0–10 vs 38–117). Fewer weeds were found in plots with hairy vetch as the cover crop, compared to canola, in three of six comparisons (26–94 vs 38–117 plants/m^2). **Methods:** Three species of winter cover crops (*Vicia villosa* hairy vetch, *Brassica napus* canola, or *Avena sativa* oats) were sown on nine plots each (6 x 12 m plots) in September 2009–2010, and no cover crops were sown on nine plots (weeded, bare soil). The cover crops were mown and used as mulch (50 cm wide) in some plots, or were chopped and tilled into the soil in other plots, in May 2010–2011. Pepper seedlings were transplanted into these plots in May, and fruits were harvested twice/year in August–October 2010–2011. Weeds were sampled 30 days after transplanting (six samples/plot). All plots were fertilized before the cover crops, but not after. All plots were irrigated.

A replicated, randomized, controlled study in 2011–2014 in irrigated potato fields in Israel (18) found fewer weeds in plots with cover crops, compared to bare soil, both in the potato-growing season and also in the winter. **Pest numbers:** During the potato-growing season, fewer weeds were found in plots with cover crops, compared to bare soil, for one of five cover crops (oats and vetch, 60 days after planting potatoes, in 2011–2012: 11 vs 44 weeds/m^2; data not reported for other cover crops or other years). During the cover-cropping season, fewer weeds were found in plots with cover crops, compared to bare soil, for all mixtures of cover crops (2–26 vs 36–82 weeds/m^2; data not reported for other years). Less weed biomass was found in plots with cover crops, compared to bare soil (2013–2014: 5–20 vs 505 g/m^2; data not reported for other years). **Implementation options:** During the potato-growing season, fewer weeds were found in plots that were cover cropped with oats and vetch, compared to canola (11 vs 43 weeds/m^2), but difference between these and other cover crops were not significant. During the cover-cropping season, similar numbers of weeds were found in plots with different mixtures of cover crops (2–26 weeds/m^2). **Methods:** Different plots were used in different years (2011–2012: 350 m^2 plots, 20 plots with cover crops, eight plots without cover crops; 2012–2013: 695 m^2 plots, 10 with, 10 without; 2013–2014: 1,800 m^2 plots, four with, four without). Different mixtures of cover crops were used in different years, but oats were used in all years, and triticale was used in Years 1 and 2 (2011–2013). Plots without cover crops were weeded (tilled bare; some plots in all years) or weedy (not tilled; some plots in Year 1). Fertilizer and herbicide (after cover crops, before potato emergence) were used on all plots. Weeds were sampled in 0.25 m^2 round quadrats (1–3 quadrats/plot).

A replicated, randomized, controlled study in 1999–2011 in an irrigated tomato-cotton field in the San Joaquin Valley, USA (19), found more weeds and different weed species in plots with winter cover crops, compared to plots without winter cover crops. **Pest numbers:** More weeds were found in plots with cover crops, in six of 12 comparisons (28–121 vs 3–98 plants/m^2). Different communities of weeds were found in plots with or without cover crops, in one of two comparisons (in plots with conventional tillage: data reported as distance in ordination space). **Methods:** Rainfed winter cover crops (triticale, rye, and vetch) were planted on 16 treatment plots, but not on 16 control plots, in October 1999–2010. Crop residues were chopped in March. Reduced tillage or conventional tillage was used on half of these plots, in 1999–2011. The plots (9 x 82 m) had six raised beds each. Different numbers of tillage practices were used for conventional tillage (19–23 tractor passes, including disk and chisel ploughing) and reduced tillage (11–12 tractor passes, not including disk and chisel ploughing). All plots were fertilized (conventional tillage: 89.2 kg/ha dry fertilizer, 111.5 kg/ha urea; reduced tillage: 124.9 kg/ha urea). Weeds were counted in January 2003 (1 m^2 quadrats, four quadrats/plot), as well as March 2006 and June 2011 (0.25 m^2 quadrats, two quadrats/plot). Soil cores were collected in June 2011 (8.25 cm diameter, 0–10 cm depth). Seeds from these soil cores were germinated, and weed species were counted.

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5.4. Plant or maintain ground cover in orchards or vineyards: Pest regulation (13 studies)

- **Pest regulation (3 studies):** One replicated, randomized, controlled study from the USA[3] found that more leafhopper eggs were parasitized in plots with cover crops, compared to bare fallows, in one of six comparisons. Two replicated, randomized, controlled studies from the USA[2,4] found inconsistent differences[2] or no differences[4] in the parasitism of leafhopper eggs between plots with or without ground cover.
- **Crop damage (1 study):** One replicated, randomized, controlled study from the USA[12] found that more grapes were damaged by pests in plots with cover crops, compared to bare fallows, in some comparisons.
- Ratio of natural enemies to pests (0 studies)
- **Pest numbers (12 studies)**

- Weeds (2 studies): One replicated, randomized, controlled study in an olive orchard in Spain[10] found fewer weeds in plots with cover crops, compared to bare soil, in one of two comparisons. One replicated, controlled study from a vineyard in the USA[5] found more weeds in plots with cover crops, compared to bare soil, in one of nine comparisons.
    - **Implementation options (4 studies):** Three studies from vineyards in the USA[7,9,13] found different numbers of weeds[7,9] or weed species[13] in plots with different types of ground cover, in some comparisons[7,9] or all comparisons[13]. One study from the USA[6] found similar numbers of weeds in vine rows with or without cover crops. One replicated, randomized, controlled study from the USA[7] found that plant diversity decreased over time in plots without tillage, but increased in plots with tillage. This study[7] found that tillage had no effects on the number of plant species and had inconsistent effects on plant biomass.
- Insects (5 studies): Two replicated, controlled studies (one randomized) from the USA[2,3] found fewer leafhoppers in plots with cover crops, in some comparisons. One replicated, randomized, controlled study from the USA[12] found more leafhoppers, in some comparisons. One replicated, randomized, controlled study from the USA[4] found similar numbers of leafhoppers. One replicated, randomized, controlled study from the USA[8] found more navel orangeworm moths in plots with resident vegetation, compared to tilled soil, in one of two comparisons.
    - **Implementation options (2 studies):** Two studies from the USA[3,8] found fewer pests in plots with mown ground cover, compared to unmown ground cover[8] or compared to ground cover before mowing[3].
- Mammals (1 study)
    - **Implementation options (1 study):** One study from the USA[6] found more gophers in plots with clover, compared to other cover crops.

- **Natural enemy numbers (6 studies):** Four replicated, controlled studies (three randomized) from Spain[11] and the USA[2,4,12] found more natural enemies in plots with ground cover, compared to plots without ground cover, in some comparisons[2,11,12] or all comparisons[4]. One replicated, controlled study from the USA[3] found fewer parasitoids in plots with ground cover, in some comparisons. One replicated, randomized, controlled study from the USA[1] found inconsistent differences in the numbers of spiders between plots with or without ground cover. One of these studies[1] found no difference in the number of spider species between plots with or without ground cover, and another[4] found no difference in the composition of spider communities.
    - **Implementation options (1 study):** One study from the USA[3] found more natural enemies in plots with mown cover crops, one week after mowing, compared to before mowing.

A replicated, randomized, controlled study in 1992–1995 in a vineyard in the San Joaquin Valley, California, USA (1), found similar numbers of spiders and spider species on grape vines with or without cover crops between the vine rows in spring and summer. **Natural enemy numbers:** Similar numbers of spiders and spider species were found on grape vines with or without cover crops between the vine rows in spring and summer (15.1 vs 13.6 spiders/vine; data on species not reported). More *Trachelas pacificus* spiders were found on grape vines with cover crops, compared to bare soil, between the vine rows in spring and summer (7.2 vs 4.7 spiders/vine), but fewer *Hololena nedra* spiders were found (0.8 vs 1.2 spiders/vine). **Methods:** Cover crops were seeded between the vine rows in autumn 1992–1994 in ten plots (1.4 ha plots; 8 rows x 80 vines). In five treatment plots, the cover crops were mown in March 1993–1995 and allowed to regrow with resident vegetation over the summer, but in five control plots they were tilled and bare soil was maintained with herbicide (1993) or cultivation between rows and ploughing within rows (1994–1995) until mid-August. In July 1995, herbicide was used on all plots. Spiders were collected in May–September 1993–1995 by shaking the grape vines over drop cloths (two samples/plot/month, 15 seconds/sample, 9 x 3 m cloth).

A replicated, randomized, controlled study in 1993–1996 in four vineyards in the San Joaquin Valley, California, USA (2), found fewer pests and more natural enemies in plots with cover crops between the vine rows, compared to plots without cover crops between the vine rows. **Pest regulation:** No consistent differences were found in the parasitism of *Erythroneura* spp. leafhopper eggs in plots with or without cover crops between the vine rows (data not reported). **Pest numbers:** Fewer leafhoppers were found in plots with cover crops, compared to plots without cover crops, in seven of eight comparisons (1–36 vs 5–48 third-generation leafhopper nymphs/20–30 vine leaves). **Natural enemy numbers:** More spiders were found on grape vines in plots with cover crops, in one of four vineyards (data not reported). **Methods:** Cover crops were grown between the vine rows in a total of 19 plots (0.05–0.6 ha plots), and no cover crops were grown in a total of 19 plots (which were treated with herbicide, mown, and/or disked between the vine rows), in a total of four vineyards. Leafhoppers were sampled on 20–30 vine leaves/plot, and vines were shaken (15 seconds/sample) to collect spiders on sheets (3 x 7.3 m) or in funnels (0.9 x 0.9 m), in May–October 1993–1996.

A replicated, controlled study in 1996–1997 in two vineyards in northern California, USA (3), found greater pest regulation and fewer pests, but fewer natural enemies, in vine rows with cover crops, compared to vine rows without cover crops. **Pest regulation:** More parasitized eggs of *Erythroneura elegantula* western grape leafhoppers were found in vine rows with cover crops, compared to those without cover crops, in one of six comparisons (July 1997: 64% vs 55% parasitism). **Pest numbers:** Fewer leafhoppers and fewer *Frankliniella occidentalis* western flower thrips were found in vine rows with cover crops, compared to those without cover crops, in most comparisons (in most of 1996: 6–53 vs 8–75 leafhopper adults/trap; in most of 1997: 60–460 vs 90–690; from 30 May to 9 August 1996: 1–33 vs 3–38 leafhopper nymphs/leaf; from 25 July to 7 August 1997: 9–10 vs 21–22; in 1996: 70–920 vs 110–1,170 thrips/trap; in 1997: 8,200–12,900 vs 11,000–17,200). **Natural enemy numbers:** Fewer *Anagrus epos* parasitoids of grape leafhopper eggs were found vine rows with cover crops, compared to those without cover crops, in some comparisons (31 July–28 August 1996: 300–1,750 vs 450–2,200 parasitoids/trap; 24 July–28 August 1997: 400–3,650 vs 400–4,100). **Implementation options:** More predators and fewer leafhopper nymphs were found in rows with mown cover crops, one week after mowing, compared to before mowing (in 1996: 6 vs 2 predators/trap, 45 vs 53 leafhoppers/trap). **Methods:** In each of two vineyards, one block of vines had cover crops between the vine rows (in every other vine row), and one block was tilled and had no cover crops between the vine rows. *Fagopyrum esculentum* buckwheat and *Helianthus anuus* sunflower were grown as cover crops. Pests and natural enemies were sampled with sticky traps in April–September 1996–1997 (10 yellow and 10 blue traps/row, 10 rows/block). Leafhopper nymphs and parasitized eggs were sampled from 10 vine leaves/row. In one of the two vineyard blocks, three rows of cover crops were mown three times/year. In these rows and three unmown rows, pests and natural enemies were sampled (five sticky traps/row).

A replicated, randomized, controlled study in 1991–1992 in an irrigated vineyard in the San Joaquin Valley, California, USA (4), found more spiders in plots with cover crops, compared to bare soil, between the vine rows. **Pest regulation:** Similar percentages of *Erythroneura variabilis* leafhopper eggs were parasitized in plots with or without cover crops between the vine rows (5–90%). **Pest numbers:** Similar numbers of leafhoppers were found in plots with or without cover crops between the vine rows (2.9 vs 2.4 nymphs/leaf; 19 vs 18 adults/trap, 9–45 vs 9–31 eggs/leaf). **Natural enemy numbers:** More spiders were found in plots with cover crops, compared to bare soil, between the vine rows (9 vs 6 spiders/sample), but there was no difference in spider species composition (data not reported). **Methods:** Cover crops (1.5 m width) were grown between the vine rows (3.7 m width) in three plots, and bare soil was maintained through cultivation between the vine rows in three control plots (two vine rows/plot, 110 m length). The cover crops (*Avena sativa* oats, *Vicia sativa* common vetch, and *V. benghalensis* purple vetch) were seeded in November 1991, mown to 20 cm height in April 1992, tilled in July 1992, and cultivated thereafter. Leafhoppers were sampled every 14–18 days in May–September 1992 (nymphs on 24 grape leaves/plot, adults on three yellow sticky traps/plot, eggs and egg parasitism on five grape leaves/plot). Spiders were sampled every month by shaking the vine canopy for 10 seconds into funnels (0.58 m^2 funnels, two samples/plot).

A replicated, controlled study in 2001–2003 in an irrigated vineyard in the Salinas Valley, California, USA (5), found more weeds under grape vines in vine rows with cover crops, compared to vine rows without cover crops. **Pest numbers:** More weeds were found under grape vines in rows with cover crops, compared to rows without cover crops, in one of nine comparisons (in winter, in cultivated rows: 65–80% vs 35% weed frequency). **Methods:** There were nine plots (0.045 ha) for each of two cover crops (*Secale cereale* Merced rye or *Triticosecale* triticale, in the central 80 cm of the 240 cm between the vine rows, which were disked every year in November, before they were planted, and were mown every year in spring), and there were nine control plots (bare soil between the vine rows, which were disked every month). One-third of the plots were cultivated under the vine rows. Weeds were sampled in summer (June 2002), winter (March 2003), and spring (May 2003) on 30.5 m transects.

A replicated, randomized, controlled study in 1996–2000 in an irrigated vineyard in the Sacramento Valley, California, USA (6), found more pocket gophers in plots that were cover cropped with clovers, compared to other species of cover crops. **Implementation options:** More *Thomomys* spp. pocket gophers were found in plots that were cover cropped with clovers, compared to other cover crops (0.9–6.7% vs 0–0.3% of each plot had signs of gophers). Similar numbers of weeds were found in plots with different cover crops (0.15–0.41 t dry weight/planted ha). **Methods:** There were four plots for each of four cover crops (1.8 m width, between vine rows of 3.4 width), and there were four control plots (periodically disked between the vine rows). Each plot was 10 contiguous vines and two adjacent interrows. The cover crops were Californian native grasses (not tilled, mown), annual clover (not tilled, mown), barley and oats (mown and disked), or legumes and barley (mown and disked in spring and used as a green manure). The Californian native grasses were seeded between the vine rows in autumn 1996. The others were seeded in autumn 1997–1999. All plots were drip irrigated, fertigated (20 kg N/ha/year), and the grass cover crops were also fertilized with urea (45 kg N/ha/year). Herbicide was used under the vines. Weeds were sampled in the cover crops in April 1998–2000 (four samples/plot, 1.0 x 0.5 m quadrats). Gophers were sampled in January, February, and March 1999 (looking for mounds and feeding holes that were less than two days old, throughout the plots).

A replicated, randomized, controlled study in 2002–2005 in an irrigated vineyard in the Napa Valley, California, USA (7), found similar numbers of weeds under grape vines, but more weeds between vine rows, in vine rows with seeded cover crops, compared to resident vegetation. Plant diversity between the vine rows decreased over time without tillage, but increased over time with conventional tillage. Tillage had inconsistent effects on plant biomass between the vine rows. **Implementation options:** Similar numbers of weeds were found under the vines in rows with or without seeded cover crops (2–32 g weed biomass/m^2). More weeds were found in interrows with seeded cover crops, compared to interrows with resident vegetation, in three of nine comparisons (cover crops with no tillage: 22–158 vs 1–2 g weed biomass/m^2). Plant diversity between the vine rows decreased over time in rows with no tillage, and increased over time in rows with conventional tillage (data reported as the Shannon index), but similar numbers of species were found (3–6 species). Less plant biomass was found between vine rows, in rows with no tillage, compared to conventional tillage, for two plant species (*Sonchus aster* spiny sowthistle: 0.03–0.09% vs 2.69–2.76% of weed biomass/sample; *Anagallis arvensis* scarlet pimpernel: 0–0.05% vs 0.12–2.65%), but more biomass was found for one species (*Medicago polymorpha* California burclover: 2–25% vs 4–8%), and inconsistent biomass was found for three species. **Methods:** No tillage or conventional tillage was used on eight plots each, between the vine rows (three vine rows/plot). A disk plough was used for conventional tillage (15 cm depth, once/year in April–June). Four plots with conventional tillage had annual cover crops (seeded in October 2002–2004) and four plots had resident vegetation. Four plots with no tillage had annual cover crops (seeded in October 2002–2004), and four had perennial cover crops (seeded in October 2002). All plots were drip irrigated in July–October (85 kl/ha/week). Weeds were sampled under the vines and between the rows (four quadrats/plot in each location, 25 x 40 cm quadrats), when the vines were in full bloom (June 2003, May 2004, and May 2005). Herbicide was used under the vine rows (Glyphosate, twice/year), but not between the rows.

A replicated, randomized, controlled study in 2002 in a pistachio orchard in the San Joaquin Valley, California, USA (8), found more pests in plots with ground cover, compared to plots with tilled soils. **Pest numbers:** More *Amyelois transitella* navel orangeworm moths were found in plots with ground cover (without tillage in the drive rows between rows of trees), compared to plots with tilled soils, in one of two comparisons (with unmown ground cover: 7 vs 1). **Implementation options:** Fewer moths were found in plots with ground cover that was mown, compared to unmown (9 vs 2). **Methods:** There were six plots (11 square feet/plot) for each of two treatments (ground cover in the drive rows, with or without mowing), and there were six control plots (tillage between the drive rows with a disk plough; depth not reported). The ground cover was resident vegetation. Before mowing or disking, two hundred pistachio nuts, infested with navel orangeworm larvae, were placed in each plot (about 71 larvae/plot). The plots were then covered with cloth, and moths were counted every week, after they emerged from the nuts.

A replicated, randomized study in 2001–2006 in an irrigated vineyard in the Central Coast, California, USA (9), found fewer weeds in plots that were cover cropped with rye, compared to trios, between the vine rows. **Implementation options:** Fewer weeds were found in plots that were cover cropped with *Secale cereale* rye, compared to *Triticale x Triosecale* Trios, in two of six comparisons (3–20 vs 60–177 g weed biomass/m^2).

Methods: There were six plots for each of two cover crops (*Secale cereale* rye or *Triticale x Triosecale* Trios, sown between the vine rows in autumn, mown in spring). All plots were tilled in autumn. The plots were each 84 x 1.8 m, between two vine rows. Weed samples were collected every 2–3 weeks in November 2005–2006 (1 x 0.5 m quadrats; three quadrats/plot).

A replicated, randomized, controlled study in 2002–2004 in a rainfed olive grove in Córdoba, Spain (10), found fewer weeds in plots with winter cover crops, compared to bare soil. **Pest numbers:** In summer, fewer weeds were found in plots with winter cover crops, compared to bare soil in winter, in one of two years (69 days after mowing, in 2004: 60% fewer weeds; 100 vs 250 weeds/m^2). **Methods:** Cover crops were grown on 16 treatment plots, and bare soil was maintained on 16 control plots, from mid-October to mid-April, when the cover crops were mown and chopped (3 x 3 m plots). Weed seeds were broadcasted over all plots, in January. Half of the plots were then rototilled (depth not reported), to incorporate the cover crop residues into the soil, and half were not tilled (but the residues were retained as mulch). Common mustard *Sinapis alba* subsp. *mairei* was used as a cover crop. Weeds were sampled in five quadrats/plot (31 x 62 cm, every week, 20–69 days after mowing). Bare soil was maintained with tillage or herbicide.

A replicated, controlled study in 2010–2011 in an olive grove in southern Spain (11) found more natural enemies in plots with ground cover, compared to bare soil, between the olive rows. **Natural enemy numbers:** More spiders and parasitoids were found in plots with ground cover, compared to bare soil (45 vs 32 spiders/plot; 109 vs 0 parasitoids/plot), but similar numbers of predatory bugs and ants were found (data not reported). **Methods:** The olive grove was divided into four subzones (two with ground cover, two without). In the subzones without ground cover, herbicides were used in early spring 2010–2011. In the subzones with ground cover, no herbicides were used, and herbaceous vegetation was allowed to grow. There were three plots (4,900 m^2 each) in each subzone. In each plot, natural enemies were sampled from the canopies of olive trees in one random sub-plot (1,600 m^2), every 10 days, with vacuum samplers (16 trees/sub-plot, two minutes/tree).

A replicated, randomized, controlled study in 2008 in an irrigated vineyard in southern California, USA (12), found more crop damage, more pests (leafhoppers), and more natural enemies in plots with cover crops, compared to bare fallows. **Crop damage:** More grapes were damaged by bees or wasps (2% vs 0% of grapes were broken) or thrips (in one of four comparisons: 28% vs 18% of grapes were scarred) in plots with cover crops, compared to bare fallows. **Pest numbers:** On sticky traps, similar numbers of pests were found in plots with cover crops or bare fallows (110–220 vs 110–140 combined pest insects/side). On grape leaves, more leafhoppers were found in plots with cover crops, compared to bare fallows, in one of four comparisons (22 vs 7 insects/leaf). **Natural enemy numbers:** On sticky traps, more natural enemies (predators and parasitoids) were found in plots with cover crops, compared to bare fallows, in one of eight comparisons (620 vs 310 combined beneficial insects/side). On grape leaves, more predators were found in plots with cover crops, compared to bare fallows, in two of four comparisons (23 vs 1–2 insects/leaf). **Methods:** Cover crops (*Fagopyrum esculentum* buckwheat) were sown between the vine rows in four plots, in summer 2008, and the cover crops were irrigated throughout the summer (sprinklers: 10 sprinklers/plot, 45 litre/hour, two hours after sowing and six hours every 7–10 days; tree sprayer: 60.5 litres/plot, thrice/week). This irrigation system was also used on three plots that did not have cover crops. Conventional management was used on six plots (bare fallows were maintained between the vine rows through cultivation and no irrigation). The plots had two vine rows each (28.7 x 6 m plots). Pests and their natural enemies were sampled with transparent sticky traps (two traps/plot, 16.7 x 13.2 cm, 145 cm above the ground, collected and replaced every week, 10 June–19 August 2008) and by observing grape leaves (five leaves/plot, observed every two weeks, 5 June–2 August 2008). Grapes were harvested in September 2008 (10 clusters from 3 m in the centre of each plot).

A replicated, randomized, controlled study in 2008–2010 in an irrigated vineyard in the San Joaquin Valley, California, USA (13), found less weed diversity in plots with cover crops between the vine rows, compared to resident vegetation. **Implementation options:** Less weed diversity was found in plots with cover crops between the vine rows, compared to resident vegetation (6–7 vs 10 species; other data on diversity reported as indices). Similar weed diversity was found in plots with different mixtures of cover crops (6–7 species). **Methods:** Cover crops (2.5 m width) were grown in the alleys between the vine rows (3.1 m width) on 16 plots (two alleys/plot, 190 vines/row), and resident vegetation was allowed to grow on 8 plots, over the winter. There were two combinations of cover crops (oats only, or oats and legumes, seeded in November, on 8 plots each). All plots were mown in spring and tilled (15–20 cm depth) in spring, summer, and autumn. Herbicide was used to control weeds in the vine rows (50 cm width), but not in the alleys. Weeds were sampled in the alleys, in April each year, at 4 m intervals on 40 m transects.

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5.5. Use crop rotations: Pest regulation (2 studies)

- Pest regulation (0 studies)
- Crop damage (0 studies)
- Ratio of natural enemies to pests (0 studies)
- **Pest numbers (1 study):** One replicated, randomized, controlled study from Australia[2] found less weed biomass in plots with a canola-wheat sequence, compared to a wheat-wheat sequence.
- Natural enemy numbers (0 studies)
- **Implementation options (1 study):** One replicated, randomized, controlled study from the USA[1] found similar amounts of weed biomass in plots with four-year or two-year crop rotations.

A replicated, randomized, controlled study in 1994–1998 on an irrigated, arable farm near Davis, California, USA (1), found similar amounts of weed biomass in plots with four-year or two-year crop rotations. **Implementation options:** Similar amounts of weed biomass were found in plots with four-year or two-year crop rotations (4–273 vs 140–467 kg dry weight/ha). **Methods:** A four-year rotation (tomato, safflower, corn and wheat, beans) was used on 16 plots (four plots for each phase, each year), and a two-year rotation (tomato, wheat) was used on eight plots (four plots for each phase, each year). Each plot was 68 x 18 m. Fertilizer and pesticide were used on all plots. Weeds were sampled in the tomato plots, at harvest, in 1994–1998.

A replicated, randomized, controlled study in 2010–2011 in a rainfed field in Western Australia (2) found less weed biomass in plots with a canola-wheat sequence, compared to a wheat-wheat sequence. **Pest numbers:** Less weed biomass was found in plots with a canola-wheat sequence, compared to a wheat-wheat sequence (36 vs 43 g/m^2). **Methods:** Wheat or canola was grown on three plots each in 2010, and wheat was grown on all plots in 2011. Each plot was 1.4 x 40 m. Fertilizer (150 kg/ha/year) and herbicide were used on all plots. Weeds were sampled at the end of 2011.

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5.6. Use no tillage in arable fields: Pest regulation (12 studies)

- Pest regulation (0 studies)

- **Crop damage (1 study):** One replicated, controlled study from Syria[9] found no differences in most diseases between plots with no tillage or conventional tillage, but found a higher incidence of Aschochyta blight in plots with no tillage.
- Ratio of natural enemies to pests (0 studies)
- **Pest numbers (9 studies)**
    - Weeds (8 studies): Three replicated, controlled studies (two randomized) from Italy[7,10] and Spain[2] found more weeds in plots with no tillage, compared to conventional tillage, in one of two comparisons[2], or in all comparisons[7,10]. Four replicated, controlled studies (three randomized) from Italy[3,11], Spain[12], and the USA[1] found inconsistent differences in weeds (sometimes more weeds in plots with no tillage, sometimes fewer). One replicated, randomized, controlled study from Lebanon[5] found similar numbers of weeds in plots with or without tillage.
    - Weed species (4 studies): One replicated, randomized, controlled study from Italy[3] found more weed species in plots with no tillage, compared to conventional tillage. Three replicated, controlled studies (two randomized) from Italy[10] and Spain[8,12] found similar numbers of weed species in plots with or without tillage.
    - Other pests (1 study): One replicated, controlled study from Italy[10] found fewer parasitic plants (broomrapes) in plots with no tillage, compared to conventional tillage.
- **Natural enemy numbers (1 study):** One replicated, controlled study from the USA[4] found similar numbers of predatory mites in plots with or without tillage.

A replicated, controlled study in 1996–1998 in an irrigated tomato field in the San Joaquin Valley, California, USA (1), found more weeds in plots with no tillage (and winter cover crops), compared to plots with tillage (and winter fallows), when herbicide was used on the fallows. When herbicide was not used, differences were inconsistent. **Pest numbers:** More weeds were found in plots with no tillage, in some comparisons (9 of 12 comparisons with herbicide use on fallows, in 1998: 4–12% vs 0–3% weed cover; two of 12 comparisons without herbicide use on fallows, in 1998: 5–6% vs 2%), but fewer weeds were found in two of 12 comparisons without herbicide use on fallows, in 1998 (4–5% vs 11%). In 1997, similar weed cover was found in plots with or without tillage (1–4%). **Methods:** There were 12 plots (4.5 x 27.5 m plots) for each of four treatments (two grass-legume mixtures, or two legumes without grasses, as winter cover crops, sown in October 1996–1997, killed and retained as mulch, with no tillage, in March 1997–1998) and each of two controls (bare-soil fallows in winter, with or without herbicide, and conventional tillage in spring). Tomato seedlings were transplanted in April 1997–1998. The tomatoes were irrigated (two inches/week) and fertilized (0, 100, or 200 lb N/acre). All plots were hand weeded in May, June, and July, and control plots were also cultivated in May and June. Weed cover was estimated before cultivation (July 1997 and May, June, and July 1998) or after cultivation (May and June 1997), in three quadrats/plot (1.8 m^2 quadrats). It was not clear whether these results were a direct effect of cover crops or tillage.

A replicated, randomized, controlled study in 1997–2001 in a rainfed pea-wheat-barley field near Barcelona, Spain (2), found more weeds in plots with no tillage, compared to conventional tillage. **Pest numbers:** More weed biomass was found in plots with no tillage, compared to conventional tillage, in one of two comparisons (grasses: 12 vs 0 g/m^2). **Methods:** No tillage or conventional tillage was used on two plots each (30 x 45 m plots). A mouldboard plough was used for conventional tillage (25 cm depth). Pre-emergence herbicide was used for no tillage. A seed drill, fertilizer, and post-emergence herbicide were used on all plots. Weeds were sampled each year, when crops were harvested (June–July 1998–2001, 10 quadrats/plot, 0.25 m^2 quadrats).

A replicated, randomized, controlled study in 1993–2001 in a rainfed cereal field in central Italy (3) (partly the same study as (7)) found more weed species in plots with no tillage, compared to conventional tillage, but tillage had inconsistent effects on weed abundance. **Pest numbers:** More weed species were found in plots with no tillage, compared to conventional tillage (19 vs 14 species). More weeds were found in plots with no tillage, compared to conventional tillage, for five of seven weed species (959–8,069 vs 13–454 weed seedlings/m^2), but fewer weeds were found, for two of seven weed species (71–97 vs 849–884). **Methods:** Conventional tillage or no tillage was used on 48 plots each (21 x 11 m sub-sub-plots, in a split-split-plot experimental design), from 1994–2000. A mouldboard plough (30 cm depth, in spring) and a standard precision seed drill were used for conventional tillage. A direct seed drill was used for no tillage. Herbicide and fertilizer were used on all plots. Winter cover crops were grown on three of four plots, and cereal crop residues were retained over winter on one of four plots. Weed seeds were sampled in soil cores in February 2001 (27 cores/plot, 0–15 cm depth, 3.5 cm diameter) and identified after germination in a greenhouse.

A replicated, controlled study in 1993–2006 in an irrigated tomato-corn field in Davis, California, USA (4), found similar numbers of natural enemies in soils with no tillage or conventional tillage. **Natural enemy numbers:** Similar numbers of predatory mites were found in soils with no tillage or conventional tillage (14 vs 7 individuals/100 g fresh soil). **Methods:** No tillage or conventional tillage was used on three plots each (conventional: 0.4 ha plots; no tillage: 3 m^2 microplots). Plots with conventional tillage were tilled about five times/year (depth not reported). Plots with no tillage were hand weeded. All plots were irrigated. Half of the plots were fertilized, and compost was added to the other half. Soil samples were collected eight times in March 2005–November 2006 (three samples/plot). Mites were sampled with soil cores (5 cm diameter, 10 cm depth).

A replicated, randomized, controlled study in 2005–2007 in a rainfed field in the central Bekaa Valley, Lebanon (5), found similar amounts of weeds in plots with no tillage or conventional tillage. **Pest numbers:** Similar amounts of weeds were found in plots with no tillage or conventional tillage (density: 43 vs 44 weeds/m^2; dry weight: 34 g/m^2). **Methods:** No tillage or conventional tillage was used on four plots each (14 x 6 m), in October. Conventional plots were ploughed (25–30 cm depth) and then shallowly disk-cultivated. Barley, chickpeas, and safflower were planted in November. Barley and safflower were fertilized (60–100 kg N/ha). Weed density and dry weight were measured on 30 March. Herbicide was used on all plots after sowing the seeds in November 2005. Herbicide was also used, and all plots were hand weeded, after the weed measurements in 2006.

A replicated, randomized, controlled study in 2002–2004 in a rainfed olive grove in Córdoba, Spain (6), found fewer weeds in plots with no tillage, compared to tillage. **Pest numbers:** Fewer weeds were found in plots with no tillage, compared to tillage, in one of two years (69 days after mowing, in 2004: 80 vs 130 weeds/m^2). **Methods:** Cover crops were grown on 16 plots, from mid-October to mid-April, when the cover crops were mown and chopped (3 x 3 m plots). Weed seeds were broadcast over all plots, in January. Half of the plots were then rototilled (depth not reported), to incorporate the cover crop residues into the soil, and half were not tilled (but the residues were retained as mulch). All plots were superficially tilled in autumn (10 cm depth). Common mustard *Sinapis alba* subsp. *mairei* was used as a cover crop. Weeds were sampled in five quadrats/plot (31 x 62 cm, every week, 20–69 days after mowing).

A replicated, randomized, controlled study in 1993–2008 in a rainfed wheat-maize-wheat-sunflower field in central Italy (7) (partly the same study as (3)) found more weeds in plots with no tillage, compared to conventional tillage. **Pest numbers:** More weeds were found in plots with no tillage, compared to conventional tillage (21 vs 12 Mg/ha). **Methods:** No tillage or conventional tillage was used on 64 plots each (21 x 11 m sub-sub-plots). A mouldboard plough was used for conventional tillage (30–35 cm depth), and crop residues were incorporated into the soil. Pre-emergence herbicide was used for no tillage, and crop residues were mulched onto the surface. Post-emergence herbicide and fertilizer were used on all plots. Some plots had winter cover crops. Weeds were collected when the crops were harvested or the cover crops were suppressed (2–4 m^2 quadrats), in 1994–2008.

A replicated, randomized, controlled study in 1985–2008 in a rainfed wheat-vetch field near Madrid, Spain (8), found similar numbers of weed species in plots with no tillage or conventional tillage. **Pest numbers:** Similar numbers of weed species were found in plots with or without tillage (6.7 vs 7.3 species), and no differences in the evenness or diversity of weed communities were found (reported as Pielou's index and Shannon's index). **Methods:** Wheat and vetch were grown in rotation. Conventional tillage or no tillage was used on four plots each (20 x 40 m). A mouldboard plough and a cultivator were used for conventional tillage (depths not reported). Pre-emergence herbicide was used for no tillage (and the wheat stubble was chopped, before the vetch was planted). Post-emergence herbicide was used on all plots, when the wheat was tillering. Fertilizer and a seed drill were used on all plots. Weeds were sampled when the wheat was tillering or the vetch stems were elongating (February–April 1986–2008, 5–20 samples/plot, 30 x 33 cm sampling areas).

A replicated, randomized, controlled study in 2005–2011 in a rainfed lentil field and wheat-chickpea-barley-lentil field in Syria (9) found similar amounts of most diseases in plots with no tillage or conventional tillage. **Crop damage:** A higher incidence of *Didymella rabiei* Ascochyta blight was found in plots with no tillage, compared to conventional tillage (13–23% vs 4–8%), but there was no difference in disease severity (3.75–5.5 vs 3.25–3.75 on a scale from 0 to 9, where 9 is the most severe). Similar incidences of three other diseases were found in plots with no tillage or conventional tillage (*Heteredora cicero* cyst nematode disease: 8% vs 9–16% incidence; *Fusarium oxysporum* lentil Fusarium wilt: 3%; *Peronospora lentis* downy mildew: 2%). **Methods:** In one experiment, wheat, chickpeas, barley, and lentils were grown in rotation. In another, lentils were grown in monoculture. In the rotation, no tillage or conventional tillage was used on three plots each, in 2008–2010, and four plots each, in 2009–2011. In the monoculture, there were four plots each (plot size not reported, but sub-subplots were 780 m^2). Plots received no tillage (direct drilling) or conventional tillage (cultivation and mouldboard ploughing; depth not reported).

A replicated, controlled study in 1991–2009 in a rainfed faba bean field in Sicily, Italy (10), found fewer root parasites, but more weeds, in plots with no tillage, compared to conventional tillage. **Pest numbers:** Fewer *Orobanche crenata* root parasites were found in plots with no tillage, compared to conventional tillage (7 vs 10 broomrapes/m^2), but there was no difference in the weights of root parasites (1.44 vs 1.59 g). More weeds were found in plots with no tillage, compared to conventional tillage (1.84 vs 1.26 Mg/ha), but there were similar numbers of weed species (16–18 species). **Methods:** No tillage or conventional tillage was used on two plots each (18.5 x 20 m plots). A mouldboard plough

(30 cm depth; in summer) and a harrow (depth not reported; before sowing) were used for conventional tillage. Herbicide (before sowing) and a seed drill were used for no tillage. In all plots, a hoe was used to control weeds (depth not reported; 1–2 times/year). Faba beans were grown in rotation with durum wheat. During durum wheat growth, herbicide was used in all plots. All plots were fertilized (46 kg P_2O_5/ha). Root parasites and weeds were measured in three samples/faba bean plot (four rows/sample, 3 m rows).

A replicated, randomized, controlled study in 2009–2011 in two irrigated pepper fields in central Italy (11) found fewer weeds in plots with no tillage, compared to conventional tillage, but tillage had inconsistent effects on weed biomass. **Pest numbers:** Fewer weeds were found in plots with no tillage, compared conventional tillage, in five of eight comparisons (14–50 vs 43–122 plants/m^2). Lower weed biomass was found in plots with no tillage, compared to conventional tillage, in one of eight comparisons (inside pepper rows: 7 vs 36 g dry matter/m^2), but higher weed biomass was found in two of eight comparisons (outside pepper rows: 41–54 vs 25–31). **Methods:** A mouldboard plough (30 cm depth) was used on all plots in autumn, before the winter cover crops were planted. Cover crops were mown or chopped in spring, before tillage. No tillage or conventional tillage was used on 12 plots each (6 x 12 m plots), in May 2010–2011. A mouldboard plough (30 cm depth) and a disk (two passes) were used for conventional tillage, incorporating the cover crop residues. Cover crop residues were mulched and herbicide was used for no tillage. Pepper seedlings were transplanted into the plots in May, and fruits were harvested twice/year in August–October 2010–2011. Weeds were sampled 30 days after transplanting (six samples/plot). All plots were fertilized before the cover crops, but not after. All plots were irrigated.

A replicated, randomized, controlled study in 1994–2009 in a rainfed pea-cereal field near Madrid, Spain (12), found that tillage had inconsistent effects on weeds. **Pest numbers:** Fewer weeds were found in plots with no tillage, compared to conventional tillage, in one of four comparisons (5.1 vs 9.3 plants/m^2), but more weeds were found in one of four comparisons (6.7 vs 3.4). Similar numbers of weed species were found in plots with no tillage or conventional tillage (data reported as an index of species richness). **Methods:** No tillage or conventional tillage was used on four plots each (each with three 10 x 25 m sub-plots, with different pea-cereal rotations), in October or November. A mouldboard plough was used for conventional tillage (30 cm depth). A seed drill and herbicide were used for no tillage. The peas were not fertilized. Weeds were identified and counted in four quadrats/sub-plot (0.125 m^2 quadrats).

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5.7. Use no tillage instead of reduced tillage: Pest regulation (8 studies)

- Pest regulation (0 studies)
- Crop damage (0 studies)
- Ratio of natural enemies to pests (0 studies)
- **Pest numbers (6 studies)**
  - Weeds (6 studies): Four replicated, controlled studies from Italy[5,6], Lebanon[3], and Spain[8] found fewer weeds in plots with no tillage, compared to reduced tillage, in some comparisons[5,6,8] or all comparisons[3]. Two of these studies[5,6] also found more weeds in some comparisons. One replicated, controlled studies from Australia[7] found more weeds in plots with no tillage, compared to reduced tillage. One replicated, randomized, controlled study from Spain[1] found similar amounts of weeds in plots with no tillage or reduced tillage.
  - Weed species (3 studies): One replicated, randomized, controlled study from Spain[4] found fewer weed species in plots with no tillage, compared to reduced tillage. Two replicated, controlled studies from Italy[5] and Spain[8] found similar numbers of weed species in plots with no tillage or reduced tillage.
- **Natural enemy numbers (1 study):** One replicated, randomized, controlled study from the USA[2] found similar numbers of predatory mites in soils with no tillage, compared to reduced tillage.

A replicated, randomized, controlled study in 1997–2001 in a rainfed pea-wheat-barley field near Barcelona, Spain (1), found similar numbers of weeds in plots with no tillage or reduced tillage. **Pest numbers:** Similar amounts of weed biomass were found in plots with no tillage or reduced tillage (36 g/m^2). **Methods:** No tillage or reduced tillage was used on two plots each (30 x 45 m plots). A chisel plough was used for reduced tillage (15 cm depth). Pre-emergence herbicide was used for no tillage. A seed drill, fertilizer, and post-emergence herbicide were used on all plots. Weeds were sampled each year, when crops were harvested (June–July 1998–2001, 10 quadrats/plot, 0.25 m^2 quadrats).

A replicated, controlled study in 1993–2006 in an irrigated tomato-maize field in Davis, California, USA (2), found similar numbers of natural enemies in soils with no tillage or reduced tillage. **Natural enemy numbers:** Similar numbers of predatory mites were found in soils with no tillage or reduced tillage (14 vs 12 individuals/100 g fresh soil). **Methods:** No tillage or reduced tillage was used on three plots each (reduced: 0.4 ha plots; no tillage: 3 m^2 microplots). Plots with reduced tillage were tilled about two times/year (depth not reported). Plots with no tillage were hand weeded. All plots were irrigated. Half of the plots were fertilized, and compost was added to the other half. Soil samples were collected eight times in March 2005–November 2006 (three samples/plot). Mites were sampled with soil cores (5 cm diameter, 10 cm depth).

A replicated, randomized, controlled study in 2005–2007 in a rainfed field in the central Bekaa Valley, Lebanon (3), found fewer weeds in plots with no tillage, compared to reduced tillage. **Pest numbers:** Fewer weeds were found in plots with no tillage, compared to reduced tillage (density: 43 vs 113 weeds/m^2; dry weight: 34 vs 61 g/m^2). **Methods:** No tillage or reduced tillage (shallow disc cultivation, 10 cm depth) was used in four plots each (14 x 6 m), in October. Barley, chickpeas, and safflower were planted in November. Barley and safflower were fertilized (60–100 kg N/ha). Weed density and dry weight were measured on 30 March. Herbicide was used on all plots after sowing the seeds in November 2005. Herbicide was also used, and all plots were hand weeded, after the weed measurements in 2006.

A replicated, randomized, controlled study in 1985–2008 in a rainfed wheat-vetch field near Madrid, Spain (4), found fewer weed species in plots with no tillage, compared to reduced tillage. **Pest numbers:** Fewer weed species were found in plots with no tillage, compared to reduced tillage (6.7 vs 8.3 species), but no differences in the evenness or diversity of weed communities were found (reported as Pielou's index and Shannon's index). **Methods:** Reduced tillage or no tillage was used on four plots each (20 x 40 m). A cultivator and/or a chisel plough were used for reduced tillage (depths not reported). Pre-emergence herbicide was used for no tillage (and the wheat stubble was chopped, before the vetch was planted). Wheat and vetch were grown in rotation. Post-emergence herbicide was used on all plots, when the wheat was tillering. Fertilizer and a seed drill were used on all plots. Weeds were sampled when wheat was tillering or vetch stems were elongating (February–April 1986–2008, 5–20 samples/plot, 30 x 33 cm sampling areas).

A replicated, controlled study in 1991–2009 in a rainfed faba bean field in Sicily, Italy (5), found fewer root parasites, but more weeds, in plots with no tillage, compared to reduced tillage. **Pest numbers:** Fewer *Orobanche crenata* root parasites were found in plots with no tillage, compared to reduced tillage (7 vs 10 broomrapes/m^2), but there were no differences in the weights of root parasites (1.44 vs 1.50 g). More weeds were found in plots with no tillage, compared to reduced tillage (1.84 vs 1.32 Mg/ha), but there were similar numbers of weed species (16–19 species). **Methods:** No tillage or reduced tillage was used on two plots each (18.5 x 20 m plots). A chisel plough (40 cm depth), a mouldboard plough (15 cm depth, in 1991–1998), and a harrow (depth not reported; before sowing) were used for reduced tillage. Herbicide (before sowing) and a seed drill were used for no tillage. In all plots, a hoe was used to control weeds (depth not reported; 1–2 times/year). Faba beans were grown in rotation with durum wheat. During durum wheat growth, herbicide was used in all plots. All plots were fertilized (46 kg P_2O_5/ha).

Root parasites and weeds were measured in three samples/faba bean plot (four rows/sample, 3 m rows).

A replicated, randomized, controlled study in 2009–2011 in two irrigated pepper fields in central Italy (6), found fewer weeds in plots with no tillage, compared to reduced tillage, but tillage had inconsistent effects on weed biomass. **Pest numbers:** Fewer weeds were found in plots with no tillage, compared to reduced tillage, in five of eight comparisons (14–50 vs 53–152 plants/m^2). Less weed biomass was found in plots with no tillage, compared to reduced tillage, in two of eight comparisons (inside pepper rows: 7–37 vs 47–58 g dry matter/m^2), but more was found in one of eight comparisons (outside pepper rows: 54 vs 31). **Methods:** A mouldboard plough (30 cm depth) was used on all plots in autumn, before winter cover crops were planted. Cover crops were mown or chopped in spring, before tillage. No tillage or reduced tillage was used on 12 plots each (6 x 12 m plots), in May 2010–2011. A rotary hoe (10 cm depth) was used for reduced tillage (which incorporated the cover crop residues into the soil). Cover crop residues were mulched and herbicide was used for no tillage. Pepper seedlings were transplanted into the plots in May, and fruits were harvested twice/year in August–October 2010–2011. Weeds were sampled 30 days after transplanting (six samples/plot). All plots were fertilized before the cover crops, but not after. All plots were irrigated.

A replicated, randomized, controlled study in 2010–2011 in a rainfed wheat field in Australia (7) found more weeds in plots with no tillage, compared to reduced tillage. **Pest numbers:** More weed biomass was found in plots with no tillage, compared to reduced tillage (36 vs 20 g/m^2). **Methods:** No tillage or reduced tillage was used on three plots each (1.4 x 40 m plots) in 2010, when the plots were fallow. A rotary hoe (12 cm depth) was used for reduced tillage. Herbicide was used for no tillage. Wheat was grown on all plots in 2011. Fertilizer (150 kg/ha) and herbicides were used on all plots in 2011. Weeds were sampled in 2011, when the wheat was mature.

A replicated, randomized, controlled study in 1994–2009 in a rainfed pea-cereal field near Madrid, Spain (8), found fewer weeds in plots with no tillage, compared to reduced tillage. **Pest numbers:** Fewer weeds were found in plots with no tillage, compared to reduced tillage, in two of four comparisons (5.1–11.9 vs 11.5–15.4 plants/m^2). Similar numbers of weed species were found in plots with no tillage or reduced tillage (data reported as an index of species richness). **Methods:** No tillage or reduced tillage was used on four plots each (each with three 10 x 25 m sub-plots, with different pea-cereal rotations), in October or November. A chisel plough was used for reduced tillage (10 cm depth). A seed drill and herbicide were used for no tillage. The peas were not fertilized. Weeds were identified and counted in four quadrats/sub-plot (0.125 m^2 quadrats).

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(2) Sánchez-Moreno, S., Nicola, N.L., Ferris, H. & Zalom, F.G. (2009) Effects of agricultural management on nematode–mite assemblages: Soil food web indices as predictors of mite community composition. *Applied Soil Ecology*, 41, 107-117.

(3) Yau, S.K., Sidahmed, M. & Haidar, M. (2010) Conservation versus Conventional Tillage on Performance of Three Different Crops. *Agronomy Journal*, 102, 269-276.

(4) Plaza, E.H., Kozak, M., Navarrete, L. & Gonzalez-Andujar, J.L. (2011) Tillage system did not affect weed diversity in a 23-year experiment in Mediterranean dryland. *Agriculture, Ecosystems & Environment*, 140, 102-105.

(5) Giambalvo, D., Ruisi, P., Saia, S., Di Miceli, G., Frenda, A.S. & Amato, G. (2012) Faba bean grain yield, N2 fixation, and weed infestation in a long-term tillage experiment under rainfed Mediterranean conditions. *Plant and Soil*, 360, 215-227.

(6) Radicetti, E., Mancinelli, R. & Campiglia, E. (2013) Influence of winter cover crop residue management on weeds and yield in pepper (Capsicum annuum L.) in a Mediterranean environment. *Crop Protection*, 52, 64-71.
(7) Manalil, S. & Flower, K. (2014) Soil water conservation and nitrous oxide emissions from different crop sequences and fallow under Mediterranean conditions. *Soil and Tillage Research*, 143, 123-129.
(8) Santín-Montanyá, M.I., Zambrana, E., Fernández-Getino, A.P. & Tenorio, J.L. (2014) Dry pea (Pisum sativum L.) yielding and weed infestation response, under different tillage conditions. *Crop Protection*, 65, 122-128.

5.8. Use reduced tillage in arable fields: Pest regulation (10 studies)

- Pest regulation (0 studies)
- Crop damage (0 studies)
- Ratio of natural enemies to pests (0 studies)
- **Pest numbers (9 studies)**
  - Weeds (8 studies): Seven replicated, randomized, controlled studies from Italy, Lebanon, Spain, Turkey, and the USA[1,3,5,6,8-10] found more weeds in plots with reduced tillage, compared to conventional tillage, in some comparisons[1,3,8-10] or all comparisons[5,6]. One of these studies[10] also found fewer weeds in plots with reduced tillage, compared to conventional tillage, in some comparisons. One replicated, randomized, controlled study from Italy[7] found similar numbers of weeds in plots with reduced tillage or conventional tillage, in all comparisons.
  - Weed species (3 studies): Two replicated, randomized, controlled studies from Spain and Turkey[3,9] found similar numbers of weed species in plots with reduced tillage or conventional tillage. One replicated, randomized, controlled study from the USA[10] found that weed communities had different compositions in plots with reduced tillage, compared to conventional tillage.
  - Diseases and pest insects (1 study): One replicated, randomized, controlled study from the USA[2] found similar numbers of diseases and pest insects in plots with reduced tillage, compared to conventional tillage.
- **Natural enemy numbers (1 study):** One replicated, controlled study from the USA[4] found similar numbers of predatory mites in soils with reduced tillage or conventional tillage.

A replicated, randomized, controlled study in 1997–2001 in a rainfed pea-wheat-barley field near Barcelona, Spain (1), found more weeds in plots with reduced tillage, compared to conventional tillage. **Pest numbers:** More weed biomass was found in plots with reduced tillage, compared to conventional tillage, in one of two comparisons (grasses: 27 vs 0 g/m^2). **Methods:** Reduced tillage or conventional tillage was used on two plots each (30 x 45 m plots). A mouldboard plough was used for conventional tillage (25 cm depth). A chisel plough was used for reduced tillage (15 cm depth). A seed drill, fertilizer, and post-emergence herbicide were used on all plots. Weeds were sampled each year, when crops were harvested (June–July 1998–2001, 10 quadrats/plot, 0.25 m^2 quadrats).

A replicated, randomized, controlled study in 1998–2000 in an irrigated vegetable field in the Salinas Valley, California, USA (2), found similar numbers of crop pests and diseases in plots with reduced tillage, compared to conventional tillage. **Pest numbers:** Similar numbers of crop pests and diseases were found in plots with reduced tillage, compared to conventional tillage (*Sclerotina minor*: 0.3–1.8 vs 0.3–1.9% of plants had symptoms; big vein disease: 3.0–3.4 vs 2.7–3.6% of plants had symptoms; pea leafminers: 10–98 vs 8–84 insects/sticky card; 2.2–3.4 vs 2.2–3.6% corky root disease severity, on a scale from 1 to 12, on which 12 is the highest severity). **Methods:** There were four plots (0.52 ha), for each of four treatments (reduced tillage or conventional tillage, with or without added organic matter). In plots with added organic matter, compost was added two times/year, and a cover crop (Merced rye) was grown every autumn or winter. Lettuce or broccoli crops were grown in raised beds. Sprinklers and drip irrigation were used in all plots. Soils were disturbed to different depths (conventional tillage: disking to 50 cm depth, cultivating, sub-soiling, bed re-making, and bed-shaping; reduced tillage: cultivating to 20 cm depth, rolling, and bed-shaping).

A replicated, randomized, controlled study in 2002–2003 in a rainfed wheat field in northwest Turkey (3) found more weeds, but similar numbers of weed species, in plots with reduced tillage, compared to conventional tillage. **Pest numbers:** More weeds were found in plots with reduced tillage, compared to conventional tillage, in three of four comparisons (36–64 vs 29–49 plants/m^2), but there were similar numbers of weed species (14–15 vs 11–13). **Methods:** Conventional tillage with a mouldboard plough, reduced tillage with a rototiller, or reduced tillage with a disc was used on three plots each (75 x 15 m plots). Fertilizer and herbicide were used on all plots. Weeds were measured in nine quadrats/plot (1 x 1 m quadrats, three times/growing season, before the herbicide was used).

A replicated, controlled study in 1993–2006 in an irrigated tomato-corn field in Davis, California, USA (4), found similar numbers of natural enemies in soils with reduced tillage or conventional tillage. **Natural enemy numbers:** Similar numbers of predatory mites were found in soils with reduced tillage or conventional tillage (8–12 vs 5–7 individuals/100 g fresh soil). **Methods:** Conventional tillage or reduced tillage was used on six plots each (0.4 ha plots). Plots were tilled about five times/year (conventional) or two times/year (reduced; depth not reported). All plots were irrigated. Half of the plots were fertilized, and compost was added to the other half. Soil samples were collected eight times in March 2005–November 2006 (three samples/plot). Mites were sampled with soil cores (5 cm diameter, 10 cm depth).

A replicated, randomized, controlled study in 2005–2007 in a rainfed field in the central Bekaa Valley, Lebanon (5), found more weeds in plots with reduced tillage, compared to conventional tillage. **Pest numbers:** More weeds were found in plots with reduced tillage, compared to conventional tillage (density: 113 vs 44 weeds/m^2; dry weight: 61 vs 34 g/m^2). **Methods:** Reduced tillage or conventional tillage was used in four plots each (14 x 6 m), in October. Conventional plots were ploughed (25–30 cm depth) and then shallowly disc cultivated. Reduced plots were shallowly disc cultivated (10 cm depth). Barley, chickpeas, and safflower were planted in November. Barley and safflower were fertilized (60–100 kg N/ha). Weed density and dry weight were measured on 30 March. Herbicide was used on all plots after sowing the seeds in November 2005. Herbicide was also used, and all plots were hand weeded, after the weed measurements in 2006.

A replicated, randomized, controlled study in 1985–2008 in a rainfed wheat-vetch field near Madrid, Spain (6), found more weed species in plots with reduced tillage, compared to conventional tillage. **Pest numbers:** More weed species were found in plots with reduced tillage, compared to conventional tillage (8.3 vs 7.3 species), but no differences in the evenness or diversity of weed communities were found (reported as Pielou's index and Shannon's index). **Methods:** Conventional tillage or reduced tillage was used on four plots each (20 x 40 m). A mouldboard plough and a cultivator were used for conventional tillage (depths not reported). A cultivator and/or a chisel plough were used for reduced tillage (depths not reported). Wheat and vetch were grown in rotation. Post-emergence herbicide was used on all plots, when the wheat was tillering. All plots were fertilized. Weeds were sampled when the wheat was tillering or the vetch stems were elongating (February–April 1986–2008, 5–20 samples/plot, 30 x 33 cm sampling areas).

A replicated, controlled study in 1991–2009 in a rainfed faba bean field in Sicily, Italy (7), found similar numbers of pests in plots with reduced tillage, compared to conventional tillage. **Pest numbers:** Similar numbers of *Orobanche crenata* root parasites were found in plots with reduced tillage, compared to conventional tillage (10 broomrapes/m^2), and the root parasites were similar in weight (1.50 vs 1.59 g). Similar amounts of weed biomass (1.3 Mg/ha) and weed species (16–19 species) were found in plots with reduced tillage or conventional tillage. **Methods:** Reduced tillage or conventional tillage was used on two plots each (18.5 x 20 m plots). A mouldboard plough (30 cm depth; in summer) and a harrow (depth not reported; before sowing) were used for conventional tillage. A chisel plough (40 cm depth), a mouldboard plough (15 cm depth, in 1991–1998), and a harrow (depth not reported; before sowing) were used for reduced tillage. In all plots, a hoe was used to control weeds (depth not reported; 1–2 times/year). Faba beans were grown in rotation with durum wheat. During durum wheat growth, herbicide was used in all plots. All plots were fertilized (46 kg P_2O_5/ha). Root parasites and weeds were measured in three samples/faba bean plot (four rows/sample, 3 m rows).

A replicated, randomized, controlled study in 2009–2011 in two irrigated pepper fields in central Italy (8) found more weeds in plots with reduced tillage, compared to conventional tillage. **Pest numbers:** More weeds were found in plots with reduced tillage, compared to conventional tillage, in four of eight comparisons (94–152 vs 73–122 plants/m^2). More weed biomass was found in plots with reduced tillage, compared to conventional tillage, in three of eight comparisons (31–58 vs 25–36 g dry matter/m^2). **Methods:** A mouldboard plough (30 cm depth) was used on all plots in autumn, before winter cover crops were planted. Cover crops were mown or chopped in spring, before tillage. Conventional tillage or reduced tillage was used on 12 plots each (6 x 12 m plots), in May 2010–2011. A mouldboard plough and a disc (two passes) were used for conventional tillage (which incorporated the cover crop residues into the soil to a depth of 30 cm). A rotary hoe was used for reduced tillage (which incorporated the cover crop residues into the soil to a depth of 10 cm). Pepper seedlings were transplanted into the plots in May, and fruits were harvested twice/year in August–October 2010–2011. Weeds were sampled 30 days after transplanting (six samples/plot). All plots were fertilized before the cover crops, but not after. All plots were irrigated.

A replicated, randomized, controlled study in 1994–2009 in a rainfed pea-cereal field near Madrid, Spain (9), found more weeds in plots with reduced tillage, compared to conventional tillage. **Pest numbers:** More weeds were found in plots with reduced tillage, compared to conventional tillage, in two of four comparisons (11.2–15.4 vs 8.8–

12.4 plants/m^2). Similar numbers of weed species were found in plots with reduced tillage or conventional tillage (data reported as an index of species richness). **Methods:** Reduced tillage or conventional tillage was used on four plots each (each with three 10 x 25 m sub-plots, with different pea-cereal rotations), in October or November. A mouldboard plough was used for conventional tillage (30 cm depth). A chisel plough was used for reduced tillage (10 cm depth). The peas were not fertilized. Weeds were identified and counted in four quadrats/sub-plot (0.125 m^2 quadrats).

A replicated, randomized, controlled study in 1999–2011 in an irrigated tomato-cotton field in the San Joaquin Valley, California, USA (10), found that tillage had inconsistent effects on weed numbers, but different weed species were found in plots with reduced tillage, compared to conventional tillage. **Pest numbers:** Fewer weeds were found in plots with reduced tillage, compared to conventional tillage, in two of six comparisons (in June 2011: 61–126 vs 158–190 plants/m^2), but more weeds were found in one of six comparisons (in tomatoes, in January 2003: 48 vs 45 plants/m^2). Different communities of weeds were found in plots with reduced tillage, compared to conventional tillage, in one of two comparisons (in plots with winter cover crops; data reported as distance in ordination space). **Methods:** Reduced tillage or conventional tillage was used on 16 plots each, in 1999–2011. The plots (9 x 82 m) had six raised beds each. Winter cover crops (triticale, rye, and vetch) were planted on half of the plots, in October 1999–2010, and crop residues were chopped in March. Different numbers of tillage practices were used for conventional tillage (19–23 tractor passes, including disc and chisel ploughing) and reduced tillage (11–12 tractor passes, not including disc and chisel ploughing). All plots were fertilized (conventional tillage: 89.2 kg/ha dry fertilizer, 111.5 kg/ha urea; reduced tillage: 124.9 kg/ha urea). Weeds were counted in January 2003 (1 m^2 quadrats, four quadrats/plot), as well as March 2006 and June 2011 (0.25 m^2 quadrats, two quadrats/plot). Soil cores were collected in June 2011 (8.25 cm diameter, 0–10 cm depth). Seeds from these soil cores were germinated, and weed species were counted.

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(2) Jackson, L.E., Ramirez, I., Yokota, R., Fennimore, S.A., Koike, S.T., Henderson, D.M., Chaney, W.E., Calderón, F.J. & Klonsky, K. (2004) On-farm assessment of organic matter and tillage management on vegetable yield, soil, weeds, pests, and economics in California. *Agriculture, Ecosystems & Environment*, 103, 443-463.

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Habitat management: Effects on pest regulation

5.9. Plant flowers: Pest regulation (8 studies)

- **Pest regulation (3 studies):** Three replicated studies from Italy and the USA found greater pest reduction[4] or higher proportions of parasitized pests[1,6] in fields and farms with planted flower strips.
- **Crop damage (2 studies):** One replicated, randomized, controlled study from Italy[8] found more damage by caterpillars, but not by aphids, in tomatoes next to planted flower strips, compared to tomatoes next to bare ground. One replicated, paired, controlled study from Italy[6] found that planted flower strips had inconsistent effects on crop damage by pests.
- **Pest numbers (2 studies):** One replicated, paired, controlled study from Italy[6] found more pests on tomatoes next to planted flower strips, compared to tomatoes next to unplanted field margins. One replicated before-and-after study from the USA[2] found more aphids in fields after flower strips were made available.
- **Natural enemy numbers (4 studies):** Two replicated studies from the USA[1,2] found more natural enemies in fields with planted flower strips, compared to fields without planted flower strips, in some comparisons. Two replicated, controlled studies from Italy[7,8] found more natural enemies in planted flower strips than on bare ground, and one of these studies[8] also found more species of natural enemies.
- **Implementation options (4 studies)**: Two replicated, controlled studies from the USA and Spain[3,5] found that some flower species were more attractive to natural enemies than others. Two replicated, controlled studies from Italy[7,8] found that planting more species of flowers, compared to fewer, had inconsistent effects on pests and pest species, but one of these[8] found less crop damage next to flower strips with more species, compared to fewer, in some comparisons. This study[8] also found more species of natural enemies in flower strips, over time, but did not find more individuals.

A replicated, randomized, controlled study in 2003 in organic tomato fields in the Sacramento Valley, California, USA (1), found that a higher percentage of stink-bug eggs were parasitized near planted flower borders than near bare borders. **Pest regulation:** Parasitism of consperse stink bug *Euschistus conspersus* eggs was significantly higher near borders planted with sweet alyssum *Lobularia maritima* than it was near bare borders in September (41 vs 22%), but not in July or August (early July: 9 vs 6%; late July–early August: 47 vs 40%). **Natural enemy numbers:** There were not significantly more predators near flower borders, compared to bare borders (3 vs 2–5 individuals/sample), except for spined stilt bugs *Jalysus wickhami* in June (2 vs 0). **Methods:** In each of four tomato fields, one 23 m border was planted with 60 alyssum plants and one border was tilled and left bare. Eight (3 and 31 July) or ten (5 September) masses of stink bug eggs were placed on the undersides of tomato leaves at each of three distances (0.3, 6, and 15 m) from each border. Yellow sticky traps were placed at four (18 June: 0.3, 1.5, 6, and 15 m) or three (26 August: 0.3, 6, and 15 m) distances, to sample predators. Eggs and cards were collected after 6–7 days.

A replicated before-and-after study in 2007 in lettuce fields in the Salinas Valley, California, USA (2), found more pests, more predators, and different distributions of predators after restoring floral resources compared to before. **Pest and natural enemy numbers:** After restoring sweet alyssum *Lobularia maritima* rows, there were more pests (12.5 vs 8.5 currant-lettuce aphids *Nasonovia ribisnigri* per lettuce) and more hoverfly eggs and larvae (2.3 vs 1.2 eggs/lettuce; 1.4 vs 0.8 larvae/lettuce) than there were before (second sampling dates). After restoration, there were more hoverfly adults near restored flower strips (72 vs 57), but fewer elsewhere in the field (60–76 vs 77–95), than there were before. **Methods:** Flower strips were planted 48 m apart on four lettuce fields. Access to one flower strip/field was restricted (strips were covered on 31 August) and then restored (covers were removed on 5 September). Insects were sampled (2–5 days after restriction and restoration) by searching lettuce heads or by counting hoverflies on transects.

A replicated, randomized, controlled study in 2009 on an organic farm in Sonoma County, California, USA (3), found that natural enemies and pests preferred different flower species planted in flower strips surrounding kale plots. **Implementation options:** More hoverflies were found on sweet alyssum *Lobularia maritima* (4–5.8 visits/sample), compared to other flower species in peak bloom (0.2–1.4), except buckwheat *Fagopyrum esculentum* (3.3 from 24 June to 10 July). More predatory bugs were found on alyssum (3.6 individuals/sample), compared to other species (0.1–1.1), except buckwheat (1.6) and wild mustard *Brassica* sp. (1.6). More parasitic wasps were found on cosmos *Cosmos sulphureus* (3.5 individuals/sample), compared to other species (0.3–0.7), except alyssum (1.4), wild arugula *Diplotaxis muralis* (1.0), and kale *Brassica oleracea* (3.9). Numbers of spiders did not differ significantly between species (0.1–1.0 individual/sample). More chrysomelid beetles were found on arugula (1.7 individuals/sample), compared to other species (0–0.6), except white borage *Borago officinalis* and alyssum (0.6–1.0). More cicadellid bugs were found on tansy phacelia *Phacelia tanacetifolia* (25 vs 1–10 individuals/sample), and more lygaeid bugs were found on arugula (23 vs 0–3), compared to other species. Aphid numbers did not differ significantly between flower-strip species, but more aphids were found on kale than on flower-strip species (480 vs 0–0.9 individuals/sample). **Methods:** Two rows of kale, between two strips (four rows) of one flower species, were planted on 16 May in each plot (3 x 6 m). There were five replicate plots for each of nine flower species. Invertebrates were sampled by counting flower visitors (6 minutes/plot, every 5–9 days) or vacuuming plants (15 seconds/plot, 25 x 50 cm area, every 12–15 days).

A replicated site comparison in 2008–2009 in broccoli fields in the Salinas Valley, California, USA (4), found that cabbage aphids *Brevicoryne brassicae* were better controlled by natural enemies on complex than on simple farms. **Pest regulation:** In August, the proportional reduction in aphid densities (PRD) was higher on complex than on simple farms, if farms were surrounded by low amounts of natural habitat (data were reported as the negative log of PRD), but not if surrounded by high amounts of natural habitat. In June, PRD was not significantly different between complex and simple farms.

Methods: Eight farms were compared in 2008 and 10 farms were compared in 2009. Flowers for beneficial insects were planted on complex but not on simple farms. Complex and simple farms also differed in field size (1.2–4 vs 6–12 ha) and crop composition (polyculture vs monoculture). Potted broccoli plants were inoculated with 50 aphids each, placed in fields for 12 days, and either caged (to exclude natural enemies) or uncaged. Farms were surrounded by high (>50%) or low (<10%) amounts of natural habitat (0.5–3 km). It was not clear whether these results were a direct effect of planting flowers, field size, or crop composition.

A replicated, randomized, controlled study in 2009–2010 in a winter barley field in the Jarama River basin, Spain (5), found that aphid-eating hoverflies visited some planted flower species more than others. **Implementation options:** In 2009, more hoverflies visited the flowers of *Calendula arvensis* (3.6 visits/minute) and *Coriandrum sativum* (3.5) than *Pimpinella anisum* (0.6), but other differences between flower species were not significant in 2009 or 2010 (0.6–5.8). Most visits were made by *Sphaerophoria* sp. (88–96% of visits). **Methods:** Six flower species were studied. There was one species/plot (1.5 x 1.5 m), with three (2009) or four (2010) blocks, and six plots/block. Hoverflies that touched the reproductive parts of flowers were counted, in the centres of plots (0.5 x 0.5 m), for six minutes/plot, every 2 to 11 days, from 7 May to 26 June 2009, and nine minutes/plot, two times/week, from 27 April to 1 July 2010.

A replicated, paired, controlled study in 2011–2012 in tomato fields in Tuscany, Italy (6), found higher rates of aphid parasitism, but more aphids, and different amounts of fruit damage by different pests, in tomatoes next to planted flower strips compared to tomatoes next to unplanted field margins. **Pest regulation:** Aphid parasitism rate was higher on tomatoes next to flower strips than on tomatoes next to unplanted margins (parasitism rates not reported). **Crop damage:** Less fruit damage by sucking bugs, but more leaf damage by other pests, was found on tomatoes next to flower strips, compared to tomatoes next to unplanted margins (amounts of damage not reported). Similar amounts of fruit damage by noctuid pests and *Tuta absoluta* were found on tomatoes next to flower strips and unplanted margins. **Pest numbers:** More aphids were found on tomatoes next to flower strips, compared to tomatoes next to unplanted margins (numbers of individuals not reported). **Methods:** In each of eight tomato fields, 150 fruits and 60 leaves were sampled for crop damage, aphid mummies (parasitism), and aphids, on transects from each of two field margins (one with flower strips, one without; 3 x 25 m each). The flower strips were planted 7–14 days after the tomatoes were planted. Samples began when the flower strips began to bloom, and continued every 15 days until harvest.

A replicated, controlled study in 2011 in an organic tomato field near Pisa, Italy (7) (same study as (8)), found more natural enemies in flower plots than on bare ground. Plots with the most flower species had the fewest tomato pests but the most generalist pests, and plots with different numbers of flower species had similar numbers of natural enemies. **Natural enemy numbers:** More ground-dwelling predators were found in flower plots than on bare ground (carabid beetles/plot: 0–28.7 vs 0–1.2; staphylinid beetles/plot 0.5–7.4 vs 0–0.4; spiders/plot: 0.4–7.1 vs 0.2–1.5). **Implementation options:** Fewer tomato pests (sap-sucking bugs), but more generalist pests (*Lygus* sp. and *Nezara viridula*), were found on flowers in plots with nine flower species, compared to plots with three flower species (numbers of individuals not reported). Similar numbers of natural enemies were found on flowers in all plots (numbers of individuals not reported). On flowers, predatory beetles *Hippodamia variegata* and parasitic wasps increased over time (beetles: minimum: 0 individuals/plot, on the first day of flowering;

maximum: 2.7 individuals/plot, 38 days after flowering; wasps: minimum: 0 individuals/plot, on the first day after flowering; maximum: 36.5 individuals/plot, 21 days after flowering), but formicid ants decreased over time (numbers of individuals not reported). On the ground, carabid beetles increased over time (minimum: 0 individuals/plot, nine days after flowering; maximum: 28.7 individuals/plot, 37 days after flowering), but staphylinid beetles and spiders did not. **Methods:** Four treatments were compared: three, six, or nine flower species/plot, and a control with no flowers. Five plots/treatment were sown with flower seeds on 6 and 21 June. Each flower plot (2 x 10 m) was next to a tomato plot (4 x 10 m). Ground-dwelling predators were sampled with pitfall traps every 7 days, and natural enemies on flowers were sampled with aspirators every 14 days, after flowering began.

A replicated, randomized, controlled study in 2011–2012 in an organic tomato field near Pisa, Italy (8) (same study as (7)), found more damage by caterpillars, but not aphids, in tomatoes grown next to flower strips, compared to bare ground. It also found more individuals and species of natural enemies in flower strips, compared to bare ground. **Crop damage:** More damage by caterpillars, but not aphids, was found in tomatoes grown next to flower strips, compared to bare ground (amounts of damage not reported). **Natural enemy numbers:** More individuals and species of ground-dwelling predators were found in flower strips than on bare ground (16–19 vs 4 individuals; numbers of species not reported). **Implementation options:** Less damage by caterpillars was found in tomatoes grown next to flower strips with more compared to fewer flower species (six or nine species vs three, in 2012, in plots with high numbers of fruit/plant; amounts of damage not reported). Fruit damage varied with the number of flower species/strip, but not all differences were significant in both years or in both varieties (Roma and Perfect Peel; amounts of damage not reported). Fewer tomato pests (sap-sucking bugs), but more generalist pests (*Lygus* sp. and *Nezara viridula*), were found in strips with nine flower species, compared to three (numbers of individuals not reported; same results as (7)). Flower strips with more, compared to fewer, flower species (six or nine vs three species) did not have significantly more natural enemies (ground-dwelling: 16–19 individuals/strip; flower-visiting parasitoids: 12–19; flower-visiting predators: 4–7; same results as (7)). Strips with six flower species had more species of flower-visiting natural enemies than strips with three or nine flower species, but did not have significantly more species of ground-dwelling natural enemies (numbers of species not reported). The diversity of flower-visiting natural enemies increased over time, but the number of individuals did not (numbers of individuals and species not reported). **Methods:** Four treatments were compared: three flower species/strip (Apiaceae species), six species/strip (three Apiaceae and three Fabaceae), nine species/strip (three Apiaceae, three Fabaceae, and three others), and a control strip with no flowers. Three strips/treatment were sown with flower seeds (2011: 6 and 21 June; 2012: 13 and 17 June). Each flower strip (2 x 4 m) was positioned between two tomato plots (4 x 10 m/plot). Ground-dwelling predators were sampled with pitfall traps every 7 days, and natural enemies on flowers were sampled with aspirators every 14 days, after flowering began. Damage by pests was assessed for 30 fruits/plot and 12 leaves/plot.

(1) Pease, C.G. & Zalom, F.G. (2010) Influence of non-crop plants on stink bug (Hemiptera: Pentatomidae) and natural enemy abundance in tomatoes. *Journal of Applied Entomology*, 134, 626-636.

(2) Gillespie, M., Wratten, S., Sedcole, R. & Colfer, R. (2011) Manipulating floral resources dispersion for hoverflies (Diptera: Syrphidae) in a California lettuce agro-ecosystem. *Biological Control*, 59, 215-220.

(3) Hogg, B.N., Bugg, R.L. & Daane, K.M. (2011) Attractiveness of common insectary and harvestable floral resources to beneficial insects. *Biological Control*, 56, 76-84.
(4) Chaplin-Kramer, R. & Kremen, C. (2012) Pest control experiments show benefits of complexity at landscape and local scales. *Ecological Applications*, 22, 1936-1948.
(5) Martínez-Uña, A., Martín, J.M., Fernández-Quintanilla, C. & Dorado, J. (2013) Provisioning Floral Resources to Attract Aphidophagous Hoverflies (Diptera: Syrphidae) Useful for Pest Management in Central Spain. *Journal of Economic Entomology*, 106, 2327-2335.
(6) Balzan, M.V. & Moonen, A.-C. (2014) Field margin vegetation enhances biological control and crop damage suppression from multiple pests in organic tomato fields. *Entomologia Experimentalis et Applicata*, 150, 45-65.
(7) Balzan, M.V., Bocci, G. & Moonen, A.-C. (2014) Augmenting flower trait diversity in wildflower strips to optimise the conservation of arthropod functional groups for multiple agroecosystem services. *Journal of Insect Conservation*, 18, 713-728.
(8) Balzan, M.V., Bocci, G. & Moonen, A.-C. (2016) Utilisation of plant functional diversity in wildflower strips for the delivery of multiple agroecosystem services. *Entomologia Experimentalis et Applicata*, 158, 304-319.

5.10. Plant hedgerows: Pest regulation (3 studies)

- **Pest regulation (1 study):** One replicated, paired, site comparison from the USA[3] found that a higher proportion of pest eggs were parasitized in tomato fields with hedgerows, compared to fields with weedy edges, but only up to 100 m into the crop.
- **Crop damage (1 study):** One replicated, paired, site comparison from the USA[3] found that pest damage to tomatoes was no different in fields with hedgerows than it was in fields with weedy edges.
- **Ratio of natural enemies to pests (2 studies):** Of two replicated site comparisons from the USA, one paired study[1] found a greater ratio of natural enemies to pests in hedgerows, compared to weedy edges, but one unpaired study[2] did not. The unpaired study[2] also found no difference in the ratio of natural enemies to pests between fields with hedgerows and fields with weedy edges.
- **Pest numbers (1 study)**: One replicated, paired, site comparison from the USA[3] found fewer pests in fields or field edges with hedgerows, compared to fields or field edges without hedgerows.
- **Natural enemy numbers (1 study):** One replicated, paired, site comparison from the USA[3] found more natural enemies in fields with hedgerows, compared to fields with weedy edges, and in hedgerows themselves, compared to weedy edges, in some comparisons.

A replicated, paired, site comparison in 1999–2000 in mixed cropland in Yolo County, California, USA (1), found more natural enemies than pests in hedgerow shrubs, and more pests than natural enemies in weedy field edges. **Ratio of natural enemies to pests:** On hedgerow shrubs, natural enemies were more abundant than pests (1–3 vs 0.2–1.0 insects/m^2). In weedy edges, pests were more abundant than natural enemies in summer (15 vs 8 insects/sample), but were not significantly different in spring (6 vs 4) or fall (9 vs 4). A higher proportion of insects were natural enemies in hedgerow shrubs than in weedy edges (0.81–0.88 vs 0.32–0.46). **Methods:** On the edges of four crop fields, native shrubs (hedgerow shrubs), bordered by native grasses (hedgerow grasses), were planted in 1996 (305–550 m), and compared to the weedy edges of the same fields every two weeks in March–November 1999–2000. Insects were observed on hedgerow shrubs (four minutes/shrub species), collected from shrubs by shaking, and collected from hedgerow grasses and weedy edges with sweep nets (10 sweeps/sample; four samples each).

A replicated site comparison in 2005–2006 on organic vegetable farms on the Central Coast, California, USA (2), found similar ratios of natural enemies to pests in hedgerows compared to weedy edges, and in fields with hedgerows compared to fields with weedy edges. **Ratio of natural enemies to pests:** The ratio of natural enemies to pests (2005: 11:1 enemies:pests; 2006: 15:1) was not significantly different between fields with hedgerows and fields with weedy edges, either at the edge (30:1 vs 6:1 enemies:pests), or 50–100 m into the field (3:1 enemies:pests). Different plant species in hedgerows had different ratios (from 4:1 enemies:pests on toyon *Heteromeles arbutifolia* in 2005 to 43:1 on coyote bush *Baccharis pilularis* in 2006). **Methods:** Two fields with hedgerows (>2 years old) and two fields with weedy edges were compared. Insects were sampled using yellow sticky cards (2005: five cards each at 0, 50, and 100 m into fields, collected after three days) and vacuums (2005: 30 seconds/plant in hedgerows; 2006: 60 seconds/plant).

A replicated, paired, site comparison in May–August 2009–2010 in tomato fields in the Sacramento Valley, California, USA (3), found that a higher proportion of pest egg were parasitized in fields with hedgerows, compared to fields with weedy edges, but only up to 100 m into the crop. Similar levels of fruit damage were found in fields with and without hedgerows. Fewer pests were found in fields or field edges with planted hedgerows, compared to fields or field edges without hedgerows. **Pest regulation:** Parasitism of stink-bug *Euschistus conspersus* eggs (a tomato pest) was higher in fields with hedgerows than in fields with weedy edges, 0–100 m but not 200 m into the crop (0 m: 0.19 vs 0.11 proportion of eggs parasitized; 10 m: 0.30 vs 0.18; 100 m: 0.20 vs 0.10; 200 m: 0.15 vs 0.11). **Crop damage:** Similar amounts of fruit damage by pests were found in fields with hedgerows or weedy edges (amounts of damage not reported). **Pest and natural enemy numbers:** In sweep-net samples, fewer pests, but not significantly fewer predators or parasitoids, were found in hedgerows than in weedy edges (pests: 2 vs 20 individuals/sample; predators: 6 vs 6; parasitoids: 6 vs 2). In shake samples, more predators (10 m: 0.25 vs 0.05 predators/sample; 100 m: 0.15 vs 0.05; 200 m: 0.30 vs 0) and fewer aphids (10 m: 0.21 vs 0.32 proportion of leaves with aphids; 100 m: 0.14 vs 0.23; 200 m: 0.11 vs 0.21) were found in fields with hedgerows than in fields with weedy edges. In sticky-card samples, more parasitoids, but not more predators, and fewer pests were found in hedgerows than in weedy edges; more parasitoids were found in fields with hedgerows than in fields with weedy edges, up to 100 m into the crop, and fewer pests were found in fields with hedgerows than in fields with weedy edges, up to 10 m into the crop (number of individuals not reported). **Methods:** Native perennial shrubs (305–550 x 7 m), bordered by native perennial grasses (3 m), were planted in 1996–2003 on the edges of six fields (hedgerows) and compared to the unplanted edges of six fields (weedy edges). Invertebrates were sampled four times/year using sweep nets (40 cm diameter; six sweeps/edge) and sticky cards (7.6 × 12.7 cm; six cards/edge and six cards/crop), and by shaking plants (late May only). Stink-bug egg masses were exposed for five days in early July on the undersides of leaves.

(1) Morandin, L., Long, R., Pease, C. & Kremen, C. (2011) Hedgerows enhance beneficial insects on farms in California's Central Valley. *California Agriculture*, 65, 197-201.
(2) Gareau, T.L.P., Letourneau, D.K. & Shennan, C. (2013) Relative Densities of Natural Enemy and Pest Insects Within California Hedgerows. *Environmental Entomology*, 42, 688-702.
(3) Morandin, L.A., Long, R.F. & Kremen, C. (2014) Hedgerows enhance beneficial insects on adjacent tomato fields in an intensive agricultural landscape. *Agriculture, Ecosystems & Environment*, 189, 164-170.

5.11. Restore habitat along watercourses: Pest regulation (1 study)

- Pest regulation (0 studies)
- Crop damage (0 studies)
- Ratio of natural enemies to pests (0 studies)
- **Pest numbers (1 study):** One replicated site comparison from the USA[1] found more weeds in orchards next to restored riparian habitats, compared to remnant habitats.
- Natural enemy numbers (0 studies)
- **Implementation options (1 study):** One replicated, site comparison from the USA[1] found more weeds in orchards next to older restored sites, compared to younger restored sites.

A replicated site comparison in 1991–2004 in 26 riparian sites along the Sacramento River, California, USA (1), found more weed seeds in orchards next to restored habitat, compared to remnant habitat. **Pest numbers:** More weed seeds were found in orchards next to restored habitat, compared to remnant habitat (data reported as log abundance). **Implementation options:** More weed seeds were found in orchards next to older restored sites, compared to younger restored sites (data not reported). **Methods:** Soil samples were collected from 26 walnut plots, 0–5.6 km from restored riparian, remnant riparian, and agricultural habitats. Restored sites were formerly farmland. Restoration included disking, burning, furrowing, levelling, and spraying with herbicide, and replanting. On each walnut farm, soil samples (10 cm depth) were collected from seven points adjacent to restored or remnant forest and nine points within the walnut orchard, in March 2004. Seeds were germinated and identified in a greenhouse.

(1) Langridge, S.M. (2011) Limited effects of large-scale riparian restoration on seed banks in agriculture. *Restoration Ecology*, 19, 607-616.

Livestock management: Effects on pest regulation

5.12. Exclude grazers: Pest regulation (1 study)

- Pest regulation (0 studies)
- **Pest damage (1 study):** One site comparison in grassland in the USA[1] found no relationship between plant numbers and gopher numbers in ungrazed sites, but found fewer plant species in grazed sites with more gophers.
- Ratio of natural enemies to pests (0 studies)
- **Pest numbers (1 study):** One site comparison in grassland in the USA[1] found more signs of gopher activity in ungrazed sites, compared to grazed sites.
- Natural enemy numbers (0 studies)

A site comparison in 1991 in annual grassland on the Central Coast, California, USA (1), found more signs of pocket gophers *Thomomys bottae* in ungrazed sites, compared to grazed sites. There was a correlation between gophers and plant species in grazed sites, but not in ungrazed sites. **Pest damage:** In grazed sites, fewer plant species were found where there were more gophers. However, in ungrazed sites, no relationship was found between gopher numbers and plant numbers (data reported as statistical results). **Pest numbers:** More signs of gopher activity were found in ungrazed sites, compared to grazed sites (5% vs 2% cover of soil that had been dug up). **Methods:** European domestic cattle were introduced to Monterey County in 1770. In 1937, grazers were excluded from one landscape (the Hastings Natural History Reservation), but not from a nearby landscape. In 1991, 43 sites in the ungrazed landscape and 37 sites in the grazed landscape were sampled (methods not clearly reported, but the cover of gopher tailings was measured in 20 x 50 cm quadrats in a different part of this study).

(1) Stromberg, M.R. & Griffin, J.R. (1996) Long-Term Patterns in Coastal California Grasslands in Relation to Cultivation, Gophers, and Grazing. *Ecological Applications*, 6, 1189-1211.

6. Pollination

Crop and soil management: Effects on pollination

6.1. Plant or maintain ground cover in orchards or vineyards: Pollination (1 study)

- Pollination (0 studies)
- Crop visitation (0 studies)
- Pollinator numbers (0 studies)
- **Implementation options (1 study):** One replicated site comparison from Greece[1] found more bee species and more deposited pollen grains in managed olive orchards, compared to abandoned olive orchards, which differed in ground cover.

A replicated site comparison in 2001 in olive orchards on the island of Lesvos, Greece (1), found more bee species and more deposited pollen grains in managed orchards (with tilled soils and ground cover dominated by annual plants), compared to unmanaged orchards (without tilled soils, and with ground cover dominated by perennial plants). **Implementation options:** More pollen grains were found on *Cistus salvifolius* in managed orchards, compared to abandoned orchards (38 vs 27 grains/stigma), but similar numbers of pollen grains were found on *Asphodelus ramosus* (33 vs 30 grains/stigma). More bee species were found in managed orchards, compared to abandoned orchards (19 vs 13 species/site), but similar numbers of individuals were found (231 vs 122 individuals/site). **Methods:** Three managed orchards were compared to three abandoned orchards (1 ha each). Bees were surveyed three times/site in March–May (three transects/site, 20 minutes/transect). Pollen grains were counted on 100 plants from each of two wildflower species (*Asphodelus ramosus*, a tall, perennial herb, and *Cistus salvifolius*, an evergreen shrub, both with large white flowers), which were collected after each bee survey.

(1) Potts, S.G., Petanidou, T., Roberts, S., O'Toole, C., Hulbert, A. & Willmer, P. (2006) Plant-pollinator biodiversity and pollination services in a complex Mediterranean landscape. *Biological Conservation*, 129, 519-529.

6.2. Use no tillage in arable fields: Pollination (1 study)

- Pollination (0 studies)
- Crop visitation (0 studies)

- **Pollinator numbers (1 study):** One replicated, randomized, controlled study from the USA[1] found more pollinators in plots with no tillage, compared to deep tillage.
- Implementation options (0 studies)

A replicated, randomized, controlled study in 2012–2013 in an irrigated squash field in the Central Valley, California, USA (1), found more soil-nesting bees in plots with no tillage, compared to deep tillage. **Pollinator numbers:** More *Peponapis pruinosa* squash bees emerged from nests in plots with no tillage, compared to deep tillage (11 vs 8 bees/cage). **Methods:** In August 2012, bee nests were established in 20 plots (3 x 3 x 1.8 m field cages), each of which contained drip-irrigated squash plants. Deep tillage (disking, ripping, and subsoiling: 41 cm maximum depth) was used on 10 of these plots, in autumn 2012. Emerging bees were collected in blue vane traps (26 May–26 September 2013).

(1) Ullmann, K.S., Meisner, M.H. & Williams, N.M. (2016) Impact of tillage on the crop pollinating, ground-nesting bee, Peponapis pruinosa in California. *Agriculture, Ecosystems & Environment*, 232, 240-246.

Habitat management: Effects on pollination

6.3. Plant flowers: Pollination (8 studies)

- Pollination (0 studies)
- **Crop visitation (1 study):** One replicated, controlled study from Spain[4] found more pollinators on coriander flowers next to planted flower strips, compared to coriander flowers next to unplanted field margins.
- **Pollinator numbers (1 study):** One replicated, controlled study from the USA[6] found more wild bee species and individuals in planted flower strips, compared to unplanted strips, in some comparisons, but found no differences for syrphid flies.
- **Implementation options (8 studies):** Five replicated studies from Spain and the USA[1,3,5,6,8] found that some planted flower species were more attractive to pollinators than others. Four replicated studies from Italy and Spain[4,5,7,8] found more pollinators where more flower species had been planted, in some comparisons, but in other comparisons found fewer pollinators where more flower species had been planted. One replicated, controlled study from Italy[2] found that bee numbers increased over time in areas planted with three or six flower species, but decreased over time in areas planted with nine flower species.

A replicated, randomized, controlled study in 2009 on an organic farm in Sonoma County, California, USA (1), found that honey bees *Apis mellifera* and wild bees preferred different flower species planted in flower strips surrounding kale plots, and this varied seasonally. **Implementation options:** From 24 June to 10 July, more honey bees were found on wild mustard *Brassica* sp. (11 visits/sample), compared to other species in peak bloom (0–5), but visits by wild bees did not differ significantly between these species (0.1–1.6). From

10 to 22 July, more honey bees were found on tansy phacelia *Phacelia tanacetifolia* (28 vs 0–4 visits/sample) and wild arugula *Diplotaxis muralis* (19 vs 0–4), and more wild bees were found on phacelia (5.4 vs 0–2.4), compared to other species in peak bloom. From 5 to 19 August, more honey bees were found on white borage *Borago officinalis* (33 vs 0–11 visits/sample), and more wild bees were found on phacelia (6.2 vs 0.1–2.0), compared to other species in peak bloom. From 9 to 23 September, more honey bees were found on borage (10 visits/sample), compared to other species in peak bloom (0–1), but visits by wild bees did not differ significantly between these species (1.0–2.5). **Methods:** Two rows of kale *Brassica oleracea*, between two strips (four rows) of one flower species, were planted on 16 May in each plot (3 x 6 m). There were five replicate plots for each of nine flower species. Invertebrates were sampled by counting flower visitors (6 minutes/plot, every 5–9 days) or vacuuming plants (15 seconds/plot, 25 x 50 cm area, every 12–15 days).

A replicated, controlled study in 2011 in an organic tomato field near Pisa, Italy (2), found that wild bees increased over time in some flower plots but decreased over time in others. **Implementation options:** In plots with three species from one plant family (Apiaceae), or six species from two plant families (Apiaceae and Fabaceae), numbers of bees increased over time (minimum: 0.3 bees/plot, 10–31 days after flowering; maximum: 3 bees/plot, 38–45 days after flowering). Similar numbers of bees were found in both of these flower-species mixtures (0.3–3 bees/plot). In plots with nine plant species (three Apiaceae, three Fabaceae, and three others), numbers of bees decreased over time (maximum: 3.7 bees/plot, on the first day of flowering; minimum: 0.2 bees/plot, 38 days after flowering). **Methods:** Four treatments were compared: three, six, or nine flower species/plot, and a control with no flowers. Five plots/treatment were sown with flower seeds on 6 and 21 June. Each flower plot (2 x 10 m) was next to a tomato plot (4 x 10 m). Bees on flowers were sampled with aspirators every 14 days after flowering began.

A replicated study in 2009–2011 in farmland in the Central Valley, California, USA (3), found more bees and bee species on one species of flowering plant than on five other species. **Implementation options:** Gum plant *Grindelia camporum* attracted more individuals and species of native bees than did five other species of flowering plants (190–220 vs 0–60 individuals; 10–11 vs 1–6 species). **Methods:** At each of three sites, five plots were planted with mixtures of native forbs in October 2009. Plots were 3 x 15 m. Bees on flowers were netted once/month (20 minutes/sample, April–September 2010–2011).

A replicated, controlled study in 2013 in coriander plots near Madrid, Spain (4), found more pollinators on coriander flowers next to planted flower strips than on coriander flowers next to unplanted field margins. **Crop visitation:** More pollinators (bees, beetles, and syrphid flies) were found on coriander flowers next to flower strips than on coriander flowers next to unplanted margins (1.2–1.6 vs 0.2 pollinators/minute). **Implementation options:** Similar numbers of pollinators were found on coriander flowers next to flower strips with one flower species, compared to six (1.2 vs 1.6 pollinators/minute). More pollinators were found in flower strips with one flower species, compared to six (1.6 vs 0.4 pollinators/minute). **Methods:** Potted coriander plants were transplanted into the field on 1 May 2013, one month before flowering. Fifteen pots were buried 1.5 m from three field margins with one flower species (*Diplotaxis tenuifolia*), three margins with six flower species, or three unplanted margins (135 pots total). All margins were 1.5 x 15 m. Flowers were planted in autumn 2012.

Pollinators were observed twice/week (3–21 June, 12 minutes/field, nine minutes/field margin), and were counted only if they touched the reproductive parts of flowers.

A replicated, randomized study in 2011–2012 in a barley field near Madrid, Spain (5), found different numbers of flower visitors on different species and mixtures of planted flowers. **Implementation options:** The highest number of bees were found on *Coriandrum sativum* in 2012 (1.7 visits/minute) and the lowest number were found on *Antirrhinum majus* in 2011 (0 visits/minute). The highest number of syrphid flies were found on *Lobelia maritima* in 2011 (0.9 visits/minute) and the lowest number in 2011 were found on *A. majus* (0 visits/minute; approximately 0 visits/minute were also seen on all flowers in 2012). The highest number of beetles were found on *Echium plantagineum* in 2011 (1.2 visits/minute) and the lowest number were found *A. majus* and *Allium schoenoprasum* in 2011 (0 visits/minute). Plots with six or seven flower species did not consistently have more or fewer flower visitors than plots with one flower species. **Methods:** For each treatment (2011: 12 one-species and 2 six-species plantings; 2012: 7 one-species and 1 seven-species plantings), there were three plots (1.3 x 1.3 m). Flower visitors were counted (twice/week, nine minutes/plot) only if they touched the reproductive parts of flowers.

A replicated, controlled study in 2010–2011 in farmland in the Central Valley, California, USA (6), found more wild bees and bee species in perennial flower plantings, compared to annual flower plantings or unplanted controls, and more wild bees in species-rich but not species-poor annual plantings, compared to unplanted controls. **Pollinator numbers:** More wild bees were found in perennial flower plantings, compared to unplanted plots (525–775 vs 75–100 individuals). More wild bees were found in ten-species annual plots, compared to unplanted plots (175–250 vs 75–100 individuals), but no difference was found between five-species annual plots and unplanted plots (100–175 vs 75–100). More bee species were found in perennial plots, compared to unplanted plots (17–21 vs 8–13 bee species), but not in annual plots, compared to unplanted plots (10–15 vs 8–13). More honey bees *Apis mellifera* were found on annual or mixed compared to unplanted plots (450–750 vs 25–75 individuals). More honey bees were found on perennial compared to unplanted plots in 2011 (650 vs 25 individuals) but not in 2010 (250 vs 75). More bumblebees *Bombus* spp. were found on annual or perennial compared to unplanted plots (5–50 vs 0 individuals), and mixed plots (5–25) were not significantly different from annual, perennial, or unplanted plots. Similar numbers of syrphid flies were found in different plots (5–40 individuals). **Implementation options:** More wild bees were found in perennial flower plots, compared to annual (525–775 vs 100–225 individuals), but not compared to mixed plots with annuals and perennials (525–775 vs 525–650). More bee species were found in eight-species perennial plots, compared to five- or ten-species annual plots (20–21 vs 10–15 bee species), and in five-species perennial plots, compared to five-species annual plots (17 vs 10–12), but not in five-species perennial plots, compared to ten-species annual plots (17 vs 12–15), or in perennial compared to mixed plots (17–21 vs 18–21). **Methods:** Six flower plots (ten-species annual, five-species annual, eight-species perennial, five-species perennial, mixed, and control) were planted on each of three sites. Plots were 3 x 15 m. Flower visitors were counted if they touched the reproductive parts of flowers (20 minutes/sample, six samples/plot).

A replicated, randomized study in 2011–2012 in an organic tomato field near Pisa, Italy (7), found similar numbers of wild bees in planted flower strips with different numbers of flower species, in most comparisons. **Implementation options:** More wild bees were found in flower strips planted with nine plant species, compared to three or six species, in 2012, but similar numbers were found in other comparisons (numbers of individuals not reported). **Methods:** Three treatments were compared: three flower species/strip (Apiaceae species), six species/strip (three Apiaceae and three Fabaceae), and nine species/strip (three Apiaceae, three Fabaceae, and three others). Three strips/treatment were sown with flower seeds (2011: 6 and 21 June; 2012: 13 and 17 June). Each flower strip (2 x 4 m) was positioned between two tomato plots (4 x 10 m/plot). Bees on flowers were sampled with aspirators every 14 days, after flowering began.

A replicated, randomized study in 2012–2013 in a barley field near Madrid, Spain (8), found different numbers of pollinators on different species and mixtures of planted flowers. **Implementation options:** The highest number of pollinators were found on *Nepeta tuberosa* in 2011 (0.95 visits/minute) and the lowest number were found on *Salvia verbenaca* in 2011 (0 visits/minute). More pollinators were found in some plots with one flower species (*N. tuberosa*: 0.85–0.95 visits/minute; *Hyssopus officinalis*: 0.65–0.75) than in plots with six flower species (0.20–0.30 visits/minute), in both years (2012–2013). However, most of the other one-species plots were no different than the six-species plots (0.15–0.40 visits/minute). **Methods:** For each treatment (6 one-species and 2 six-species plantings), there were three plots (2.4 x 2.4 m), which were planted with three-month-old Lamiaceae seedlings in February 2011. Pollinators were counted (nine minutes/plot, once/week) only if they touched the reproductive parts of flowers.

(1) Hogg, B.N., Bugg, R.L. & Daane, K.M. (2011) Attractiveness of common insectary and harvestable floral resources to beneficial insects. *Biological Control*, 56, 76-84.

(2) Balzan, M.V., Bocci, G. & Moonen, A.-C. (2014) Augmenting flower trait diversity in wildflower strips to optimise the conservation of arthropod functional groups for multiple agroecosystem services. *Journal of Insect Conservation*, 18, 713-728.

(3) Wilkerson, M.L., Ward, K.L., Williams, N.M., Ullmann, K.S. & Young, T.P. (2014) Diminishing Returns from Higher Density Restoration Seedings Suggest Trade-offs in Pollinator Seed Mixes. *Restoration Ecology*, 22, 782-789.

(4) Barbir, J., Badenes-Pérez, F.R., Fernández-Quintanilla, C. & Dorado, J. (2015) Can floral field margins improve pollination and seed production in coriander Coriandrum sativum L. (Apiaceae)? *Agricultural and Forest Entomology*, 17, 302-308.

(5) Barbir, J., Badenes-Pérez, F.R., Fernández-Quintanilla, C. & Dorado, J. (2015) The attractiveness of flowering herbaceous plants to bees (Hymenoptera: Apoidea) and hoverflies (Diptera: Syrphidae) in agro-ecosystems of Central Spain. *Agricultural and Forest Entomology*, 17, 20-28.

(6) Williams, N.M., Ward, K.L., Pope, N., Isaacs, R., Wilson, J., May, E.A., Ellis, J., Daniels, J., Pence, A., Ullmann, K. & Peters, J. (2015) Native wildflower plantings support wild bee abundance and diversity in agricultural landscapes across the United States. *Ecological Applications*, 25, 2119-2131.

(7) Balzan, M.V., Bocci, G. & Moonen, A.-C. (2016) Utilisation of plant functional diversity in wildflower strips for the delivery of multiple agroecosystem services. *Entomologia Experimentalis et Applicata*, 158, 304-319.

(8) Barbir, J., Azpiazu, C., Badenes-Pérez, F.R., Fernández-Quintanilla, C. & Dorado, J. (2016) Functionality of Selected Aromatic Lamiaceae in Attracting Pollinators in Central Spain. *Journal of Economic Entomology*, 109, 529-536.

6.4. Plant hedgerows: Pollination (8 studies)

- **Pollination (1 study):** One replicated, paired site comparison from the USA[7] found higher seed-set in canola plants due to flower visitation by native bees in fields next to planted hedgerows, compared to fields next to unplanted edges. However, this study found no difference in seed-set due to flower visitation by honey bees or syrphid flies.
- **Crop visitation (2 studies):** One replicated, paired, site comparison from the USA[7] found higher crop visitation rates by native bees, but not by honey bees or syrphid flies, in fields next to planted hedgerows, compared to fields next to unplanted edges. Another replicated, paired, site comparison from the USA[6] found no difference in flower visitation rates by bees in fields next to planted edges.
- **Pollinator numbers (6 studies):** Five replicated studies from the USA[1,3-6] found more bee species in fields with hedgerows[1], or in hedgerows themselves[1,3-6], compared to fields or field edges without hedgerows. Three of these studies[1,3,4] found more syrphid fly species in hedgerows, compared to field edges without hedgerows. One of these studies[1] found similar numbers of syrphid fly species in fields with or without hedgerows. Two of these studies found more native bee and hoverfly individuals[1] or more specialist bees[6] in hedgerows, compared to field edges without hedgerows. One replicated site comparison from the USA[8] found fewer ground-nesting bees, but similar numbers of bee species and flower-visiting bees, in planted hedgerows, compared to unplanted edges.
- **Implementation options (3 studies):** Two replicated site comparisons from the USA[4,5] found more bee species in old hedgerows, compared to young hedgerows, and one of these studies[4] also found more syrphid fly species. One replicated site comparison from the USA[2] found more bee species on native plants, compared to non-native plants, in old hedgerows, but not in young hedgerows.

A replicated, paired, site comparison in May–August 2009–2010 in tomato fields in the Sacramento Valley, California, USA (1), found more individuals and species of flower-visiting bees and syrphid flies in hedgerows than in weedy field edges, and more individuals and species of bees but not syrphid flies in fields with hedgerows than in fields with weedy edges. **Pollinator numbers:** More individuals (10 m: 1.2 vs 0.3 individuals/sample; 100 m: 0.8 vs 0.3; 200 m: 0.5 vs 0.2) and more species (10 m: 0.63 vs 0.25 species/sample; 100 m: 0.54 vs 0.22; 200 m: 0.39 vs 0.16) of native bees were found 10–100 m, but not 200 m, into fields with hedgerows than in fields with weedy edges. More honey bees were found 10 m into fields with hedgerows, but there was not a significant difference between these fields in honey bees or syrphid flies at greater distances (honey bees: 10 m: 0.50 vs 0.14 individuals/sample; 100 m: 0.13 vs 0.04; 200 m: 0.20 vs 0.17; syrphid flies: 10 m: 0.63 vs 0.60; 100 m: 0.50 vs 0.67; 200 m: 0.20 vs 0.56). Flower-visitor communities had more species and greater diversity in hedgerows than in weedy edges (bees: 5.7 vs 3.6 species; syrphid flies: 2.7 vs 1.8 species). Twenty bee species were found only in hedgerows, not in weedy edges. Uncommon bee species (species represented by <1% of collected individuals) had larger populations in hedgerows than in weedy edges (6 vs 1 individuals), but uncommon syrphid fly species did not (numbers not reported). Honey bee, native bee, and syrphid fly species had larger populations in hedgerows than in weedy edges (numbers of individuals not reported). The number of flower species and the amount of bare ground did not differ significantly between hedgerows and weedy edges (6 vs 4 species; amount of bare ground not reported), but floral cover was higher and there was more dead wood in hedgerows (amounts not reported). **Methods:** Native perennial shrubs (305–550 x 7 m), bordered by native perennial grasses (3 m), were planted in 1996–2003 on the edges of six fields (hedgerows) and compared to the unplanted edges of six fields (weedy edges). Insects were netted if they touched the reproductive parts of flowers (in field borders) or they were identified landing on flowers or flying through quadrats (1 m^3 quadrats; four minutes/quadrat; three quadrats/field-edge; six quadrats/field).

A replicated site comparison in 2009 in farmland in the Sacramento Valley, California, USA (2), found more bee species on native plants than on exotic plants in mature hedgerows. **Implementation options:** Species richness of bees was higher on native plants than on exotic plants in mature hedgerows, but not in new hedgerows (mature: 3.7 vs 1 species; new: 4.2 vs 2.8 species). Abundance of bees was higher on native than on exotic plants in both mature and new hedgerows (mature: 17 vs 3 individuals; new: 19 vs 9). **Methods:** Similar but not identical species of native flowering shrubs and forbs were planted in four mature hedgerows (305–550 m; planted in 1996) and four new hedgerows (350 m x unreported width; planted in 2008). New hedgerows were sampled three times (April–August) and mature hedgerows were sampled four times (May–July). In timed surveys (30 minutes/mature vs 60 minutes/new hedgerow), bees were netted if they touched the reproductive parts of a flower.

A replicated, before-and-after study in April–August of 2006–2013 in field borders in the Central Valley, California, USA (3) (same study as (4)), found that flower-visiting insect species were more likely to be present after woody hedgerows were planted than before. **Pollinator numbers:** Insects that specialize in relatively few flower species (specialists) were more likely to be present six years after planting, compared to the first year after planting (bee species: 0.3 vs 0.0 probability of occurrence/transect; syrphid fly species: 0.1 vs 0.02), and so were generalist syrphid fly species, but not generalist bee species (syrphid fly species: 0.12 vs 0.07; bee species: 0.2 vs 0.2). **Methods:** Field borders (350 x 3–6 m) were planted with native shrubs and trees in 2007–2008 in five fields, and unplanted borders in ten fields were used as controls. Fields borders had an irrigation ditch or slough. Fields were approximately 80 acres of row crops, vineyards, or orchards. Hedgerows were watered and weeded for three years. At least three times per year, insects were collected from flowers on one-hour transects at each site.

A replicated site comparison in April–August of 2006–2013 in field borders in the Central Valley, California, USA (4) (same study as (3)), found more species of bees and syrphid flies in planted hedgerows than in unplanted field borders, but only after several years of hedgerow growth. **Pollinator numbers and Implementation options:** More species of bees and syrphid flies were estimated to be present in planted hedgerows than in unplanted field borders, 4–6 years after planting (2013: 65 vs 45 species; 2012: 60 vs 40; 2011: 55 vs 40), but not 0–3 years after planting (2010: 50 vs 40 species; 2009–2008: 45 vs 40; 2007: 35 vs 35). **Methods:** Field borders (350 x 3–6 m) were planted with native shrubs and trees in 2007–2008 in five fields, and unplanted borders in ten fields were used as controls. Fields borders had an irrigation ditch or slough. Fields were approximately 80 acres of row crops, vineyards, or orchards. Hedgerows were watered and weeded for three years. At least three times per year, insects were collected from flowers on one-hour transects at each site.

A replicated site comparison in 2007–2013 in farmland in the Central Valley, California, USA (5), found greater bee diversity in mature hedgerows compared to weedy field edges or immature ("maturing") hedgerows. **Pollinator numbers and Implementation options:** Greater bee diversity was found in mature hedgerows compared to weedy field margins or immature hedgerows, but not in immature hedgerows compared to weedy field margins (data was reported as beta-diversity, which is change in the diversity of species between sites). Twenty-eight percent of bee species were found only in hedgerows. Thirteen percent were found only in weedy edges. **Methods:** Native, perennial shrubs and trees (3–6 x 350 m) were planted 1–10 years (immature hedgerows) or >10 years (mature hedgerows) before bees were collected. Bees were collected if they touched the reproductive parts of flowers, in one-hour samples of 21 hedgerows and 24 weedy edges, 2–5 times/year, in April–August 2007–2013.

A replicated, paired site comparison in 2012–2013 in sunflower fields in the Central Valley, California, USA (6), found more bees, more sunflower-specialist bees, fewer generalist bees, and more bee species in hedgerows than in bare/weedy edges. **Crop visitation:** Visitation rates to sunflowers were not significantly different in fields with hedgerows than in fields with bare/weedy edges (rates not reported). **Pollinator numbers:** Bee abundance and species richness were higher in hedgerows than in bare/weedy edges (abundance: 17 vs 6 individuals/sample; richness: 5 vs 2 species/sample). More sunflower-specialist bees, but fewer generalist bees, were found in hedgerows than in bare/weedy edges (specialists: 0.6 vs 0.1 relative abundance; generalists: 0.0 vs 0.3). **Methods:** In field edges, when >90% of sunflower heads were blooming in adjacent fields, bees were netted for 16 minutes/field (2012: 10 fields; 2013: 8 fields), and bees that touched the reproductive parts of flowers were counted for 2 minutes/plot in 8 plots/field (visitation rates). Half of fields had bare/weedy edges (managed by burning, scraping, or herbicides). Half had hedge rows (3–6 x 250–300 m, 5–12 years old). Sunflower specialists and generalists were netted in 26 hedgerows and 21 bare/weedy edges (one hour/sample; five samples in April–August 2012–2013).

A replicated, paired site comparison in 2009–2011 in tomato fields in Yolo County, California, USA (7), found more native bees, and higher seed-set due to native bees, in fields next to planted hedgerows, compared to fields next to conventional edges. **Pollination:** Seed-set in canola plants, due to flower visitation by native bees, was higher in fields next to hedgerows, compared to fields next to unplanted edges (21% higher estimated seed yields). Seed-set, as a result of flower visitation by honey bees or syrphid flies, was similar in fields next to hedgerows or unplanted edges (data not reported). **Crop visitation:** More native bees were found on canola flowers in fields next to hedgerows, compared to fields next to unplanted edges (4.2 vs 1.0 visitors/observation), but similar numbers of honey bees (1.4 vs 2.6), syrphid flies (2.9 vs 3.5), or total visitors (8.4 vs 7.1) were found. **Methods:** Hedgerows (300–350 m length) were planted along the edges of four treatment fields, but not four control fields, about 10 years before this study began. The edges of control fields were mown, disked, or sprayed with herbicide. Tomatoes were grown in all fields, but pollination was measured in clusters of potted canola plants, placed at four distances from the edges (0, 10, 100, and 200 m), in 2010 and 2011. Flower visitors were observed for four minutes/cluster (one observation period in 2010 and four in 2011). Pollination deficits were measured by comparing seed-set in open-pollinated and hand-pollinated canola flowers.

A replicated site comparison in farmland in the Central Valley, California, USA (8) (years of study not reported), found fewer ground-nesting bees in planted hedgerows, compared to unplanted field edges. **Pollinator numbers:** Fewer ground-nesting bees were found in planted hedgerows, compared to unplanted edges (13 vs 33 individuals/site), but there were similar numbers of flower-visiting bees (data reported as statistical results), and similar numbers of bee species (2.9 vs 3.2 rarified species richness). Indicators of ground-nesting bee habitat did not differ between planted hedgerows and unplanted edges (data on bare ground, soil compaction, particle size, and surface heterogeneity reported as statistical results). **Methods:** Eight field edges with planted hedgerows (mostly Californian native shrubs and forbs, at least five years after planting) were compared to eight field edges without planted hedgerows. Ground-nesting bees were sampled with emergence traps (0.6 m^2, 30 traps/site/sample, three samples in two years, in May–August). Foraging bees were netted on inflorescences (one hour/site/sample, within 10 days of emergence samples). Nesting indicators were assessed using soil samples (0–10 cm depth, two samples/site) and visual estimates.

(1) Morandin, L.A. & Kremen, C. (2013) Hedgerow restoration promotes pollinator populations and exports native bees to adjacent fields. *Ecological Applications*, 23, 829-839.

(2) Morandin, L.A. & Kremen, C. (2013) Bee Preference for Native versus Exotic Plants in Restored Agricultural Hedgerows. *Restoration Ecology*, 21, 26-32.

(3) Kremen, C. & M'Gonigle, L.K. (2015) EDITOR'S CHOICE: Small-scale restoration in intensive agricultural landscapes supports more specialized and less mobile pollinator species. *Journal of Applied Ecology*, 52, 602-610.

(4) M'Gonigle, L.K., Ponisio, L.C., Cutler, K. & Kremen, C. (2015) Habitat restoration promotes pollinator persistence and colonization in intensively managed agriculture. *Ecological Applications*, 25, 1557-1565.

(5) Ponisio, L.C., M'Gonigle, L.K. & Kremen, C. (2015) On-farm habitat restoration counters biotic homogenization in intensively managed agriculture. *Global Change Biology*, 22, 704-715.

(6) Sardiñas, H.S. & Kremen, C. (2015) Pollination services from field-scale agricultural diversification may be context-dependent. *Agriculture, Ecosystems & Environment*, 207, 17-25.

(7) Morandin, L.A., Long, R.F. & Kremen, C. (2016) Pest Control and Pollination Cost–Benefit Analysis of Hedgerow Restoration in a Simplified Agricultural Landscape. *Journal of Economic Entomology*, 109, 1020.

(8) Sardiñas, H.S., Ponisio, L.C. & Kremen, C. (2016) Hedgerow presence does not enhance indicators of nest-site habitat quality or nesting rates of ground-nesting bees. *Restoration Ecology*, 24, 499-505.

6.5. Restore habitat along watercourses: Pollination (1 study)

- Pollination (0 studies)
- **Flower visitation (1 study):** One replicated, paired site comparison from the USA[1] found that bee visitation rates to native flowers did not differ between restored and remnant sites, but there were different plant-insect interactions.
- **Pollinator numbers (1 study):** One replicated, paired site comparison from the USA[1] found similar numbers of bees and bee species, but different bee communities, in restored and remnant sites.
- Implementation options (0 studies)

A replicated, paired site comparison in 2003 in 10 riparian sites along the Sacramento River in California, USA (1), found that bee visitation to native flowers, and the number of bees and bee species, did not differ between restored and remnant sites, but there were different bee species and different plant-insect interactions at different sites. **Flower visitation:** The proportion of native plants visited did not differ between restored and remnant sites (0.67 vs 0.48 visits/minute), but different species visited flowers (15% of plant-visitor interactions were shared between restored and remnant sites). **Pollinator numbers:** The number of bees (253–702 vs 225–499) and bee species (19–58 vs 37–47) did not differ between restored and remnant sites. Different bee species were present at remnant and restored sites (36% of bee species were present at both sites in a pair; other data reported as ordination results). **Methods:** Each of five restored sites was paired with a remnant site (5.5–10 km apart). Plots within sites (1 ha) were 0.5–3.7 km apart. Restored sites were previously walnut and almond orchards (6 years before sampling) and were planted with similar vegetation to remnant sites (maple *Acer* spp., oak *Quercus* spp., willow *Salix* spp., and grass). The proportion of native plants (common to both sites: willow *Salix* spp., mule fat *Baccharis salicifolia*, lupin *Lupinus* spp., California rose *Rosa californica*, and ash-leaved maple *Acer negundo*) did not differ between restored and remnant sites (0.49 vs 1.82 individuals, 0.39 vs 0.89 species/flower head). Bees were sampled every six weeks in February–August 2003 (transect walks and pan traps). Flowers were sampled in each plot (60 quadrats, 0.25 x 4 m).

(1) Williams, N.M. (2011) Restoration of Nontarget Species: Bee Communities and Pollination Function in Riparian Forests. *Restoration Ecology*, 19, 450-459.

Livestock management: Effects on pollination

Our search found no studies of the effects of livestock management on pollination.

7. Other biodiversity

Crop and soil management: Effects on other biodiversity

7.1. Add compost to the soil: Other biodiversity (5 studies)

- Amphibians (0 studies)
- Birds (0 studies)
- **Invertebrates (1 study):** One replicated, controlled study from the USA[4], found no differences in invertebrate biodiversity between plots with or without added compost.
- Mammals (0 studies)
- **Plants (4 studies):** Four replicated, controlled studies (three randomized) from Italy[3], Spain[1], and the USA[2,5] found more plant biomass in plots with added compost, compared to plots without added compost. One of these studies[1] also found more plant cover and faster tree growth in plots with added compost. Another one[5] also found sixteen species of rare plants only in plots with added compost. Another one[3] found more plants in plots with added compost, compared to plots without added compost, in one of two years, but found similar numbers of plant species in plots with or without added compost.
- Reptiles (0 studies)
- Implementation options (0 studies)

A replicated, controlled study in 2001–2003 in a degraded wood pasture in Catalonia, Spain (1), found more plant cover, more plant biomass, and faster tree growth in plots with added compost, compared to plots without added compost. **Plants:** More plant cover, more herbaceous biomass, and faster oak tree *Quercus humilis* growth were found in plots with added compost (cover: 89% vs 60%; biomass: 2,700 vs 1,700 kg dry weight/ha; growth: 41 vs 34 cm/year). **Methods:** Composted sewage sludge was added to five treatment plots (10 t dry matter/ha), but not five control plots (no compost). Each plot was 20 x 5 m. To restore the wood pasture, shrubs and small trees were crushed and scattered on the soil, and grass seeds were sown. Soil was collected in soil cores (10 cores/plot, 0–20 cm depth).

A replicated, randomized, controlled, paired study in 2008–2011 in grazed annual grasslands in California, USA (2), found more plant biomass in plots with added compost, compared to plots without added compost. **Plants:** More plant biomass (measured as carbon) was found in plots with added compost (50–175 more g C/m^2/year, above ground, dry weight). **Methods:** Composted organic green waste was added to three treatment plots (129 g total N/m^2), but not six control plots, at each of two sites (coastal grassland in Nicasio and valley grassland in Browns Valley). The plots were 25 x 60 m. Above-ground plant biomass was measured at the end of the growing season (1,800 cm^2/plot).

A replicated, randomized, controlled study in 2007–2013 in a fallow field in Campania, Italy (3), found more plants and plant biomass in plots with added compost, compared to plots without added compost. **Plants:** More plants were found in plots with added compost, compared to plots without it, in one of two years (2013: 1,023 vs 473 individuals/m^2). More plant biomass was found in plots with added compost, compared to plots without it, in both years (2012: 401 vs 119 g dry weight/m^2; 2013: 301 vs 111). Similar numbers of plant species were found in plots with or without added compost (12–21 species). **Methods:** Compost was added to four treatment plots (2007–2009: 30 Mg/ha dry weight; 2010–2013: 15 Mg/ha dry weight), but not to four control plots. The plots were 10 x 5 m. The compost was made from municipal solid waste and urban yard trimmings. The compost was added, and plots were tilled, in April each year (20 cm depth). Horticultural crops were grown in 2007–2011. In March 2012 and 2013, all plants (spontaneous growth) were collected from 1 x 1 m quadrats in each plot.

A replicated, controlled study in 2014 in 29 organic vegetable fields on the Central Coast, California, USA (4), found no differences in invertebrate biodiversity between plots with or without added compost. **Invertebrates:** Similar numbers of invertebrates and invertebrate families were found in plots with or without added compost (data reported as model coefficients). **Methods:** In each of 29 vegetable fields, compost was added to one plot, but not to one adjacent plot (5 x 5 m plots), 1–2 months before lettuces were planted (25 t compost/ha, made from cow, chicken, and green manures). Lettuces were planted in spring (5–28 March) and summer (30 May–5 July). Invertebrates (insects, springtails, and spiders) were collected in pitfall traps (three/plot, 7.5 cm diameter) and pan traps (two/plot, blue and yellow, 15 cm diameter) after 48 hours of trapping (one sample when lettuces were seedlings and one when mature).

A replicated, randomized, controlled study in 2008–2012 in two grazed grasslands in California, USA (5), found more plant biomass in plots with added compost. Sixteen species of rare plants were found only in plots with added compost. **Plants:** Before grazing, more plant biomass was found in plots with added compost, compared to plots without it (coastal prairie: 41% more; valley grassland: 71% more). Higher plant diversity was found in plots with added compost, compared to plots without it, in one of eight comparisons (coastal prairie, 2009: 7.5 vs 6 species/m^2; Shannon evenness index). In the valley grassland, increases in the relative abundance of three grass species, and decreases in that of two forb and one bulb species, were found in plots with added compost, compared to plots without it. In the coastal prairie, sixteen rare species (<5% of observations) were found only in plots with added compost. The abundance of an invasive grass (medusahead *Elymus caput-medusae*) was lower in plots with added compost, in one of four comparisons (13% higher abundance in plots with compost), but that of an invasive forb (*Carthamus lanatus*) was no different. **Methods:** In December 2008, composted green waste (7 kg dry matter/m^2, 129 g N/m^2, C to N ratio of 11) was added to three plots at each of two sites (one valley grassland and one coastal prairie, both dominated by non-native annuals), but compost was not added to three control plots at each site. All plots (25 x 60 m plots) were in cattle-grazed paddocks (15 ha, rotationally grazed to 84 g standing/m^2).

(1) Tarrasón, D., Ortiz, O. & Alcañiz, J.M. (2007) A multi-criteria evaluation of organic amendments used to transform an unproductive shrubland into a Mediterranean dehesa. *Journal of Environmental Management*, 82, 446-456.

(2) Ryals, R. & Silver, W.L. (2013) Effects of organic matter amendments on net primary productivity and greenhouse gas emissions in annual grasslands. *Ecological Applications*, 23, 46-59.

(3) Baldantoni, D., Bellino, A., Morra, L. & Alfani, A. (2015) Compost Amendment Enhances Natural Revegetation of a Mediterranean Degraded Agricultural Soil. *Environmental Management*, 56, 946-956.

(4) Karp, D.S., Moses, R., Gennet, S., Jones, M.S., Joseph, S., M'Gonigle, L.K., Ponisio, L.C., Snyder, W.E. & Kremen, C. (2016) Agricultural practices for food safety threaten pest control services for fresh produce. *Journal of Applied Ecology*, 53, 1402-1412.
(5) Ryals, R., Eviner, V.T., Stein, C., Suding, K.N. & Silver, W.L. (2016) Grassland compost amendments increase plant production without changing plant communities. *Ecosphere*, 7, e01270-n/a.

7.2. Add manure to the soil: Other biodiversity (1 study)

- Amphibians (0 studies)
- Birds (0 studies)
- Invertebrates (0 studies)
- Mammals (0 studies)
- **Plants (1 study):** One replicated, randomized, controlled study from Spain[1] found more plant species in plots with added manure, compared to plots without added manure, in one of three comparisons.
- Reptiles (0 studies)
- Implementation options (0 studies)

A replicated, randomized, controlled study in 1998–2001 in a wood pasture in Spain (1) found more plant species in plots with added manure, compared to plots without added manure. **Plants:** More plant species were found in plots with added manure, compared to plots without added manure, in one of three comparisons (20 vs 17 species). **Methods:** Plots (1 x 1 m) had added manure (90 g in a 50 x 50 cm section of each plot) or no added manure (40 replicates each). Vegetation was sampled in spring 1998, 1999, and 2001 (20 x 20 cm quadrats). The vegetation consisted of Holm Oak *Quercus ilex* and dry annual grasses.

(1) Traba, J., Levassor, C. & Peco, B. (2003) Restoration of species, richness in abandoned Mediterranean grasslands: Seeds in cattle dung. *Restoration Ecology*, 11, 378-384.

7.3. Add sewage sludge to the soil: Other biodiversity (2 studies)

- Amphibians (0 studies)
- Birds (0 studies)
- Invertebrates (0 studies)
- Mammals (0 studies)

- **Plants (2 studies):** Two replicated, controlled studies from Spain[1,2] found greater plant cover and faster tree growth in plots with added sewage sludge, compared to plots without it, in some or all comparisons. One of these studies[2] found similar numbers of plant species in plots with or without added sewage sludge. The other one[1] found more plant biomass in plots with added sewage sludge.
- Reptiles (0 studies)
- **Implementation options (1 study):** One study from Spain[1] found faster tree growth in plots with composted or thermally dried sewage sludge, but not with digested sewage sludge, compared to plots without sewage sludge. Another one[2] found no differences in pasture cover, tree growth, or numbers of species between plots with different types of sewage sludge.

A replicated, controlled study in 2001–2003 in a degraded wood pasture in Catalonia, Spain (1) (same study as (2)), found higher plant cover, more plant biomass, and faster tree growth in plots with added sewage sludge, compared to plots without it. **Plants:** Greater plant cover and more herbaceous biomass were found in plots with added sewage sludge, compared to plots without it (cover: 85–93% vs 60%; biomass: 2,700–2,800 vs 1,700 kg dry weight/ha). Faster oak tree *Quercus humilis* growth was found in plots with added sewage sludge (composted or thermally dried), compared to plots without it (41–42 vs 34 cm/year). **Implementation options:** No difference in tree growth was found in plots with added digested sewage sludge, compared to plots without it (39 vs 34 cm/year). **Methods:** There were five plots (20 x 5 m) for each of three sewage-sludge treatments (10 t dry matter/ha of composted, digested, or thermally dried sewage sludge) and there were five control plots (no sewage sludge). To restore the wood pasture, shrubs and small trees were crushed and scattered on the soil, and grass seeds were sown.

A replicated, controlled study in 2001–2003 in a degraded wood pasture in Catalonia, Spain (2) (same study as (1)), found greater pasture cover and faster tree growth in plots with added sewage sludge, compared to plots without. **Plants:** Greater pasture cover and faster tree growth were found in plots with added sewage sludge, compared to plots without it, in two of three comparisons (90–98% vs 80–90% cover; 0.25 vs 0.16–0.17 cm/year). Similar numbers of species were found in plots with or without added sewage sludge (data not reported). **Implementation options**: No differences in pasture cover, tree growth, or numbers of species were found in plots with dewatered, composted, or thermally dried sewage sludge (0.07–0.25 cm/year; other data not reported). **Methods:** Plots (100 m^2) growing shrubs and trees such as *Quercus ilex* and *Q. humilis* through natural regeneration had added sewage sludge (dewatered, composted, or thermally dried) or no sewage sludge (five plots for each): dewatered (11 Mg/ha), composted (mixed with pinewood splinters and composted; 14 Mg/ha), or thermally dried (dried at 130 ^{o}C; 50 Mg/ha). All sewage sludge was anaerobically digested before being processed. All plots were seeded with grasses *Lolium perenne, Festuca arundinacea* and *Dactylis glomerata*, and were weeded to simulate grazing. Woody vegetation remnants were crushed and scattered over the soil surface. Cover and number of species was estimated using a line-intercept method (every 10 cm along 10 m transect) in June 2001 and 2002. Tree growth was measured in January 2001 and December 2001–2003.

(1) Tarrasón, D., Ortiz, O. & Alcañiz, J.M. (2007) A multi-criteria evaluation of organic amendments used to transform an unproductive shrubland into a Mediterranean dehesa. *Journal of Environmental Management*, 82, 446-456.
(2) Tarrasón, D., Ojeda, G., Ortiz, O. & Alcañiz, J.M. (2014) Can organic amendments be useful in transforming a mediterranean shrubland into a dehesa? *Restoration Ecology*, 22, 486-494.

7.4. Use organic fertilizer instead of inorganic: Other biodiversity (1 study)

- Amphibians (0 studies)
- Birds (0 studies)
- Invertebrates (0 studies)
- Mammals (0 studies)
- **Plants (1 study):** One replicated, randomized, controlled study from Italy[1] found more plants and plant biomass, but similar numbers of plant species, in plots with organic fertilizer, compared to plots with inorganic fertilizer.
- Reptiles (0 studies)
- Implementation options (0 studies)

A replicated, randomized, controlled study in 2007–2013 in a fallow field in Campania, Italy (1), found more plants and plant biomass, but similar numbers of plant species, in plots with organic fertilizer, compared to inorganic fertilizer. **Plants:** More plants were found in plots with compost, compared to mineral fertilizer, in one of two years (2013: 1,023 vs 655 individuals/m^2). More plant biomass was found in plots with compost, compared to mineral fertilizer, in both years (2012: 401 vs 126; 2013: 301 vs 162 g dry weight/m^2). Similar numbers of plant species were found in plots with compost or mineral fertilizer (12–18 species). **Methods:** Compost was added to four plots (2007–2009: 30; 2010–2013: 15 Mg/ha dry weight). Mineral fertilizer was added to four other plots (NPK fertilizer, twice/year, 50 kg/ha). The plots were 10 x 5 m. The compost was made from municipal solid waste and urban yard trimmings. The compost was added, and plots were tilled, in April each year (20 cm depth). Horticultural crops were grown in 2007–2011. In March 2012 and 2013, all plants (spontaneous growth) were collected from 1 x 1 m quadrats in each plot.

(1) Baldantoni, D., Bellino, A., Morra, L. & Alfani, A. (2015) Compost Amendment Enhances Natural Revegetation of a Mediterranean Degraded Agricultural Soil. *Environmental Management*, 56, 946-956.

7.5. Plant or maintain ground cover in orchards or vineyards: Other biodiversity (3 studies)

- Amphibians (0 studies)
- **Birds (1 study):** One site comparison from Spain[3] found more birds and higher bird diversity in a vineyard with resident vegetation (without tillage), compared to a vineyard with bare soil (with conventional tillage), between the vine rows.
- Invertebrates (0 studies)
- **Fungi (1 study):** One replicated, randomized, controlled study from Portugal[2] found more mushrooms and mushroom species in plots with cover crops (without tillage), compared to plots without cover crops (with conventional tillage).
- Mammals (0 studies)
- Plants (0 studies)
- Reptiles (0 studies)
- **Implementation options (3 studies):** One site comparison from Spain[3] found more birds and higher bird diversity in a vineyard with mown resident vegetation, compared to a vineyard with herbicide-treated resident vegetation, between the vine rows. One replicated, randomized, controlled study from Portugal[2] found fewer mushrooms and fewer mushroom species, but similar mushroom diversity, in plots with seeded cover crops, compared to resident vegetation. One replicated site comparison from Greece[1] found more flowering plant species, and higher flowering plant cover, in managed orchards, compared to abandoned orchards.

A replicated site comparison in 2001 in olive orchards on the island of Lesvos, Greece (1), found more species and higher cover of flowering plants in managed orchards (with tilled soils and ground cover dominated by annual plants), compared to unmanaged orchards (without tilled soils, and with ground cover dominated by perennial plants). **Implementation options:** More species and higher cover of flowering plants were found in managed orchards, compared to abandoned orchards (38 vs 25 species/site, 5,235 vs 770 cm^2/site). **Methods:** Three managed orchards were compared to three abandoned orchards (1 ha each). Open flowers that could potentially be visited by bees were sampled three times/site in March–May (50 x 0.4 m transects).

A replicated, randomized, controlled study in 2001–2008 in a chestnut orchard in northeast Portugal (2) found more mushrooms and mushroom species in plots with cover crops (without tillage), compared to plots without cover crops (with conventional tillage). **Fungi:** More mushrooms, more mushroom species, and greater mushroom diversity were found in plots with cover crops, compared to plots without cover crops (85–115 vs 20 kg fresh weight/ha; 18–23 vs 11 species; diversity reported as Shannon Index). **Implementation options:** Fewer mushrooms and fewer mushroom species were found in plots with seeded cover crops, compared to resident vegetation (85 vs 115 kg fresh weight/ha; 18 vs 23 species), but there was no difference in mushroom diversity (reported as Shannon Index). **Methods:** There were three plots for each of two treatments (resident vegetation or grasses and legumes, sown in 2001; both without tillage), and there were three control plots (conventional tillage, 15–20 cm depth, thrice/year). Each plot (600 m^2) had six chestnut trees (40 years old in 2001) and was fertilized but not irrigated. Mushrooms were collected in 2006–2008 (weekly in May–July and September–November, under three trees/plot). It was not clear whether these results were a direct effect of cover crops or tillage.

A site comparison in 2012–2013 in three irrigated vineyards in the Ronda Mountains, southern Spain (3) found more birds and higher bird diversity in a vineyard with mown resident vegetation (without tillage), compared to bare soil (with conventional tillage), between the vine rows. **Birds:** The most birds and bird species, and highest diversity, were found in a vineyard with resident vegetation, and the fewest birds and bird species, and lowest diversity, were found in a vineyard with bare soil (59 vs 33 birds/hour, 6.5 vs 3 species, diversity reported as the Shannon index). **Implementation options:** More birds and bird species, and higher bird diversity, were found in a vineyard with mown resident vegetation, compared to a vineyard with herbicide-treated resident vegetation (59 vs 36 birds/hour, 6.5 vs 3.9 species). **Methods:** Resident vegetation between the vine rows was mown in one vineyard (January–February and May), treated with herbicide in a second vineyard (January–April; tillage in November), and treated conventionally in a third vineyard (herbicide in January–April; tillage in January–February, May–August, and November). Larger habitat patches with different configurations (mean shape index), were found in the landscape surrounding the mown vineyard, compared to the other two. Birds were sampled on 34 days in May–July 2012–2013 (ten-minute counts of birds within 50 m, at three random points/vineyard/day, at dawn and dusk). It was not clear whether these results were a direct effect of resident vegetation, herbicide, tillage, or habitat patches in the landscape.

(1) Potts, S.G., Petanidou, T., Roberts, S., O'Toole, C., Hulbert, A. & Willmer, P. (2006) Plant-pollinator biodiversity and pollination services in a complex Mediterranean landscape. *Biological Conservation*, 129, 519-529.

(2) Martins, A., Marques, G., Borges, O., Portela, E., Lousada, J., Raimundo, F. & Madeira, M. (2011) Management of chestnut plantations for a multifunctional land use under Mediterranean conditions: effects on productivity and sustainability. *Agroforestry Systems*, 81, 175-189.

(3) Duarte, J., Farfán, M.A., Fa, J.E. & Vargas, J.M. (2014) Soil conservation techniques in vineyards increase passerine diversity and crop use by insectivorous birds. *Bird Study*, 61, 193-203.

Habitat management: Effects on other biodiversity

7.6. Plant flowers: Other biodiversity (3 studies)

- Amphibians (0 studies)
- Birds (0 studies)
- Invertebrates (0 studies)
- Mammals (0 studies)

- **Plants (2 studies)**: One replicated, paired, controlled study from Italy[1] found similar numbers of plant species in planted flower strips and unplanted field margins, but found higher plant diversity in unplanted margins. One replicated study from the USA[2] found that most flower species persisted for at least two years after planting.
- Reptiles (0 studies)
- **Implementation options (2 studies):** One replicated study from the USA[2] found that more plant species persisted in flower strips when twice as many seeds were sown, but there was no further increase in persistence at higher seeding rates. One replicated, randomized, controlled study from Spain[3] found that tillage had inconsistent effects on the emergence of planted flowers.

A replicated, paired, controlled study in 2011–2012 in tomato fields in Tuscany, Italy (1), found similar numbers of plant species in planted flower strips, compared to unplanted field margins, but found higher plant diversity in unplanted margins. **Plants:** Similar numbers of plant species were found in planted and unplanted margins (numbers of species not reported). However, a higher turnover in species was found between unplanted margins than between planted margins (data reported as beta-diversity). **Methods:** In each of eight tomato fields, plants were sampled in each of two field margins (one with flower strips, one without, 3 x 25 m each), in five 1 x 1 m quadrats/field margin, in early August.

A replicated study in 2008–2010 in farmland in the Central Valley, California, USA (2), found that a higher percentage of flower species persisted over time in flower plots that were planted with higher amounts of seed. **Plants:** Eight of nine species persisted for two years. Six species persisted for three years. **Implementation options:** Over the two years that followed planting, a higher percentage of species persisted in plots that were planted with two to four times as much seed (2x–4x) as the plots that were planted with the least seed (1x: 17–60%; 2x: 33–74%; 4x: 35–77%), but there was not a significant difference between the plots with 2x and 4x. The amount of seed planted had a significant effect on the percentage cover of plants, but it was not clear which treatments were significantly different from one another (data reported as log aggregate forb cover). **Methods:** Nine plots (1 x 8 m) were sown with the seeds of nine flower species in each of six hedgerows.

A replicated, randomized, controlled study in 2011–2012 in a barley field near Madrid, Spain (3), found that more seedlings of five planted flower species, but fewer seedlings of one planted flower species, emerged after no tillage, compared to shallow tillage. **Implementation options:** A higher density of seedlings emerged after no tillage, compared to shallow tillage, in *Calendula arvensis* (2011: 4,523 vs 2,817 plants/m^2; 2012: 1,223 vs 231), *Phacelia tanacetifolia* (2011: 318 vs 226; 2012: 116 vs 2), *Centauria cyanus* (2012: 190 vs 59), *Diplotaxis tenuifolia* (2012: 153 vs 5), and *Echium plantagineum* in 2012 (236 vs 2) but not in 2011 (230 vs 235). A lower density of seedlings emerged after no tillage, compared to shallow tillage, in *Coriandrum sativum* in 2011 (16 vs 314 plants/m^2), but not in 2012 (0 vs 2). Similar densities of seedlings emerged after no tillage, compared to shallow tillage, in *Borago officinalis* (2011: 27 vs 27 plants/m^2; 2012: 20 vs 2). **Methods:** For each of seven flower species, there were three plots (1.3 x 1.3 m). In July, half of each plot was tilled, and half was not. In January, seedlings were counted in quadrats (25 x 25 cm).

(1) Balzan, M.V. & Moonen, A.-C. (2014) Field margin vegetation enhances biological control and crop damage suppression from multiple pests in organic tomato fields. *Entomologia Experimentalis et Applicata*, 150, 45-65.
(2) Wilkerson, M.L., Ward, K.L., Williams, N.M., Ullmann, K.S. & Young, T.P. (2014) Diminishing Returns from Higher Density Restoration Seedings Suggest Trade-offs in Pollinator Seed Mixes. *Restoration Ecology*, 22, 782-789.
(3) Barbir, J., Badenes-Pérez, F.R., Fernández-Quintanilla, C. & Dorado, J. (2015) The attractiveness of flowering herbaceous plants to bees (Hymenoptera: Apoidea) and hoverflies (Diptera: Syrphidae) in agro-ecosystems of Central Spain. *Agricultural and Forest Entomology*, 17, 20-28.

7.7. Plant hedgerows: Other biodiversity (3 studies)

- Amphibians (0 studies)
- Birds (0 studies)
- Invertebrates (0 studies)
- Mammals (0 studies)
- **Plants (1 study):** One replicated, paired site comparison from the USA[1] found no difference in the number of flower species in hedgerows, compared to weedy field edges.
- Reptiles (0 studies)
- **Implementation options (2 studies):** One replicated site comparison from the USA[3] found more plant species in narrow hedgerows, compared to wide hedgerows, and higher plant cover in younger hedgerows, compared to older hedgerows. One replicated site comparison from the USA[2] found higher cover of exotic plants, compared to native plants, in young hedgerows, but not in old hedgerows.

A replicated, paired, site comparison in May–August 2009–2010 in tomato fields in the Sacramento Valley, California, USA (1), found similar numbers of flower species and similar amounts of plant cover in planted hedgerows and unplanted field edges. **Plants:** The number of flower species and the amount of bare ground did not differ significantly between hedgerows and weedy edges (6 vs 4 species; amount of bare ground not reported). **Methods:** Native perennial shrubs (305–550 x 7 m), bordered by native perennial grasses (3 m), were planted in 1996–2003 on the edges of six fields (hedgerows) and compared to the unplanted edges of six fields (weedy edges).

A replicated site comparison in 2009 in farmland in the Sacramento Valley, California, USA (2), found higher coverage of exotic plants than native plants in newly planted hedgerows. **Implementation options:** Exotic plants had higher percent cover than native plants in new hedgerows, but not in mature hedgerows (percent cover not reported). **Methods:** Similar but not identical species of native flowering shrubs and forbs were planted in four mature hedgerows (305–550 m; planted in 1996) and four new hedgerows (350 m x unreported width; planted in 2008). Plants were sampled in fifty quadrats/hedgerow (1 x 1 m).

A replicated site comparison in 2009–2010 in the Central Valley, California, USA (3), found more plant species in narrow compared to wide hedgerows, and higher plant cover in younger compared to older hedgerows. **Implementation options:** More non-native and native plant species were found in narrow compared to wide hedgerows, and higher non-native and native plant cover were found in younger compared to older hedgerows (numbers of species and amounts of cover not reported). **Methods:** Thirty-one hedgerows were compared (2–7 x 120–800 m, 0–15 years old). Hedgerows <3 m wide were "narrow" (16 hedgerows), and other hedgerows were "wide" (15 hedgerows). Hedgerows were planted with similar native species. Plants were sampled at the edges (outer 1 m) of narrow and wide hedgerows and in the interior (at least 2 m from the edges) of wide but not narrow hedgerows.

(1) Morandin, L.A. & Kremen, C. (2013) Hedgerow restoration promotes pollinator populations and exports native bees to adjacent fields. *Ecological Applications*, 23, 829-839.

(2) Morandin, L.A. & Kremen, C. (2013) Bee Preference for Native versus Exotic Plants in Restored Agricultural Hedgerows. *Restoration Ecology*, 21, 26-32.

(3) Wilkerson, M.L. (2014) Using hedgerows as model linkages to examine non-native plant patterns. *Agriculture, Ecosystems & Environment*, 192, 38-46.

7.8. Restore habitat along watercourses: Other biodiversity (24 studies)

- **Amphibians (1 study):** One replicated site comparison from the USA[8] found similar numbers of amphibian species in restored and remnant sites.
- **Birds (8 studies):** Two replicated site comparisons from Spain[20] and the USA[24] found similar numbers of bird species in restored and remnant sites. Two replicated site comparisons from the USA[8,19] found fewer bird species in restored riparian sites, compared to remnant sites. One replicated site comparison from Spain[20] found similar numbers of birds and bird species in restored contaminated sites and uncontaminated sites. One replicated site comparison from the USA[2] found that an endangered bird nested in restored sites, and had similar nesting success in restored and remnant sites. One replicated site comparison from the USA[12] found that bird populations increased with the area of restored habitat in the landscape, in some comparisons. One replicated site comparison from the USA[22] found similar levels of nest parasitism in restored and remnant sites.
- **Fish (1 study):** One before-and-after site comparison from the USA[18] found differences in fish communities, before and after changing river flow.
- **Invertebrates (3 studies):** One replicated site comparison from the USA[9] found fewer native ants, but similar numbers of invasive ants, in restored sites, compared to remnant sites. One before-and-after site comparison from the USA[11] found similar numbers of freshwater invertebrates in restored and reference sites, after restoration. One replicated, before-and-after study from the USA[6] found more invertebrates and invertebrate species in plots with added gravel, compared to plots without added gravel, in some comparisons. One replicated before-and-after study from France[21] found relatively more alien species after restoring river flow.
- **Mammals (2 studies):** Two replicated site comparisons from the USA[8,24] found similar numbers of mammal species in restored and remnant sites.
- **Plants (11 studies)**

- Abundance (6 studies): Four replicated site comparisons from Spain[4] and the USA[5,10,15] found lower plant cover in restored sites, compared to remnant sites. One of these studies[15] also found higher cover of exotic plants, but another one[5] did not. One replicated, paired site comparison from the USA[16] found similar numbers of flowers in restored and remnant sites. One replicated site comparison from the USA[13] found more seeds, but fewer native seed, in orchards next to restored riparian habitats, compared to orchards next to remnant habitats. One replicated site comparison from the USA[5] found similar exotic plant cover in remnant and restored forests.
- Diversity (6 studies): Two replicated studies from the USA[5,15] found fewer native plant species in restored forests, compared to remnant forests. One of these studies[15] also found more exotic species, but another one[5] did not. One replicated site comparison from the USA[8] found more plant species in restored sites, compared to remnant sites. One replicated, paired site comparison from the USA[16] found similar numbers of flower species in restored and remnant sites. One replicated site comparison from the USA[13] found fewer seed species and native seed species in orchards next to restored riparian habitats, compared to remnant riparian habitats. One controlled study from the USA[17] found different plant communities in restored and unrestored habitats.
- Survival (2 studies): One replicated study from the USA[1] found that about one-third of planted willows survived for one year. One site comparison from the USA[3] found that some species survived after planting, as part of riparian restoration, but others did not.
- Habitat suitability (1 study): One replicated site comparison from the USA[2] found that vegetation at one of five sites met the criteria for Bell's Vireo nesting habitat.
- Size (1 study): One replicated site comparison from the USA[9] found smaller elderberry plants in restored sites.

- **Reptiles (1 study):** One replicated site comparison from the USA[8] found similar numbers of reptile species in remnant and restored sites.
- **Implementation options (7 studies)**
  - Plants (3 studies): One study from the USA[14] found more tree, shrub, vine, and perennial species, higher canopy cover, and higher native tree cover, in older restored plots, compared to younger restored plots, but this study also found fewer annual plant species, lower vegetation cover, lower annual forb cover, and lower grass cover. One study from the USA[15] found an increase in native species and overstorey cover in restored sites, over time, but it found similar numbers of species and overstorey cover in sites planted at different densities. One study from the USA[1] found that willow cuttings planted on the stream bottom had a higher survival rate than those planted on the streambank or terrace.
  - Birds (3 studies): Three studies from the USA[7,12,23] found more birds[7,12] or bird species[23] in older restored plots, compared to younger restored plots. One of these studies[12] also found that the populations of some bird species increased with tree-planting density.

A replicated study in 1987–1988 in three riparian meadows in the northern Sierra Nevada, California, USA (1), found that Geyer willow *Salix geyeriana* cuttings planted on the stream bottom had a higher survival rate than those planted in the streambank or terrace. **Plants:** Out of 2,700 cuttings, 32% survived in 1987 and 26% survived in 1988. **Implementation options:** Willow cuttings planted on the stream bottom had a higher survival rate (82%), compared to those planted on the streambank (34%) or the stream terrace (3%). **Methods:** Geyer willow cuttings were planted (30 cm depth, in May 1987) in three locations (stream bottom, streambank, and stream terrace). At each site, cuttings (over two years old; diameter: 10.5 mm; length: 42.3 cm) were planted along thirty transects perpendicular to the stream, crossing the stream, and extending 10 m from the top of both banks. Survival was measured in September 1987 and 1988.

A replicated site comparison in 1989–1993 in riparian forests along the San Luis Rey and San Diego Rivers, California, USA (2), found that the endangered Bell's Vireo *Vireo bellii pusillus* nested in restored sites, and similar numbers of fledglings were found in restored and remnant sites, even though four of five sites did not meet modelled criteria for nesting habitat. **Birds:** Similar numbers of fledglings were found in restored and remnant sites, at least along the San Luis Rey River (1.9–4 vs 1–1.4 fledglings/nest; 3–4 vs 1.6–2.4 fledglings/breeding pair), and nests were established within 1–5 years. **Plants:** By 1993, the vegetation at one of five sites met the modelled criteria (e.g., height and cover) for Bell's Vireo nesting habitat. **Methods:** Five restored sites (3–13 ha) were surveyed along the San Luis Rey River (three sites, established in 1989) and the San Diego River (two sites, established in 1990). The sites were planted with willows and/or other species, based on the natural habitat of Bell's Vireo. These sites were compared to natural habitats along these rivers. Birds were surveyed every 1–2 weeks. Nests were surveyed between mid-March and August.

A replicated site comparison in 1990–1995 in restored riparian forests along the Sacramento River, California, USA (3), found that some species survived after planting, as part of riparian restoration, but others did not. **Plants:** Box elder *Acer negundo* had 75–100% survival after two years (planted in five sites). Oregon ash *Fraxinus latifolia* had 0% survival in two of three sites but had 100% survival in one of three sites. Western sycamore *Platanus racemosa* had 53–100% survival in four of five sites and 0% in one of five sites. Fremont's cotton wood *Populus fremontii* had 14–66% survival in three of four sites and 0% in one of four sites. Valley oak *Quercus labata* had 18–100% survival (planted in five sites). Californian Rose *Rosa californica* had 21–100% survival (planted in three sites). Sandbar willow *Salix exigua* had 5–88% survival (planted in two sites). Goodding's willow *Salix gooddingii* had 17–94% survival (planted in two sites). Arroyo willow Salix lasiolepis had 26–100% survival (planted in four sites). Blue elderberry *Sambucus mexicana* had 8–68% survival (planted in five sites). **Methods:** Sites were on flood plains and were ≥200 ha. Seven sites were selected, with varying planting dates: Lohman (1994), Princeton (1992), River (1990), Sam (1991), Vista 1 (1992), Vista 2 (1993), and Vista 3 (1994). All sites had previously been cleared of vegetation. All species were collected from natural stands. Plants were protected by sleeves (35 cm height). Sites were irrigated and weeds were controlled through monthly spraying. Survival and height were measured in 405 m^2 plots (the number of plots varied to cover 5–10% of each site). Planting rows were sampled in Lohman and Vista 3 plots. Plants were sampled at the end of each growing season.

A replicated site comparison in 1991–1999 along rivers in southeast Spain (4) found lower herb and shrub cover, and lower liana frequency, in restored sites, compared to undisturbed sites. **Plants:** Lower shrub and herb cover was found in restored plots, compared to undisturbed plots (shrubs: 20–39% vs 79%; herbs: 0–2% vs 4–5%), but no difference was found in the cover of trees, lianas, or annuals (trees: 1.3–1.5% vs 1.5–2.3%; lianas: 0–0.05% vs 0.5%; annuals: 0.03–0.15% vs 0.09–0.12%). Tree frequency was higher in restored sites, compared to undisturbed sites, in 1991 (8% vs 4%), but not in 1993–1999 (4–7% vs 4%). Liana frequency was lower in restored sites (0–2% vs 5–7%). The frequency of shrubs, herbs, and annuals was similar in restored and undisturbed sites (shrubs: 60–71% vs 60%; herbs: 1–2% vs 2–3%; annuals: 2–5% vs 2–3%). **Methods:** Two riparian forest sites had two plots each: one restored, and one undisturbed (120 x 3 m each). Restored plots were planted with root cuttings and seeds (broom *Retama sphaerocarpa*) from undisturbed forests in December 1991, and plants were monitored and irrigated weekly (in the first summer) for a few months. Plants were surveyed on transects (October: 1993, 1995, 1999; September: 1997).

A replicated site comparison in 1989–2001 in 23 riparian forest sites along the Sacramento River, California, USA (5), found that vegetation cover, native species cover, and the number of native species was lower in restored sites, compared to remnant sites. **Plants:** In the understorey, the cover of total and native vegetation was lower in restored sites, compared to remnant sites (total: 40–50% vs 73%; native: 2–10% vs 51%), as was the number of native species (3–5 vs 12), but the cover and number of exotic species was no different (15–17 vs 10 species; 40–42% vs 21% cover). In the overstorey, total cover was lower in remnant sites (0–29% vs 82%). **Methods:** Native riparian tree and shrub species were planted (520–1,300 tree/ha) on former farmland along 150 km of the Sacramento River (15 sites restored in 1989–1996; three sites restored in 2000). Plants were surveyed in quadrats (1 x 1 m) in spring 2001 at restored sites and five remnant sites.

A replicated, before-and-after study in 1996–2000 at seven salmon-spawning sites along the lower Mokelumne River, in the Central Valley, California, USA (6), found more macroinvertebrates, 10 weeks after gravel addition, compared to before gravel addition. **Invertebrates:** Similar numbers of macroinvertebrate species and individuals were found in sites with or without gravel addition, by week 6 (0–30 vs 21 species; 350,000 vs 300,000 individuals/m^3). However, by week 10, more individuals were found in sites with gravel addition (290,000 vs 150,000 individuals/m^3). **Methods:** Gravel was added to seven sites, between 15 August and 15 September, in 1996–2000 (different sites in different years, approximately 30 x 65 m sites, each of which was approximately 1–2% of remaining Chinook salmon *Oncorhynchus tschawytscha* spawning habitat). Macroinvertebrates were collected from the substrate (15 cm depth) with a stream sampler (bottom open area: 0.086 m^2) and a dolphin bucket (368 µm) in flowing water (0.25–1 m/s, <60 cm depth), one week before and every two weeks after gravel addition, in September–January 1996–2000.

A replicated site comparison in 1993–2003 on ten sites along the Sacramento River, California, USA (7), found that 13 of 20 bird species were increasing on plots revegetated as part of riparian reforestation, although abundances did not reach that of plots of remnant forest. **Birds:** Thirteen of 20 bird species were increasing on plots revegetated as part of riparian reforestation, although abundances did not reach that of plots of remnant forest. Nine of these were also increasing on the remnant plots, with a further three only increasing in remnants. Three species were stable on both plot types and one, lazuli bunting *Passerina amoena*, declined on both (mirroring a regional trend). **Methods:** Restoration focused on revegetating with native trees, shrubs and understory plants, and restoring natural river processes.

A replicated site comparison in 1996–2001 in five riparian sites in Carmel-by-the-Sea, California, USA (8), found more plant species, fewer bird species, and similar numbers of amphibian, mammal, and reptile species, in restored forests, compared to mature forests. **Amphibians, Mammals, and Reptiles:** Similar numbers of amphibian (3), mammal (16), and reptile (4) species were found in restored plots and mature plots. **Birds:** Fewer bird species were found in restored plots, compared to mature plots, in summer (26–29 vs 48–52), but not in spring (53–56 vs 62–69), fall (17–23 vs 26–32), or winter (22–33 vs 40–41). Restored sites had fewer breeding bird species (4–7 vs 28–33). **Plants:** More plant species were found in restored forests, compared to mature forests (15–26 vs 8–11). **Methods:** In 1996–1998, 15 ha of woody riparian species and 2.4 ha of freshwater wetland species were planted. Three restored sites (17,400 m^2, 28,000 m^2, 65,000 m^2) were compared to two mature riparian forest sites (47,420 m^2 and 24,780 m^2). Vegetation was sampled using transects (30 m) in April, August, October, and January 1999–2000. Amphibians and reptiles were sampled using pitfall traps (May–August 2000) and visual surveys (25 x 25 m area). Bird species were identified in ten-minute point counts (25 m radius, twice/season, March 2000–February 2001) and on transects (1.5 km/hr for 1–2.5 hours). Mammals were captured in live traps (7.6 x 8.9 x 22.9 cm and 7.6 x 8.93 x 30.5 cm), marked, and released (November 1999–April 2001, except spring 2000).

A replicated site comparison in 2005–2006 in 46 riparian sites in the Central Valley, California, USA (9) (same study as (10)), found smaller elderberry plants *Sambucus mexicana*, and fewer native ants, but similar numbers of non-native ants, in restored sites, compared to natural sites. **Invertebrates:** Fewer native ants but similar numbers of Argentine ants were found in restored sites. **Plants:** Smaller elderberry plants were found in restored sites. **Implementation options:** The number of Longhorn beetles *Desmocerus californicus* increased with site size and age. Elderberry seedlings grew faster than plant transplants. Elderberry plants grew slower in older sites. **Methods:** Thirty restored sites (with <30 planted elderberry plants) were compared with 16 natural sites (within 20 km). Restored sites were surveyed in July–early November 2005 and February–April 2006 and natural sites in April–September 2006. Restored sites were 24% of the size of natural sites.

A replicated site comparison in 2005–2006 in 46 riparian sites in the Central Valley, California, USA (10) (same study as (9)), found that restored sites had lower canopy cover, stem diameter, and height than natural sites. **Plants:** Elderberry canopy size (400 vs 272 cm), stem diameter (8 vs 5 cm), and height (428 cm vs 320 cm) were larger in natural sites, compared to restored sites. **Methods:** Thirty restored sites (urban: 19; agricultural: 11; all with <30 planted elderberry plants; 2–15 years old) and 16 natural sites (within 20 km of restored sites) were compared. Restored sites were surveyed in July–early November 2005 and August–October 2006 and natural sites in April–September 2006. Restored sites were 24% of the size of natural sites. Growth rate was measured for 30 shrubs at each restored site (growth rate for natural sites came from a previous study).

A before-and-after site comparison in 2001–2003 in a grazed riparian meadow in Bagley Valley Creek, Sierra Nevada, California, USA (11), found different communities of freshwater invertebrates in a restored site, compared to two reference sites. **Invertebrates:** Before it was restored, the restored site had fewer mayfly, stonefly, and caddisfly taxa (2000: 6–9 fewer taxa) than two reference sites (a 10-year-old restored site and a similar site with less disturbance). After it was restored, it had similar or higher numbers than the two reference sites (no data provided). **Methods:** To restore the site, a new channel was constructed (rocks, erosion control fabric), *Salix* spp. willow trees were planted, and gullies and roads in the meadow and its watershed were rehabilitated, in 2001. Invertebrates were collected from randomly selected riffle habitats in the water (three 30 x 30 cm sampling areas; D-frame net; 250 µm mesh; 30 cm width; three samples/site). Samples were collected before restoration (1999 and 2000) and after (2002 and 2003).

A replicated site comparison in 1998–2003 in 17 riparian sites along the Sacramento River in California, USA (12), found that the abundance of some bird species increased with the cover of restored area in the landscape. **Birds:** Abundance increased with the cover of restored habitat in the landscape, for six of seven species. **Implementation options:** Species abundance increased (15–51%) with age. The abundance of Nuttall's woodpecker, ash-throated flycatcher, and black-headed grosbeak increased with the number of tree species planted. For three species, abundance increased with the planting density of tree species (western wood-pewee: abundance increased by a factor of 1.9 for each additional 100 *Salix* willows planted/ha; Bewick's wren and spotted towhee: abundance increased by a factor of about 1.04 for each additional 100 valley oak trees *Quercus lobata*/ha). However, Bewick's wren abundance decreased by a factor of 0.84 for each additional 100 cottonwood *Populus fremontii* trees/ha. **Methods:** Restored sites (4–74 ha each; former farmland; adjacent to remnant riparian forest) were disked, burned, furrowed, levelled, and sprayed with herbicides, and trees and shrubs were planted. Birds were surveyed with point counts (45 points, 50 m radius, 200 m apart, during the breeding season, from dawn until 4 h after sunrise, twice/year for 3–10 years; 5 minutes/point).

A replicated site comparison in 1991–2004 in 26 riparian sites along the Sacramento River, California, USA (13), found fewer seed species and native seed species, more seeds in total, but fewer native seeds, in orchards next to restored habitats, compared to orchards next to remnant habitats. **Plants:** Fewer species (36–50 vs 68) and native species (6–10 vs 13) were found in orchards next to restored habitats. More seeds were found next to restored habitats (data reported in log units), but fewer native seeds were found, and there was no difference in invasive seeds. **Implementation options:** More seeds were found next to older restored habitats, compared to younger (data not reported). **Methods:** Soil samples were collected from 26 walnut plots, 0–5.6 km from restored riparian, remnant riparian, or agricultural habitats. Restored sites were formerly farmland. Restoration included disking, burning, furrowing, levelling, and spraying with herbicide, and replanting. On each walnut farm, soil samples (10 cm depth) were collected from seven points adjacent to restored or remnant forest and nine points within the walnut orchard, in March 2004. Seeds were germinated and identified in a greenhouse.

A replicated, before-and-after site comparison in 2011 in 102 riparian forest sites in California, USA (14), found that riparian vegetation changed over time in restored sites, for 16 of 21 measurements. **Implementation options:** The following metrics increased over time: species of trees, perennial plants, and shrubs and vines; density of woody vegetation, native trees, and native and exotic shrubs and vines; absolute cover of the total canopy, native tree canopy, ground cover, exposed roots, and litter (data reported as model results). The following metrics decreased over time: absolute cover of total vegetation; relative cover of annual grasses and forbs; species of annual herbaceous plants. The number of exotic tree species and the cover of native and exotic perennial grasses and forbs did not change over time. **Methods:** A total of 102 riparian sites from three coastal counties (Marin, Mendocino, and Sonoma) were surveyed (restored: 89 sites, 0–39 years after restoration; non-restored: 13 sites). Restoration involved willow *Salix* planting. Vegetation cover was estimated using a Daubenmire Frame (20 x 50 cm). Canopy density was measured with a spherical densitometer.

A replicated, before-and-after site comparison in 1989–2008 in riparian forests along the Sacramento River, California, USA (15), found fewer native species, with lower ground and canopy cover, and more exotic species in restored sites, compared to remnant sites. **Plants:** Fewer native species (5–7 vs 10 species; 21–32% vs 65% relative cover, 48–56% vs 87% frequency) and more exotic species (15–16 vs 9 exotic species; 79–67% vs 34% relative cover; 91–84% vs 56% frequency) were found in the 15 sites planted with overstorey species, compared to forest remnants. Fewer native species (4–6 vs 10 species; 16–19% vs 65% relative cover; 41–42% vs 87% frequency) and lower overstorey cover (31–39% vs 79%) were found in the 20 sites planted in 1997–2003, compared to forest remnants, in some comparisons. **Implementation options:** Between 2001 and 2007, increases in native species (5 vs 7 species) and overstorey cover (29% vs 60%) were found in the 15 sites planted with overstorey species in 1989–1996. Similar numbers of native species (5–6 species, 16–29% relative cover; 41–65% frequency) and similar overstorey cover (31–39%) were found in plots planted with understorey species at high or low densities in 1997–2003. Lower overstorey cover (31% vs 64) was found in plots planted with both overstorey and understorey species, compared to overstorey species, in one of two comparisons (31% vs 64%). **Methods:** Native overstorey species (trees and shrubs) were planted on 15 sites in 1989–1996 and 20 sites (14 of which were also planted with understory species, at high or low densities: herbs, vines, grasses, and low shrubs) in 1997–2003 (5–60 ha sites; 530–1,300 plants/ha; disked, planted, mown, irrigated, and weeds controlled for three years). Plants were surveyed in plots planted with overstorey species (in 2001 and 2007) or non-woody vegetation (2007) and in 10 forest remnants (15–20 ha, five sites in 2001, five sites in 2008). Vegetation was surveyed in quadrats (1 x 1 m, 20–80 quadrats/site) along a transect (part of a 40 x 80 m grid).

A replicated, paired site comparison in 2003 in 10 riparian sites along the Sacramento River in California, USA (16), found similar numbers of flowers and flower species in restored and remnant forest sites. **Plants:** Similar numbers of flowers (401–2,458 vs 317–1,668) and flower species (37–47 vs 21–36) were found in restored and remnant sites, but different communities were found (data reported as relative Sørensen index). **Methods:** Each of five restored sites was paired with a remnant site (5.5–10 km apart). Plots within sites (1 ha) were 0.5–3.7 km apart. Restored sites were previously walnut and almond orchards (6 years before sampling) and were planted with similar vegetation to remnant sites (maple *Acer* spp., oak *Quercus* spp., willow *Salix* spp., and grass). Flowers were sampled in each plot, in February-August 2003 (60 quadrats, 0.25 x 4 m).

A controlled study in 2000–2008 along a stream on a farm in the Central Valley, California, USA (17), found different plant communities in a restored area, compared to an unrestored area. **Plants:** Different plant communities were found in the restored and unrestored areas (data reported as ordination results: restoration explained 12% of the variation in plant communities). **Methods:** Part of the streambank was graded to create a floodplain (4 m width) and planted with native perennial grasses, sedges, forbs, shrubs, and trees. Herbaceous biomass was collected in the restored area and the unrestored area in October 2007 and April–May 2008 (0.25 x 0.5 m plots).

A before-and-after site comparison in 1991–2008 in six sites along the Putah Creek, California, USA (18), found different fish communities before and after a change in river flow. **Fish:** Different communities were found 6 km and 21 km from a dam, after the change, but no differences were found 0, 16, 25, and 30 km from the dam. **Methods:** Habitat was restored through a change in hydrology. Three-day pulses, between 15 February and 31 March, followed by a month of higher flows, were used to initiate spawning. Five-day pulses (in November or December) were used to promote salmon *Oncorhynchus tshawytscha* migration. Six sites at different distances from a dam (0, 6, 16, 21, 25, or 30 km) were sampled annually in September and October for eight years before and nine years after the change in the flow (1991–2008). Fish were captured through electroshocking.

A replicated site comparison in 1989–2008 in riparian forests in the Sacramento and San Joaquin river valleys, California, USA (19), found fewer bird species, but similar numbers of birds, in restored riparian forests, compared to remnant riparian forests. **Birds:** Fewer bird species were found in restored sites, compared to remnant sites (permanent species: 18 vs 45; all species: 33 vs 76), but similar numbers of overwintering bird species were found (15 vs 23). Similar numbers of birds were found in restored and remnant sites (all species: 39–40; permanent: 12–18; overwintering: 28–29). **Methods:** Forest was restored on three sites (Sacramento: two sites, 66–86 ha, planted in 1989–1992; San Joaquin: one site, 8 ha, planted in 2002–2003), by planting trees, shrubs, and grasses. Remnant forest was used for comparison (Sacramento: two sites, 25–45 ha; San Joaquin: three sites, 6–7 ha). Birds were captured in mist nests (12 x 2.5 m, 30 mm mesh; in November, December–January, and January–February 2003–2008). Sites were sampled for at least three years. Captured birds were ringed and re-sighted in November–February (Sacramento: 2004–2005 and 2006–2007; San Joaquin: 2004–2005). Bird abundance (birds captured/100 mist net hours), diversity (Shannon index), evenness, and richness were recorded.

A replicated site comparison in 2001–2009 in riparian forest along the Guadiamar and Alcarayón Rivers, Spain (20), found a similar number of birds and bird species in restored sites and uncontaminated sites. **Birds:** Similar numbers of birds and bird species were found in restored and uncontaminated sites (24 vs 20 species; 76 vs 87 individuals). **Implementation options:** More birds were found eight years after restoration, compared to one year (2009 vs 2001: 102 vs 67 individuals/10 ha), but there was not a significant difference in the number of bird species (71 vs 45). **Methods:** Riparian areas along the Guadiamar River were contaminated by heavy metals from a mine accident in 1998. Sites were restored from 1998–2001 by planting native trees and shrubs and removing exotic and cultivated plants. Birds were surveyed along seven transects (8 km long and 2 km apart) in 2001–2006 and 2009 (winter: 15 October–15 February; breeding season: 15 April–15 June) in restored sites and a non-contaminated site (10 km away, along the Alcarayón River, in 2004–2006). These surveys were compared with data from before the contamination (bird atlas).

A replicated, before-and-after study in 2003–2008 in 36 riparian sites in France (21) found relatively more alien species, but fewer still-water species, after restoring river flow, compared to before. **Invertebrates:** Relatively more alien species were found after restoration, compared to before (4% vs 2% of functional diversity), but there were relatively fewer still-water (lentic) species (64% vs 72%) and similar numbers of flowing-water (lotic) species (31% vs 26%). **Methods:** There were three types of restoration: increasing flow (6 sites), dredging (6 sites), and reconnecting sites to the main river through dredging (8 sites). Another sixteen sites had no restoration activities. Macroinvertebrates were sampled with four 0.25 x 0.25 m quadrats and nets (500 µm mesh) along a 30 m stretch in each site in spring and summer, one year before restoration and two years after.

A replicated site comparison in 2002–2012 in 21 riparian sites in the Central Valley, California, USA (22), found similar amounts of parasitism by the cowbird *Molothrus ater* in restored or remnant forest sites. **Birds**: Similar amounts of parasitism were found in restored or remnant forest sites. Lower parasitism rates were found for spotted towhee *Pipilo maculatus* (Sacramento River: 26% vs 47%) and red-winged blackbird *Agelaius phoeniceus* (San Joaquin River: 0% vs 25%) in restored sites, compared to remnant sites, in some comparisons. **Methods:** Restored sites were formerly farmland, and restoration included planting. Bird nests were observed every three days in April–July (Sacramento River: 1993–2003; San Joaquin River: 2007–2009).

A replicated site comparison in 2004–2009 in 33 restored riparian sites in the Central Valley and North Coast, California, USA (23), found more bird species in older restored plots, compared to younger restored plots**. Implementation options:** The number of bird species increased as restoration sites matured. For each year after restoration, the number of bird species increased by 0.4 in the Central Valley and 0.5 in the North Coast regions. **Methods:** Bird surveys were conducted in April–June in restored riparian plots (0.33–10 acres; 0–20 years after restoration; Central Valley: 18 sites; North Coast: 15 sites). Restoration included excluding grazers and planting native riparian vegetation. In the Central Valley, there were two surveys (152 points, 200 m apart) in the breeding seasons in 2004–2008. Birds heard and seen within 50 m of the points were recorded. On the North Coast, there were 2–3 surveys (area searches, 0.33–10 acres), at least 10 days apart, for 20 mins each, in 2001–2002, 2004–2005, and 2009.

A replicated site comparison in 2010–2012 in riparian forests along the Sacramento River, California, USA (24), found similar numbers of birds and mammals in restored and remnant forests. **Birds and Mammals:** Overall, similar numbers of species were found in restored or remnant forests (4–5 vs 4). More species were found in restored forests, compared to remnant forests, in the wet seasons (4–5 vs 2), but not in the dry seasons (3–5 vs 3). More predator species were found in young restored forests, compared to remnant forests (1.9 times as many species as in remnant forests). Most animals were black-tailed deer *Odocoileus hemionus columbianus* (66% of all observations) or wild turkeys *Meleagris gallopavo* (21%). Most predators were raccoons *Procyon lotor* (8% of all observations), coyotes *Canis latrans* (4%), or bobcats *Felis rufus* (1%). **Methods:** All sites were part of The Nature Conservancy's Sacramento River Project. Camera traps were set along a 100 km section of the river in restored forests (young: restored in 2003–2007, five sites; old: restored in 1991–2000, six sites) or remnant forests (five sites). Sites were 5.34 km apart, on average. Camera traps (2.1 m height) were placed on trees at each site, near animal signs (tracks, scat, or scratch marks). Cameras were visited every 1–1.5 months.

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Livestock management: Effects on other biodiversity

7.9. Exclude grazers: Other biodiversity (45 studies)

- **Amphibians (1 study):** One replicated, randomized, controlled study in wet grasslands in the USA[36] found no difference in the abundance of Yosemite toads between areas with cattle excluded and grazed areas.
- **Birds (2 studies):** One replicated site comparison in desert in the USA[10] found more bird species, and more species that were nesting, in areas with sheep excluded, compared to grazed areas. Two replicated site comparisons in desert[10] and wetlands[33] found higher abundances of

some or all species of birds in areas with cattle or sheep excluded, compared to grazed areas. The wetland study also found lower abundances, in some comparisons.

- **Fish (2 studies):** One replicated site comparison in grasslands in the USA[7] found higher biomass and abundance of golden trout in areas with cattle excluded, compared to grazed areas. Another one[9] found fewer trout nests in part of a stream with a livestock exclosure, compared to part without a livestock exclosure.
- **Invertebrates (5 studies):** Two replicated studies (one randomized and controlled) in wetlands[17] and grasslands[35] in the USA found more species or families of invertebrates in areas with cattle excluded, compared to grazed areas, for some or all groups. One replicated, randomized, controlled study in grasslands in the USA[21] found fewer aquatic invertebrate species in areas with cattle excluded, compared to grazed areas, in some comparisons. Two replicated studies (one randomized and controlled) in grasslands in the USA[29,35] found no difference in invertebrate abundance between ungrazed and cattle-grazed plots. One replicated, before-and-after site comparison in grasslands in the USA[12] found that populations of a threatened, endemic butterfly declined in sites with cattle excluded, but also declined in cattle-grazed sites.
- **Mammals (4 studies):** Two replicated site comparisons in deserts and grasslands in Spain[26] and the USA[6] found more mammal species in areas with cattle or sheep excluded, compared to grazed areas. One of these studies[6] also found higher mammal diversity, and both studies found higher mammal abundance, in areas with grazers excluded, compared to grazed areas, in some or all comparisons. One replicated site comparison in desert in the USA[10] found lower abundances of black-tailed hares in ungrazed sites, compared to grazed sites, and one replicated, randomized, controlled study in wooded grassland in the USA[20] found no difference in ground squirrel abundance between ungrazed plots and cattle-grazed plots.
- **Plants (41 studies)**
  - Abundance (38 studies): Thirty-two studies (13 replicated, randomized, and controlled) in grasslands, shrublands, wetlands, deserts, and mixed habitats in the USA[1,2,4,6,7,10,12,13,15-18,20,22,24,31,35,39,40,42-45], Israel[14,19,27], Chile[23], Spain[25,26,37,38], and Australia[28] found higher biomass, cover, or abundance of some or all plant groups (or lower cover of non-native species[15,16,39]), in areas with cattle, sheep, goats, or alpacas excluded, compared to grazed areas, in some or all comparisons. Fourteen studies (four replicated, randomized and controlled) from the USA[6,8,10-12,21,39,41,42,44,45], Israel[19], Spain[38], and Australia[28] found lower biomass, cover, or abundance of some or all plant groups (or higher cover of non-native species[8,21,28]), in areas with grazers excluded, compared to grazed areas, in some comparisons. Five replicated, controlled studies (four randomized) in grasslands in the USA[17,32,34,41,43] found no difference in the cover of plants (and/or non-native plants[17,32,41,43]) between ungrazed and grazed areas.
  - Diversity (19 studies): Five studies (three replicated) in forests, shrublands, and grasslands in Israel[14], Spain[38], and the USA[4,8,16] found more species, or fewer non-native species, in areas with cattle or sheep excluded, compared to grazed areas, in some or all comparisons. Nine studies in grasslands and shrublands in Australia[28], Israel[14,30], Spain[38], and the USA[21,41-44] found fewer species or native species, larger decreases in the number of species, or smaller increases in the number of species, in areas with cattle, sheep, or alpacas excluded, compared to grazed areas, in some or all comparisons. Six studies in grasslands, wetlands, and deserts in the USA[4,6,15,17,21,28] found no differences in the number of species between areas grazed by cattle, sheep, or alpacas, and ungrazed areas. Four studies in shrublands, grasslands, and wetlands in the USA[13,17,24] and Israel[14] found higher plant diversity, or different community

composition, in plots with cattle excluded, compared to grazed plots, in some comparisons. Three studies in wetlands and grasslands in the USA[17,24,42] found lower plant diversity in plots with cattle excluded, compared to grazed plots, in some comparisons. Three studies in deserts and shrublands in the USA[6,10] and Israel[27] found no difference in plant diversity between plots with cattle or sheep excluded and grazed plots.

  - Survival (2 studies): One replicated, randomized, controlled study along creeks in the USA[3] found that similar percentages of planted willows survived in pastures with or without cattle excluded. One replicated, randomized, controlled study in grasslands in the USA[5] found higher plant survival in plots with cattle excluded, compared to grazed plots, in some comparisons.

- **Reptiles (1 study):** One replicated site comparison in desert in the USA[10] found lower abundances of reptiles, and of some reptile species, in areas with sheep excluded, compared to grazed areas, in some comparisons.
- **Implementation options (1 study):** One site comparison in the USA[8] found that more plant species were found in historically cultivated sites that were ungrazed, compared to grazed, but similar numbers of plant species were found in historically uncultivated sites that were ungrazed or grazed.

A replicated, randomized, controlled study in 1982–1984 in alpine meadows in central California, USA (1), found higher biomass of some plant groups in plots from which cattle were excluded, compared to grazed plots. **Plants:** The peak biomass of non-grass plants was higher in plots with cattle excluded, compared to grazed plots, in one of two meadows, one year after fertilizer was added (252 vs 99–138 g/m^2). However, there were no differences in the other meadow, in the other two years, or when plots were not fertilized (30–249 g/m^2). There was no difference in the biomass of grass between ungrazed and grazed plots for either meadow, in any year (170–480 g/m^2). There were no differences between ungrazed and grazed plots in the cover of sedges and rushes (7–71% cover) or non-grass plants (20–71% cover). **Methods:** Eighteen plots were established in two grazed meadows in 1982, with cattle excluded from half. The vegetation in plots was sampled at 30 points in July and August 1982–1984. Half of the plots were also fertilized in 1982.

A controlled study in 1983–1985 in the central Sierra Nevadas, California, USA (2), found more herbaceous vegetation and more vegetation cover in plots with cattle excluded, compared to grazed plots. **Plants:** At the end of the growing season, more herbaceous vegetation was found in ungrazed, compared to grazed plots (1,580 vs 150–760 kg/ha). By the end of the grazing season, cover of vegetation less than 50 cm tall was higher in ungrazed, compared to grazed plots (49–85% vs 17–68% cover), although these differences were present before cattle were introduced, in one of three vegetation types. Cover of vegetation less than 1 m tall was higher in ungrazed plots, in one of three vegetation types (75% vs 52–54%). Taller vegetation did not differ between ungrazed and grazed plots (10–72%). **Methods:** Three plots (22–29 ha) were fenced in 1983, and were grazed in 1984–1985 at one of three levels (no cattle, moderate grazing, or heavy grazing) for 48–74 days. Densities were 0.65–0.76 and 1–1.7 animal unit months/ha, respectively, and plots were grazed for up to 100 days each year. Each plot received a different treatment in each year. Vegetation cover was monitored in quaking aspen *Populus tremuloides* (all years), willow *Salix* sp., and corn lily *Veratrum californicum* (1984–1985) throughout each grazing season.

A replicated, randomized, controlled study in 1987–1988 in pastures along three creeks in the northern Sierra Nevada, California, USA (3), found that Geyer willow *Salix geyeriana* plantings had similar survival rates in pastures without or with cattle, but fewer were grazed in pastures without cattle. **Plants:** Similar percentages survived in pastures without or with cattle (33% vs 18–26%), but fewer were grazed in pastures without cattle (0.2 vs 0.7–1). **Methods:** The cuttings (over two-years old, 10.5 mm diameter, 42.3 cm length) were planted (30 cm depth) along three creeks (Cow, Freeman, and Big Grizzly), on thirty transects (3 m apart) across each creek and extending 10 m from the top of each bank, in May 1987 (300 plantings/creek). Along each creek, three pastures were fenced: one pasture was ungrazed by cattle, one was grazed early (1987: 22 June–7 August; 1988: 21 June–1 July) and one was grazed late (1997: 4 August–23 September; 1988: 18 August–31 August). The cuttings were measured in September 1987 and 1988.

A replicated, controlled study in 1982–1985 in mixed savanna, shrubland, and grassland in northern California, USA (4), found more plant species and higher plant cover in ungrazed plots, compared to sheep-grazed plots. **Plants:** More plant species were found in ungrazed plots, compared to grazed plots, in autumn-winter grazed pastures in woodland (8 vs 7 species/50 sample points), but there were no differences with spring grazing or in grassland (data not reported). Plant cover was higher in ungrazed plots, compared to grazed plots, within spring grazed pastures in both woodland and grassland (75–88% vs 67–76% cover), and in autumn-winter grazed pastures in woodland, but not grassland (65% vs 58%). Seven of 15 species of plant had different amounts of cover in ungrazed, compared to grazed plots, in one of four habitat-grazing combinations each time. **Methods:** Two pastures were established in mixed blue oak *Quercus douglasii* woodland and grassland areas in 1982 and were grazed by sheep from May until October each year, with autumn or spring grazing. Plants were monitored throughout the year in 20 plots within both woodland and grassland in each pasture, with 75 x 75 cm cages to exclude grazers.

A replicated, randomized, controlled study in 1989–1991 in grasslands in north-central California, USA (5), found few differences in the survival of, or damage to, blue oak *Quercus douglasii* seedlings planted in pastures from which cattle were excluded, compared to grazed pastures. **Plants:** There were no differences in 15-month survival between seedlings planted in ungrazed plots, compared to those grazed by cattle in spring or summer (9–24% survival). Seedlings had lower survival in ungrazed plots, compared to winter grazed plots (15% vs 46%). The proportion of seedlings damaged by browsing or trampling did not differ between ungrazed and grazed plots (0–85% damaged). **Methods:** In December 1989, oak seedlings were planted in three pastures, each containing ten plots: one with cattle excluded and nine grazed for a week each at different intensities and at different times. Ungrazed plots were accessible to wild herbivores. Each plot received 24 seedlings (720 in total), of which half had the area around them treated with glyphosate herbicide to reduce competition from grass.

A replicated site comparison in 1990–1992 in a desert in south-central California, USA (6), found more species, and higher densities, of some small mammal species, in plots from which sheep were excluded, compared to grazed plots. More plant biomass was found in ungrazed plots, compared to grazed plots. **Plants:** Similar plant diversity was found in ungrazed and grazed plots (3.5–4.3 vs 1.5–3.7 species; diversity reported as diversity indices). More plant biomass was found in ungrazed plots (12–199 vs 5–57 kg/ha). Plant biomass was higher in ungrazed areas, in 21 of 23 species, in at least one year, and the two species with lower biomass were non-native. The cover of two of 13 species of perennial shrub was higher in ungrazed areas (*Ambrosia dumosa*: 2.8% vs 1.5% cover; *Lycium andersonii*: 0.9% vs 0.1%). The density of one of 13 species of perennial shrubs was lower in ungrazed areas (*Acamptopappus sphaerocephalus*: 85 vs 333 plants/ha). The density of seeds was higher in ungrazed plots, in one of three years (1992: 193 vs 56 kg/ha; other years: 50–121). The biomass of non-grasses was higher than that of non-native annual grasses in all years in the ungrazed area, but only in one year in the grazed area. **Mammals:** More species of small nocturnal rodents were found in ungrazed areas (3.7 vs 2.5 species/sample), and diversity was higher in ungrazed areas in all three years (data reported as diversity indices). The densities of three of five small, nocturnal rodents were higher in ungrazed plots (long-tailed pocket mouse: 26 vs 6 animals/ha; Merriam's kangaroo rat: 31 vs 13; southern grasshopper mouse: 3 vs 0). **Methods:** Two pairs of 65 ha plots were established in 1990 (one plot inside an area fenced since 1978–1979 and one outside). Vegetation was sampled in ten 1 m^2 plots and at ten points on each of ten 100 m transects in April and June 1990–1992. Seeds were sampled in the top 2 cm of the soil in ten 6 cm diameter circles. Mammals were caught in 64 Sherman traps in each plot (in five periods of 4–6 nights).

A replicated site comparison in 1993–1994 in alpine meadows in central California, USA (7), found more golden trout *Oncorhynchus mykiss aguabonita* in streams, and more willows on stream banks, in areas of meadows from which cattle were excluded, compared to grazed areas. Ungrazed plots also contained larger willows and more young willows. **Fish:** More golden trout were found in streams in ungrazed plots, compared those in three of four grazed plots (1.4–2.7 vs 1.3–2.2 fish/m^2). Golden trout biomass was higher in streams in ungrazed plots, compared those in three of four grazed plots (20–21 vs 16–18 g/m^2). **Plants:** Ungrazed plots contained more willows than grazed plots (124–246 vs 11–70 trees/125 m of bank), and contained larger willows than three of four grazed plots (140–220 vs 20–70 cm height for largest tree). Young willows less than 20 cm were more abundant in ungrazed plots (16–134 vs 1–8 trees/125 m of bank). Canopy shading over streams was higher in ungrazed plots, for three of four plots (32–35% vs 2–24% shading). **Methods:** Fences were erected in 1983 and 1991 in two meadows to exclude cattle from a total of three areas. Fish and vegetation were monitored in 125 m sections either upstream or downstream of the exclosures and inside them (a total of seven sites, three ungrazed) in August 1993–1994. Fish were surveyed by electrofishing and vegetation using transects every 5 m along the stream. Areas outside the exclosures were grazed by cattle in July and September.

A site comparison in 1991 in annual grassland on the Central Coast, California, USA (8), found more plant species and different plant communities in ungrazed grassland, compared to grazed grassland, after over 50 years of grazer exclusion. **Plants:** More plant species were found in ungrazed sites, compared to grazed sites (33 vs 27 species), and there were differences in the plant communities (reported as differences in ordination space). The invasive, non-native medusahead grass *Elymus* (*Taeniatherum*) *caput-medusae* was found only in grazed sites, but the native grass *Elymus glaucus* was found only in ungrazed sites (see publication for details of other species). **Implementation options:** When split into cultivated or uncultivated sites, more plant species were found in historically cultivated sites that were ungrazed, compared to grazed (32 vs 24 species), but similar numbers of plant species were found in uncultivated sites that were ungrazed or grazed (33 vs 30). **Methods:** European domestic cattle were introduced to Monterey County in 1770. In 1937, grazers were excluded from one landscape (the Hastings Natural History Reservation), but not from a nearby landscape. In 1991, 43 sites in the ungrazed landscape and 37 sites in the grazed landscape were sampled (methods not clearly reported, but plant cover was measured in 20 x 50 m plots in April–May in a different part of this study).

A replicated site comparison in 1994 in meadow streams in Inyo National Forest, California, USA (9), found fewer California golden trout *Oncorhynchus mykiss aguabonita* nests in part of a stream with a livestock exclosure, and fewer nests in narrower, deeper streams. **Fish:** Fewer trout nests (redds) were found in part of stream with a livestock exclosure, compared to part without a livestock exclosure (0 vs 52 nests; 0 vs 0.42 nests/m^2), in the Upper Ramshaw Creek. In Mulkey Creek, fewer trout nests were found in narrow streams, compared to wide streams (0 vs 0.27 nests/m^2), and grazer exclusions were associated with narrower streams in this area, in previous studies. **Methods:** Trout nest density was measured in narrow (45–125 m) and wide (53–130 m) stretches of streams (five replicates each) in Mulkey Creek. In the Upper Ramshaw Creek, nest density was measured inside (upstream) and outside (downstream) of a livestock exclosure. Nests were surveyed six times between 1 May and 5 June.

A replicated site comparison in 1994–1996 in a desert site in south-central California, USA (10), found more birds and bird species in plots with grazers excluded, compared to sheep-grazed plots. Fewer black-tailed hares *Lepus californicus*, but more lizards were found in fenced plots, compared to unfenced plots. Perennial plant cover was higher in fenced plots, compared to unfenced plots. **Birds:** More bird species were observed nesting in fenced plots, compared to unfenced plots (3 vs 1 species). More birds and bird species were found in fenced plots (0.9–3.1 vs 0.7–2.6 species/survey; 1–11 vs 1–9 birds/survey), and six of 22 species were more abundant in fenced plots. **Mammals:** Fewer black-tailed hares were found in fenced plots (0–1.5 vs 1–4 hares/survey; 11 vs 22–31 droppings/m^2). **Plants:** There were no differences in species diversity of perennial plants in fenced or unfenced plots (data reported as Shannon-Weiner indices). Perennial plant cover was higher in fenced plots (13–14% vs 6–7% cover). There were no differences in diversity of height, cover, or volume of perennial plants between fenced and unfenced sites (data reported as Shannon-Weiner indices). **Reptiles:** Fewer lizards were found in ungrazed plots, compared to grazed plots (1–4 vs 2–10 lizards/survey), and two of six species were less abundant in ungrazed plots, in some comparisons. **Methods:** Two 2.25 ha plots that were fenced in 1980 were compared to two plots that were grazed by sheep until 1994. Sites were matched for environmental variables. Birds were counted using 16 point counts in each plot, four times during breeding seasons (1994–1995) and twice during winter (December 1994, January 1996). Lizards were surveyed using 1.25 km transects three times in summer (1994–1995). Hares numbers were estimated with four 1.25 km transects and in sixty 40 x 50 cm sampling units in each plot. Plants were surveyed at 16 points in each plot in June 1995. Unfenced plots were also driven over by off-highway vehicles.

A replicated, randomized, controlled study in 1989–1999 in coastal grasslands in central California, USA (11), found that the occurrence of native grasses declined by more in plots with grazers excluded, compared to cattle-grazed plots, but different species responded in different ways. **Plants:** The occurrence of native grasses declined by more in plots with grazers excluded than in grazed plots (20% vs 3% decline). Percentage cover of native grasses did not differ between plots with grazers excluded and grazed plots (11% decrease to 5% increase vs 3–8% increase). Cover of one of three native grass species (*Danthonia californica*) decreased by 12% on ungrazed plots, but increased by 10% on grazed plots. Occurrence of *D. californica* was affected by the plot's location, decreasing by more in ungrazed plots than in grazed plots on lower slopes (58% vs 8% decline), but not on middle or upper slopes (1–16% increase). Occurrence of *Nassella* *lepida* decreased by more on ungrazed, compared to grazed, upper slopes (10% vs 3% decrease), but increased more on ungrazed, compared to grazed, lower slopes (5% increase vs 13% decrease). *Nassella pulchra* occurrence decreased by more on ungrazed, compared to grazed, upper slopes (20 vs 3% decrease). **Methods:** Three 0.25 ha areas were established in 1989 in the upper, middle, and lower slopes of the site, with grazers excluded from one plot in each area. The remaining area was grazed by cattle and sheep. The cover and occurrence of native grasses was assessed in spring 1989 and 1991.

A replicated, before-and-after site comparison in 1991–1998 in serpentine grasslands in the San Francisco Bay Area, California, USA (12), found that populations of the threatened, endemic, Bay checkerspot butterfly *Euphydryas editha bayensis* declined in sites with cattle excluded, but also declined in cattle-grazed sites. One host plant of this butterfly had lower cover in sites with cattle excluded, compared to cattle-grazed sites, and two non-native grasses had higher cover. **Invertebrates:** Numbers of Bay checkerspot butterfly larvae first increased, but then decreased to local extinction, after cattle were excluded from two sites in Silver Creek (excluded from 1989 and 1992 onwards, respectively; maximum: 75,000 larvae in 1993; minimum: 0 in 1995–1997). However, decreases were also seen in 1994–1997 at nearby sites from which cattle were not excluded (Coyote Ridge, maximum: 38,000 in 1994; minimum: 0 in 1997). Decreases, but not local extinction, were seen in a different site from which cattle were excluded from 1985 onwards (Kirby Canyon, maximum: 135,000 in 1992; minimum: 25,000 in 1997). **Plants:** Lower cover of *Plantago erecta* (a host plant of this butterfly) was found in sites with cattle excluded, compared to cattle-grazed sites (Silver Creek and Kirby Canyon: 4–8% cover; Coyote Ridge: 16% cover). Higher cover of total grasses (54–62% vs 25–35%), and also some non-native grasses (*Lolium multiflorum*: 45% vs 18–32%; *Avena* sp.: 18% vs 2%), was found in sites with cattle excluded. No differences were found in the cover of *Vulpia microstachys*, *Bromus hordaceous*, and *B. rubens* (about 2% cover for each). **Methods:** Postdiapause butterfly larvae were sampled in 1991–1997 in three sites with cattle excluded (two in Silver Creek, one in Kirby Canyon) and three sites with cattle (Coyote Ridge). Plants were sampled in 1996.

A replicated, randomized, controlled study in 1993–1997 in grasslands in northern California, USA (13), found that plant community composition changed and the cover of herbaceous vegetation was higher in ungrazed plots, compared to cattle-grazed plots. **Plants:** Herbaceous plant cover was higher in ungrazed plots, compared to grazed plots, along creeks for three of six years (84–87% vs 46–59% cover). There were no differences in cover for plots by springs (data not provided). The plant community changed significantly in one plot with moderate grazing intensity but not in ungrazed plots (data reported as eigenvalues). **Methods:** From 1993 to 1997, three pastures in each of three areas were ungrazed, lightly grazed, or moderately grazed (three replicates of each). Cattle were allowed on grazed pasture in November and February–April each year. Plants were monitored at springs and along creeks in each pasture, each spring. Before the study, the area had been moderately grazed since 1960.

A replicated, controlled study in 1996–1999 in rangelands in Israel (14) (same study as (19)) found more species of plants in plots from which grazers were excluded, in two of four sites, but fewer species in one site. More plants and more plant biomass were found in plots from which grazers were excluded. **Plants:** More plant species were found in ungrazed plots, in two of four sites (5–12 vs 5–9 species/quadrat), but fewer were found in one site (6–13 vs 9–15). Total plant biomass was higher in ungrazed plots (10–490 vs 10–155 g/m^2), and there were more plants in ungrazed plots in three of four sites (28–134 vs 28–94 plants/quadrat). There were more plants and plant species in grazed sites in less productive areas, but not in more productive areas. The abundance of common species increased with productivity in ungrazed plots, but not in grazed plots, in less productive sites. There was no difference for rare and abundant species. In more productive sites, the abundance of rare plants increased with productivity in grazed, but not ungrazed sites. There were no differences between grazed and ungrazed sites for common or abundant species. **Methods:** Four sites (one considerably more productive than the others) were established in 1993, each with a 10 x 10 m fenced plot to exclude sheep. Plants were surveyed in April 1996–1999, when vegetation was at a peak.

A replicated, randomized site comparison in 1999 in blue oak savanna in the foothills of the Sierra Nevada, California, USA (15), found lower coverage of alien plants in ungrazed sites, compared to cattle-grazed sites. **Plants:** Similar numbers of alien plant species, but lower coverage of alien plants, were found in ungrazed sites, compared to cattle-grazed sites (40% vs 55% alien cover; 20 vs 26 alien species). Grazed and ungrazed sites had fewer native plants than alien plants, and fewer native plants were found where there were fewer alien plants, at one of three scales (1 m^2: data reported as test statistics). Fewer perennial herbs were found on ungrazed sites, compared to cattle-grazed sites (data reported as test statistics). **Methods:** Grazers were excluded from five sites in Sequoia National Park at least 100 years before the study began, but they were not historically excluded from five sites on the nearby Bureau of Land Management land. Plants were sampled in 0.1 ha sites, at three scales (1 m^2, 100 m^2, and 1,000 m^3).

A site comparison in 2001 in grassland in southern California, USA (16), found more native plant species and lower cover of non-native plants in an area with cattle excluded, compared to a grazed area. **Plants:** More plant species were found in an area of grassland from which cattle were excluded, compared to a grazed area (24 vs 12 species), and one less non-native species was found in the ungrazed area (5 vs 6). Cover of non-native species was lower in the ungrazed area, compared to the grazed area (57% vs 75%), but the cover of native plants did not differ (49% vs 46%). **Methods:** In 1990, a fence was used to exclude cattle from one area of a grazed grassland. In April 2001, plants were recorded in 1,000 points on each side of the fence.

A replicated, randomized, controlled study in 1992–2002 in grazed wetlands in northern California, USA (17), found more families of insects in streams in ungrazed plots, compared to grazed plots, in a ten-year experiment. Plant diversity was lower at one of two grazing intensities. In a separate three-year experiment, diversity decreased in plots from which cattle were removed, but not in grazed plots. **Invertebrates:** There were more families of insects in streams in ungrazed plots, compared to grazed plots (data not reported). **Plants:** In a ten-year experiment, there was no difference in the number of plant species, or the relative cover of native and non-native species, in ungrazed plots, compared to grazed plots (data not reported). Lower plant diversity was found after the experiment, compared to before, in ungrazed plots, compared to lightly grazed plots (but not moderately grazed, plots). Plant community composition differed between plots with or without grazers along creeks, but not at springs (data reported as ordination scores). Plant cover at the end of the experiment was higher in ungrazed plots, compared to moderately grazed plots but not lightly grazed plots (data not reported). In a separate three-year experiment, plant diversity decreased in ungrazed plots, but not in grazed plots. **Methods:** The ten-year experiment from 1992–2002 was established in three meadows. Within each, three watersheds were randomly assigned to one of three grazing intensities: cattle excluded, light grazing (leaving 800–1,000 pounds of residual dry matter at the end of the season), or moderate grazing (leaving 600–700 pounds). Samples were taken from both the spring and along the creek in each watershed. The three-year experiment was in 1999–2002 in marshy areas within four meadows. Two plots were established in each: one ungrazed and one with moderate grazing. Insects were surveyed every three months in one year. Plants were surveyed each June using line transects.

A replicated, randomized, controlled study in 1995–1998 in forested pastures in central California, USA (18), found no difference in plant cover on stream banks and the surrounding grass between ungrazed pastures and most cattle grazing regimes. **Plants:** There was no difference in plant cover on stream banks and the surrounding grass between ungrazed and grazed pastures, for three of four grazing regimes (6–94% cover). There was higher plant cover in ungrazed plot, compared to grazed plots, for high intensity, dry-season grazing (72–94% vs 31–51%). **Methods:** One pasture in each of three streams was ungrazed and the other four were grazed moderately or intensively (reducing stubble to 2–3 and less than 2 inches, respectively) and in the dry season or the wet season (July–October and October/November–May, respectively). Plant cover was measured in June on 10 transects across the streams.

A replicated, controlled study in 1996–1999 in shrublands in Israel (19) (same study as (14)) found that total plant cover increased with grazer exclusion, and plant communities differed between plots with or without grazers excluded. Differences depended on the productivity of the site. **Plants:** Total plant abundance was higher in plots with grazers excluded, compared to grazed plots (data reported as model results). There were bigger differences in plant communities between ungrazed and grazed plots in more productive areas (data reported as Sorenson's quantitative similarity index). Of the 36 most common annual plants, 20 showed a response to grazer exclusion: 11 species increased after grazer exclusion (only in low-productivity sites, in two of 11 species); seven species decreased (only in high-productivity sites, in one of seven species); and two species decreased in high-productivity sites but increased in low-productivity sites. Overall, more species increased than decreased in low-productivity sites (6–11 vs 1–2 species), but the opposite was true in high productivity sites (6 vs 15). Generally, large species were more abundant in ungrazed plots, compared to grazed plots (15% vs 9% relative abundance), smaller species were less abundant (54% vs 63%), and medium species showed variable responses (20% in both). These responses were more pronounced in high-productivity sites. **Methods:** Four 10 x 10 m plots from which sheep were excluded were established in 1993 in each of four sites, differing in topography and productivity. Vegetation samples were collected in April 1996–1999.

A replicated, randomized, controlled study in 1991–1994 in grassland and blue oak *Quercus douglasii* savannas in central California, USA (20), found that live plant cover, native plant cover, and plant biomass were lower in areas with high numbers of ground squirrel burrows in grazed plots, but not in ungrazed plots. **Mammals:** The number of active ground squirrel burrows, relative to pre-experiment numbers, did not differ between ungrazed and grazed plots (60–100% vs 40–100% of pre-experiment numbers). The spatial distribution of burrows did not differ between ungrazed and grazed plots (2.6–3.4 vs 2.2–4.1 m between nearest burrows). **Plants:** Live plant cover, plant biomass, and native plant cover did not decrease with increasing numbers of ground squirrel burrows in ungrazed plots, but did decrease in grazed plots (3%, 60 g/m^2, and 1.8% declines, respectively, for every additional burrow in a colony). **Methods:** Three sites, each with four plots, were established in 1991. Half of the plots were in grassland, and half were in savanna. Half had cattle excluded from them by a fence, and half were grazed from spring to summer. Three ground squirrel colonies were monitored in each plot, and vegetation was measured in a 625 cm^2 plot near the centre of each, at the end of the 1992–1994 growing seasons.

A replicated, randomized, controlled, before-and-after study in 2000–2003 in wet alpine meadows in central California, USA (21) (same study as (22)), found fewer aquatic invertebrate species, and greater declines in the number of native plant species, in plots from which cattle were excluded, compared to grazed plots. Lower native-plant cover and higher exotic-grass cover was found in ungrazed plots, compared to grazed plots. **Invertebrates:** There were fewer aquatic invertebrate species in pools in ungrazed plots, compared to pools in grazed plots, in one of three years (10 vs 11–14 species). **Plants:** The number of native plant species in pool edges and surrounding dry land declined more in 2001–2003 in ungrazed plots, compared to grazed plots (pool edges: 1.3 fewer species vs 0.5 fewer to 1.8 more species; dry land: 0.5 fewer vs 1–1.2 more). Changes within pools did not differ between ungrazed and grazed plots. There was lower relative cover of native species in pool edges and surrounding dry land in ungrazed plots, compared to grazed plots (pool edges: 40% vs 54–72; dry land: 13 vs 18–31). There was no difference in relative cover of native species within pools between ungrazed and grazed plots. There was higher cover of exotic grasses in ungrazed and dry-season-grazed plots, compared to continuously-grazed and wet-season-grazed plots (84–86% vs 52–70%). **Methods:** Twenty-four plots were established in 2000, each with three pools (70–1,130 m^2) and nine times more dry land than pool. Areas were either continuously or seasonally grazed by cattle (dry season: October–November; wet season: April–June), or grazers were excluded. Before the experiment, the area had been grazed for at least 100 years.

A replicated, randomized, controlled study in rangelands in central California, USA (22) (same study as (21)), found higher grass cover in plots from which grazers were excluded, compared to cattle-grazed plots. **Plants:** Grass cover was higher in ungrazed plots, compared to grazed plots (54% vs 30% cover). **Methods:** Thirty-six pools in 12 groups across a cattle ranch were studied, 18 of which (six groups) had fences erected around them to exclude cattle. The rest of the ranch was grazed at a density of 1 cow-calf pair/ha. Plant cover was monitored in the pools, edges, and surrounding dry land.

A replicated, controlled study in 2000–2002 in pastures and forests on Robinson Crusoe Island, Chile (23), found seasonal variation in the number of species found in ungrazed plots, but not in grazed plots. Species diversity did not vary in ungrazed plots, but did in cattle-grazed plots. The cover of two of 22 species of plants varied over the course of the experiment. **Plants:** There was seasonal variation in the number of species found in ungrazed plots, but not grazed plots (5–8 vs 4–7 species). Diversity did not vary over time in ungrazed plots, but did in grazed plots (data reported as Shannon-Weaver-Weiner values). The cover of two of 22 species of plants varied over the experiment: *Acaena argentea* did not vary in cover over time in ungrazed plots, but did in grazed plots (found in 69–85% vs 51–69% of points); *Conium maculatum* showed variation in cover over time in ungrazed plots, but it was not found in grazed plots (found in 2–28% of points). Plant height varied over time only in ungrazed plots (22–78 vs 22–29 cm). **Methods:** In 2000, six 25 m^2 plots were established: three in grazed pastures and three inside a cattle-exclusion fence in grazed pastures. These were then compared to six more plots in the grazed areas (three 13 m from the fence, three 44 m from the fence). Plants were monitored every three months at 121 points within each plot.

A replicated, randomized, controlled study in 1993–2002 in wetlands in central California, USA (24), found higher plant diversity in plots with cattle excluded, compared to grazed plots. Herbaceous plant cover increased over time in ungrazed plots, and lightly grazed plots, but decreased in moderately grazed plots. The species composition of plant communities differed between ungrazed and grazed plots, for one of two habitats. **Plants:** One measure of plant diversity along creeks was higher in ungrazed plots, compared to grazed plots. Another measure along creeks was lower in ungrazed plots, compared to moderately but not lightly grazed plots. There were no differences in diversity at springs. Herbaceous plant cover increased over time in ungrazed and lightly grazed plots, but decreased in moderately grazed plots (data reported as model results). The species composition of plant communities differed between ungrazed and grazed plots for creeks, but not springs (data reported as statistical results). Plant communities showed more variability over time in ungrazed, compared to grazed plots (data presented as coefficients of variation). **Methods:** In 1993, three wetlands in each of three watersheds were assigned to light grazing (reducing dry matter to 250 g/m^2), moderate grazing (reducing dry matter to 150 g/m^2), or no grazing (grazers excluded). Plots of 2–5 ha were established at springs and creeks in each wetland. Vegetation biomass was sampled each year in 1993–1998 from three 0.0625 m^2 quadrats in each plot, and plant communities were sampled with transects in 1993–2002.

A replicated, controlled study in 1995–2001 in upland forest pastures in northeast Spain (25) found that both shrubby and herbaceous vegetation increased more in plots from which cattle were excluded than in grazed plots. **Plants:** Shrub and herbaceous biomass increased in ungrazed plots, but not in grazed plots (shrub: 530 kg dry matter/ha/year; herbaceous: 220 kg). After six years, shrub and herbaceous biomass were higher in ungrazed plots, compared to grazed plots (shrub: 5,100 vs 1,200 kg dry matter/ha; herbaceous: 1,700 vs 680 kg). The number of shrubs did not differ between grazed and ungrazed plots (17–26 shrubs/transect). Herbaceous biomass contained a lower proportion of living vegetation in ungrazed plots, compared to grazed plots (23–44% vs 42–75%). **Methods:** In 1995, four 10 x 10 m plots were established to exclude cattle in forest pastures, which had been grazed at low intensities each March–June and October–December since 1985. Vegetation inside and outside the plots was monitored each December using transects and random points.

A replicated site comparison in 1999–2001 in grasslands in central Spain (26) found more species and individuals of small mammals, and higher plant biomass in plots from which cattle were excluded, compared to grazed plots. **Mammals:** More individuals and species of small mammals were found in plots from which cattle were excluded, compared to grazed plots (3–6 vs 0 individuals/plot; species data reported as ordination results). Three species of mammal were found: white-toothed shrews *Crocidura russula* (61.6% of all captures), common voles *Microtus arvalis* (31.9%), and wood mice *Apodemus sylvaticus* (6.5%). Abundances of all three species appeared to be higher in ungrazed plots, although this was not tested. **Plants:** Plant biomass was higher and plants were taller in plots from which cattle were excluded, compared to grazed plots, although plant cover did not differ (reported as principal component analyses) **Methods:** Six plots to exclude cattle were established in reforestation areas in grasslands grazed at 2–10 animals/ha. These areas were used to move livestock until the 1950s and they were reforested in 1990, but few planted trees survived. Eight live traps were placed in each of 22 trapping plots (11 inside and 11 outside cattle exclosures). Traps were set and vegetation was monitored during autumn 1999 and 2000 and summer 2000 and 2001.

A replicated, randomized, controlled study in 2003–2005 in shrubland in north-east Israel (27) found that plant communities in formerly grazed plots became more similar to those in ungrazed plots when cattle were excluded for two years. **Plants:** Plant community composition became more similar between formerly grazed and ungrazed plots over the course of the experiment (data reported as Sorensen's quantitative similarity index). At the start of the experiment, the biomass of one of six plant functional groups differed between formerly grazed and ungrazed plots, but none differed after two years of cattle exclusion. **Methods:** In February 2003, fences to exclude cattle were erected around five 10 x 10 m plots in six areas: two grazed at either 0.55 or 1.1 cows/ha/year and two in areas from which cattle had been excluded for 30–40 years. Vegetation was sampled in spring of each year.

A replicated, randomized, controlled study in 1997–2000 in grassland in South Australia (28) found fewer native plant species in plots with grazers excluded, compared to grazed plots. There was no difference in the number of non-native species. Ungrazed plots had higher cover of two grass species in most years. **Plants:** Fewer native species were found in ungrazed plots, compared to grazed plots, in three of four years (1.4–2.1 vs 2.0–2.5 species/quadrat). There was no difference in the number of non-native species (2.4–4.8 species/quadrat). Cover of *Austrostipa* sp. (a native grass) was higher in ungrazed plots, compared to grazed plots, in all years (18–31% vs 7–16% cover). Cover of *Avena barbata* (a non-native grass) was higher in ungrazed plots in the last two years of the study (15% vs 6–7%) and no different from grazed plots in the first two (4–13%). Total plant cover was higher in ungrazed, compared to grazed plots (data not provided). There were no differences in the presence or absence of different species between ungrazed and grazed plots. **Methods:** Six 50 x 50 m plots were established in November 1997. Half were fenced to exclude grazers and half were grazed by combinations of sheep, cattle, and alpacas *Vicugna pacos*. Vegetation was monitored in twenty-five 1 x 1 m quadrats in each plot in November–December each year.

A replicated, randomized, controlled study in 2002–2004 in grasslands in northern California, USA (29), found similar numbers of ants in plots with or without cattle excluded. **Invertebrates:** Similar numbers of ants were found in ungrazed plots, compared to grazed plots (data not reported). **Methods:** A total of eighteen 30 x 30 m plots were established in winter 2002–2003 in two sites normally grazed (one cow-calf pair/8 ha, between November and May). Twelve plots were fenced to prevent cattle grazing, of which six were also burned. Ants were surveyed with pitfall traps 14 days after burning and one year after burning.

A replicated, randomized, controlled before-and-after study in 2003–2005 in shrubland in northern Israel (30) found that plant diversity decreased in previously grazed plots from which cattle were excluded, but only in moderately-grazed plots, and not in heavily-grazed plots. **Plants:** The number of plant species decreased in plots, after grazers were excluded, at one of two grazing intensities (data reported as effective number of species). Species diversity decreased in all plots, whether or not they had been previously grazed. **Methods:** Areas were ungrazed or grazed at moderate or heavy stocking densities (0.55 and 1.1 cows/ha/year, respectively) for 10 years before the start of this study. In 2003, two sites were established in each of these areas (0.4–2 ha for ungrazed plots, 20–30 ha for grazed plots). Fences were erected around five 10 x 10 m plots in the grazed sites, and vegetation was monitored in these plots and also in corresponding plots in the ungrazed area.

A controlled study in 2005–2008 in restored riparian habitat on a farm in the Central Valley, California, USA (31), found more plant biomass in plots without grazers, compared to plots grazed by goats and sheep. **Plants:** More plant biomass was found in plots without grazers, compared to plots with grazers (data reported as model results: grazing explained 21% of the variation in biomass). One-third of the identified plant species were planted during restoration (21 of 68 species), and 47 of 68 species were non-natives. **Methods:** Grazers were introduced to half of a streambank in 2005 (14 animals/ha), but they were excluded by a fence from the other half. Herbaceous biomass was collected in the ungrazed area and the grazed area in October 2007 and April–May 2008 (0.25 x 0.5 m plots).

A replicated, randomized, controlled study in 2008–2010 in grasslands in central California, USA (32), found no difference in the cover of exotic species in plots from which cattle were excluded, compared to grazed plots. **Plants:** The cover of exotic species did not differ between plots from which cattle were excluded and grazed plots (data reported as model results). **Methods:** Ten sets of plots were established in grassland that had been grazed for decades: five in 2008 and five in 2009. Half of the plots were fenced to exclude cattle and half were left open and typically grazed in winter at approximately 0.25 cow-calf pairs/ha.

A replicated site comparison in 2007–2008 in marshes in northeast California, USA (33), found that California black rails *Laterallus jamaicensis* were more likely to occupy ungrazed areas, compared to cattle-grazed areas, in unirrigated marshes, but were less likely to occupy ungrazed areas in irrigated marshes. Ungrazed marshes had greater cover of wetland vegetation in one of two years. **Birds:** The probability of marshes containing California black rails was higher for ungrazed areas, compared to grazed areas, that were not irrigated, but lower for ungrazed areas, compared to grazed areas, that were irrigated (results reported as model coefficients). **Plants:** The cover of wetland vegetation was higher in ungrazed areas, compared to grazed areas, in one of two years (2007: 57–65% vs 40–58% cover; 2008: 58–69%). **Methods:** Fourteen ungrazed marshes (fenced between 1998–2005) and 20 winter-spring grazed marshes were surveyed for rails up to twice monthly in April–August (2007) or February–October (2008, excluding September). Vegetation was sampled every month in April–July (2007) or March–August (2008). Not all marshes were surveyed for rails or vegetation each year.

A replicated, randomized, controlled study in 2006–2010 in alpine meadows in central California, USA (34), found no difference in non-woody plant cover in pools in meadows from which cattle were excluded, compared to pools in grazed meadows. **Plants**: There was no difference in the cover of non-woody plants in pools in ungrazed meadows, compared to grazed meadows (56–80% cover). **Methods:** Nine meadows were studied, with cattle completely excluded from three meadows in 2006–2008 and excluded from Yosemite toad *Bufo canorus* breeding habitat in three meadows. The other three meadows were grazed over summer. All meadows had previously been grazed for at least a decade before the study. Plant cover was measured each summer in transects across the pools.

A replicated, paired, site comparison in 2010–2011 in alpine meadows in central California, USA (35), found few differences in invertebrate communities, green plant cover or plant height between grazed and ungrazed meadows. **Invertebrates:** Similar numbers of invertebrate species were found in ungrazed or grazed meadows (21–34 species/sample). However, there were more species in ungrazed meadows, compared to grazed meadows, in one of four comparisons (non-ground-dwelling invertebrates sampled in mid-grazing season: data not reported). There were more individuals in ungrazed meadows, compared to grazed meadows, in mid-season, but not early season (data not reported). Three of 99 families of invertebrates had more individuals in ungrazed, compared to grazed meadows (data not reported). There were no differences in nine other measures of invertebrate communities between ungrazed and grazed meadows. **Plants:** Green plant cover and plant height did not differ between grazed and ungrazed meadows (54–76% cover and 7–15 cm height). **Methods:** Ten pairs of meadows were selected in 2010: one that had not been grazed for at least two decades, and one grazed by cattle from July–September with an average stocking density of

18.5 grazed nights/ha/year. Invertebrates and plants were sampled in July/August and September each year at four points within each meadow.

A replicated, randomized, controlled study in 2006–2010 in alpine meadows in central California, USA (36), found no difference in the density of young Yosemite toads *Anaxyrus canorus*, the density of tadpoles, or the proportion of pools occupied by toads between plots with or without cattle excluded. **Amphibians:** The densities of young toads and tadpoles, and the proportion of pools that were occupied by toads, did not differ between plots with or without cattle excluded (0–12 toads/ha, 20–4,100 tadpoles/ha, 15–63% occupied pools). **Methods:** In 2005, 14 meadows were selected and randomly assigned to one of three treatments: unfenced (grazed, five meadows), fenced around toad breeding areas (five meadows), or fenced around the whole meadow (four meadows). Before the experiment, all meadows had been grazed been late June and September. Tadpoles were surveyed once/summer and young toads were surveyed twice/year.

A replicated, randomized, controlled study in 2001–2005 in upland shrub pastures in northeast Spain (37) found that shrubs and herbaceous vegetation grew faster in ungrazed plots, compared to cattle-grazed plots, resulting in greater biomass by the end of the study. **Plants:** Shrub biomass increased faster in ungrazed plots (2,600 vs 1,200 kg dry matter/ha/year). After five years, shrub biomass was higher in ungrazed plots (14,000 vs 6,500 kg dry matter/ha). Similar numbers of shrubs were found in ungrazed plots or grazed plots (18–45 vs 18–41 plants/transect). Herbaceous vegetation increased by 290 kg/ha/year in ungrazed plots, but did not increase in grazed plots. Herbaceous biomass was higher in ungrazed plot, in four of five years (2,100–2,800 vs 990–1,800 kg dry matter/ha). After five years, the percentage of dead herbaceous biomass was higher in ungrazed plots, compared to grazed plots (42% vs 21%). **Methods:** Twelve 10 x 10 m plots were established in 2001, in six shrub-dominated pastures that were grazed by cattle or sheep. Plots were fenced to exclude livestock, and vegetation was monitored with transects, quadrats, and random points in April and December each year.

A replicated, controlled study in 2002–2007 in oak savannas in central Spain (38) found that excluding grazers had different effects on plants at different elevations. Plant height was higher in ungrazed plots, compared to grazed plots. **Plants:** Fewer plant species were found in plots from which sheep were excluded, compared to plots grazed by sheep, at low elevation (6–16 vs 10–20 species/sample), but, at high elevation, more plants species were found in ungrazed plots, in two of six years (14–17 vs 13–15). Live plant cover was higher in ungrazed plots, compared to grazed plots, at high elevation (41–71% vs 34–52% cover), but it was lower at low elevation (34–95% vs 84–95%). Plant height was higher in ungrazed plots, compared to grazed plots (3–50 vs 3–34 cm). **Methods:** Thirty 36 m^2 plots were established in 2001 at low elevation (highly productive) and high elevation (less productive), either open to grazing by sheep and rabbits, fenced to exclude sheep, or fenced to exclude both sheep and rabbits. Plants were monitored every year in April (in the low productivity site) or May–June.

A before-and-after study in 1980–2012 on Santa Cruz Island, California, USA (39), found that the cover of woody vegetation increased and the cover of exotic grasses and bare ground decreased following the eradication of feral sheep from the island in 1984. **Plants:** Cover of woody vegetation estimated using transects increased from 1980 to 2012 (1% vs 24%), whilst bare ground decreased (40% vs 9%) and the cover of herbaceous vegetation did not change (60% vs 67%). Woody overstory plant cover (estimated from photographs) increased from 27% in 1979/1980 to 53% in 2009. Total woody vegetation cover across the island (estimated from aerial photos) increased from

26% to 77% between 1985 and 2005. Cover of non-native grasses and bare ground decreased (grasses: 68% vs 21%; bare ground: 7% vs 2%). **Methods:** Vegetation was monitored using transects (1980, 2012), photographs (1979/1980, 2009), and aerial photographs (1985, 2005). Before eradication, sheep had grazed the island since around 1850, at a density of approximately 2 sheep/ha (in 1980).

A replicated site comparison in 2013 in oak woodlands in northern California, USA (40), found higher densities of young coast live oaks *Quercus agrifolia* in areas that were not grazed by cattle, compared to grazed areas. Young oaks were also larger in ungrazed, compared to grazed, areas, but there were no differences in density or size of adult trees. **Plants:** There were higher densities of oak seedlings and saplings in areas without cattle, compared to grazed areas (22 vs 11 trees/200 m^2), but there were no differences in the density of adult trees (2 trees/200 m^2). Trees were larger in ungrazed areas, compared to grazed areas (data reported as model results). Trees were less likely to have grazing damage in ungrazed areas, compared to areas with cattle, and damage was less likely to be serious (0% vs 6% of trees with at least 70% of edible biomass damaged). **Methods:** Areas of open oak woodland in eight ranches (four no-longer grazed, three with year-round grazing, and one with grazing from November–May) were surveyed in 2013 for oak trees of all ages using belt transects.

A replicated, randomized, controlled study in 2008–2011 in lowland grasslands in central California, USA (41), found smaller increases in the number of native plant species in ungrazed plots, compared to cattle-grazed plots, but found no change in the cover of native or non-native species. **Plants:** The number of native species declined, or increased more slowly, in ungrazed plots, compared to grazed plots (1.8 fewer to 1.0 more species vs 1.2–2.4 more species). Change in the cover of native and non-native species did not differ between ungrazed and grazed plots (native species: 8% decline to 5% increase; data not reported for non-native species). Native, non-grass species tended to be less affected by grazing than non-native grass species (results reported as principal response curves analysis). **Methods:** In 2008, five experimental blocks were established, each with two 5 x 5 m plots: one that excluded cattle and one that was grazed. Plants were surveyed in 0.5 x 0.5 m quadrats each spring. Before the experiment, the area had been grazed for several decades at 0.25 animal units/ha.

A replicated, randomized, controlled study in 2007–2013 in grasslands in central California, USA (42), found that native plant species were lost from plots from which cattle were excluded, but increased in grazed plots, in one of two experiments. There were also differences in the plant community between plots with and without grazers, in one of two experiments. **Plants:** The number of native plant species decreased in plots from which cattle were excluded but increased in plots grazed by cattle, in one of two experiments (experiment 1: 4.5 species/year lost vs 0.5 species/year gained; experiment 2: 2.2 species/year lost vs. 0.5 species/year gained). The cover of native non-grass species increased more slowly in ungrazed plots, compared to plots grazed by cattle (data reported as log response ratios). The cover of grasses was higher in ungrazed, compared to grazed plots, in one of two experiments (experiment 1: 25–61% cover vs 8–47%; experiment 2: 17–58% for both). The diversity of native non-grass species increased more slowly in plots from which grazers were excluded, compared to plots grazed by cattle, in one of two experiments (data reported as log response ratios). Community composition varied between ungrazed and grazed plots, in one of two experiments (data reported as canonical regression coefficients). The number of native species, cover of native, non-grass species, and the diversity of measures were also less stable over time in plots from which grazers were excluded, compared to cattle-grazed plots (data reported as the ratio of average to standard deviations). **Methods:** Experiment 1 was established in 2007 and experiment 2 was established in 2009, both in cattle-grazed grassland. In each experiment, ten 5 x 5 m plots were established, with cattle excluded from half and allowed to graze the other half. Plants were monitored in March–April 2008–2013 in two 0.5 x 0.5 m quadrats within each plot.

A replicated controlled study in 2012–2013 in grasslands in central California, USA (43), found fewer species but higher cover of native plants in plots not grazed by cattle, compared to grazed plots. Cover of invasive species and the emergence of native seedlings did not differ between grazed and ungrazed plots. **Plants:** Fewer species of native plants were found in plots from which cattle were excluded, compared to grazed plots (8.5–8.8 vs 10.2 species/m^2). The same number of native seedlings emerged in grazed and ungrazed plots (0–1.1 seedlings/m^2). Cover of native plants was higher in plots from which cattle were excluded, compared to grazed plots (72–83% vs 55–65% cover). Cover of invasive species did not differ between grazed and ungrazed plots (18–29% cover). **Methods:** Sixty 1 x 1 m plots were established in summer 2012: half in an area grazed at 0.25 cow-calf pairs/ha and half in an area fenced in 2012 to exclude cattle. Plant species and cover was assessed once in 2013.

A replicated, randomized, controlled, before-and-after study in 2000–2010 in grasslands and wetlands in central California, USA (44) (same study as (21)), found fewer species and lower cover of native plants in plots with cattle excluded, compared to grazed plots. Community composition differed, and biomass at the end of the summer was higher, in ungrazed plots, in some comparisons. **Plants:** Fewer native plant species were found in ungrazed plots, compared to cattle-grazed plots, in all but the first year of the experiment (6–8 vs 7–9 species/sample). Cover of native plant species was lower in ungrazed plots, compared to cattle grazed plots (32–61% vs 50–67%). This effect was stronger at pool edges than within pools or on dry land (lower native cover in four of 10 years for edges vs two of 10 years for other habitats). Ungrazed plots were more dominated by grasses in five of 10 years (0.7–4.6 vs 0.3–0.8 times more grass than non-grass cover). Ungrazed plots had higher plant biomass at the end of the grazing season, compared to grazed plots, in seven of 10 years (2,100–4,000 vs 860–2,200 kg dry mass/ha). **Methods:** Twenty-four plots were established in 2000, each with three pools (70–1,130 m^2) and nine times more dry land than pool area. In 2000–2003, cattle were excluded from six pools, six were grazed continuously from October to June, and 12 were grazed seasonally (either October–January or April–June). In 2003, the seasonal grazing experiment was stopped and only ungrazed and continuously grazed plots were continued. Plants were monitored in April–May each year within pools, at pool edges, and on dry land. The area had been grazed for at least 100 years before the start of the experiment.

A site comparison in 2014 in an alpine meadow in southern California, USA (45), found more and larger willow *Salix* sp. trees in a plot from which cattle were excluded, compared to a grazed area. **Plants:** Streamside vegetation within a plot from which cattle were excluded had more willows than the surrounding grazed area (980 trees in 1,200 m vs 75 in 900 m) and had a lower cover of sedges *Carex* sp. (data not reported). Willows within the ungrazed plot were larger than those in the grazed area (average height: 48 vs 25 cm; maximum height: 300 vs 170 cm). **Methods:** Cattle were excluded from a 1,200 m section of stream in 1991 but were allowed to graze on the remaining 900 m. Vegetation within 2 m of the stream was surveyed in 2014.

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7.10. Use fewer grazers: Other biodiversity (12 studies)

- Amphibians (0 studies)
- Birds (0 studies)
- **Invertebrates (1 study):** One replicated, randomized, controlled study in wet grasslands in the USA[6] found more families of insects in streams in areas grazed by cattle at lower, compared to higher, intensities.
- Mammals (0 studies)
- **Plants (11 studies)**
  - Abundance (11 studies): Six studies (four replicated, randomized, and controlled) in grasslands or wood pasture in the USA[1,6,10,11], Chile[9], and Israel[12] found higher cover of some species of plants, herbaceous plants, or native plants in areas grazed by cattle or sheep at lower, compared to higher, intensities. One controlled study in forest in Israel[4] found higher cover of woody vegetation in areas with lower grazing intensity. Four of these studies[1,4,9,12] also found lower cover or biomass of some groups of plants in sites with lower grazing intensity. Four studies in grasslands in the USA[3,7,8] and Israel[5] found no effect of grazing intensity on biomass, cover, or abundance of plants.
  - Diversity (6 studies): Three replicated, randomized, controlled studies in grasslands and wet grasslands in the USA[10,11] and Israel[12] found no differences in plant diversity between sites with different cattle-grazing intensities, in some or all comparisons. One of these[10] also found higher diversity in some comparisons and lower diversity in others. One replicated, randomized, controlled study in wet grasslands in the USA[6] found that plant community composition differed in sites with different cattle-grazing intensities, in some comparisons. Two replicated, randomized, controlled studies in grasslands and wet grasslands in Israel[5] and the USA[6] found no differences in the number of plant species between sites with different cattle grazing intensities, in some or all comparisons. One of these studies[5] also found more species in some comparisons and fewer species in others. One controlled study in wood pasture in Chile[9] found fewer native species and more non-native species in paddocks with lower sheep-grazing intensities.
  - Survival (3 studies): Three controlled studies (two replicated and randomized) in grasslands in the USA[2,8] and forests in Israel[4] found no difference in native grass, tree, or shrub survival in areas grazed by cows at lower, compared to higher, intensities.
- Reptiles (0 studies)
- Implementation options (0 studies)

A controlled study in 1979–1984 in improved and wooded grasslands in northern California, USA (1), found that the cover of different plant species varied with sheep-grazing intensity, and that the effects differed between improved and wooded grasslands. **Plants:** On improved grasslands, cover of one of five species was higher on plots with lower grazing intensity, whilst cover of two species was lower. Cover of two species either peaked at intermediate grazing intensities or did not vary. In wooded grasslands, cover of three of eight species was higher on plots grazed at lower intensities, whilst cover of five was either highest or lowest at intermediate intensities, or did not vary. In improved grassland, total herbaceous plant biomass was highest under intermediate grazing and lowest under high intensity (data not provided). In wooded grasslands, total herbaceous plant biomass did not vary with grazing intensity (data not provided). **Methods:** Improved grassland was seeded with subterranean clover and fertilized with sulphur (12 kg/ha) and triple super phosphate (11.3 kg P/ha). One plot in each habitat was grazed at each of low, medium, and high intensities (0.6, 1.8 and 3.1 sheep/ha for woodland and 5.3, 8.0 and 10.0 for improved grassland, respectively). Vegetation was monitored in April–May each year using point-step transects and clipping vegetation from ten 0.9 m^2 plots in each pasture.

A replicated, randomized, controlled study in 1989–1991 in grasslands in north-central California, USA (2), found that blue oak *Quercus douglasii* seedlings survived at similar rates but had less damage from cattle when planted in plots grazed by cattle at lower densities. **Plants:** Survival of seedlings after 15 months did not differ between plots grazed at low, medium, or high densities (7–50% survival). Fewer seedlings were damaged by browsing and trampling as grazer densities decreased (12–57%, 38–74%, and 52–93% of seedlings damaged in low, medium, and high density plots, respectively). **Methods:** In December 1989, oak seedlings were planted in three pastures, each containing nine plots grazed for a week each in winter, spring, or summer with low, medium and high densities of cattle (2.5, 7.5, and 15 animals/ha, respectively). Each plot received 24 seedlings (720 in total), of which half had the area around them treated with glyphosate herbicide to reduce competition from grass.

A replicated, randomized controlled study in 1993–1997 in grasslands in northern California, USA (3), found no difference in the cover of herbaceous vegetation between plots that were lightly or moderately grazed by cattle, but cover was more stable in lightly grazed plots. **Plants:** Similar cover of herbaceous vegetation was found in lightly-grazed and moderately-grazed plots, but cover was more stable in lightly-grazed plots (along creeks: 46–47% vs 35–80% cover; by springs: data not provided). **Methods:** In November and February–April 1993–1997, three pastures in each of three areas had either light grazing or moderate grazing (three replicates of each). In spring, plants were monitored at springs and alongside creeks in each pasture. The area had been grazed at moderate intensity since 1960.

A controlled study in 1984–1991 in grazed broadleaf forests in northern Israel (4) found higher cover of woody vegetation, taller trees and less herbaceous vegetation in an area moderately, compared to heavily, grazed by cattle. **Plants:** Woody vegetation did not decline over time in a moderately grazed area, but did in a heavily grazed area (change from 48% to 55% cover vs 49% to 41%). At the end of the study, regrowing Kermes oak *Quercus calliprinos* trees were taller in the moderately, compared to the heavily, grazed area (1.1 vs 0.3 m). There were no differences at the beginning of the study (0.6 m for both). Herbaceous vegetation cover and biomass increased in both areas, but increased by less in the moderately, compared to the heavily, grazed area (cover: increase from 13% to 24% vs 20% to 52%; biomass: increase from 28 to 56 g/m^2 vs 17 to 218 g/m^2). There was no difference in the percentage of shrubs that were alive between the areas (data not provided). **Methods:** In 1984, an area of woodland (mechanically cleared, treated with herbicide, and grazed for two years) was split into two areas. One was grazed moderately and one was grazed heavily (0.30 and 0.54 cows/ha, respectively). Animals were removed for December–March and May–November each year. Vegetation was monitored each April in 20–30 25 x 25 cm quadrats in each major habitat.

A replicated, randomized, controlled study in 1993–1997 in grassland in northeast Israel (5) (same study as (12)) found few differences in the number of plant species between plots that were moderately or heavily grazed by cattle. **Plants:** In early-grazed plots, more plant species were found with moderate grazing, compared to heavy grazing, in three of four years (46–49 vs 36–44 species/plot). In late-grazed plots, however, fewer plant species were found with moderate grazing, in three of four years (28–42 vs 41–50 species/plot). Similar numbers of species were found in moderately-grazed and heavily-grazed plots, with continuous grazing (49–66 species/plot). Cover of tall annual grasses was higher in moderately, compared to heavily, grazed plots, for three of four years, and two of three grazing timings (12–40% vs 5–21% cover). Cover of annual thistles was lower in moderately, compared to heavily, grazed plots for two or three out of four years, depending on the timing of grazing (4–9% vs 6–18% cover). Cover of crucifers was lower with moderate, compared to heavy, grazing for two to four years, depending on timing of grazing (1–14% vs 10–20%). With early season grazing, crucifer cover was higher with moderate grazing for one year (16% vs 8%). Seven other functional groups did not vary between plots of different grazing intensities. **Methods:** In 1993 eight plots were established with half grazed continuously (January–October) and half grazed seasonally. In seasonal plots, half the plot was grazed early (January–April/May) and half late (April/May–October). In addition, half the plots were subject to moderate grazing (0.55 or 1.1 cow-calf pairs/ha for continuous and seasonal respectively) and half to heavy (1.1 or 2.2 cow-calf pairs/ha). Plants were surveyed every spring every two steps along permanent transects.

A replicated, randomized, controlled study in 1992–2002 in grazed wetlands in northern California, USA (6), found more families of aquatic insects in streams in lightly, compared to moderately, grazed plots. There were no differences in the number of plant species or the relative cover of native and non-native species, although diversity and community composition in one of two habitats did differ between grazing intensities and total plant cover was lower in moderately grazed plots. **Invertebrates:** There were more families of insects in streams in lightly grazed plots, compared to moderately grazed plots (data not provided). **Plants:** There were no differences in the number of plant species or the relative cover of native and non-native species (data not reported). Diversity relative to before the experiment was higher in lightly grazed plots, compared to moderately grazed plots. Plant community composition varied between lightly and moderately grazed plots along creeks, but not at springs, in wetlands (data reported as ordination scores). Plant cover at the end of the experiment was higher in lightly grazed, compared to moderately grazed, plots (data not provided). **Methods:** Three meadows were studied, with three watersheds in each randomly assigned to a grazing intensity: one with cattle excluded, one with light grazing (leaving 800–1,000 pounds of residual dry matter at the end of the season) and one with moderate grazing (leaving 600–700 pounds). Samples were taken from both the spring and along the creek in each watershed. Insects were surveyed every three months in one year. Plants were surveyed each June using line transects.

A replicated, randomized, controlled study in 1995–1998 in forested pastures in central California, USA (7), found no difference in plant cover on stream banks and surrounding grass between pastures moderately and intensively grazed by cattle. **Plants:** There was no difference in plant cover on stream banks and the surrounding grass between moderately and intensively grazed (31–84% cover). **Methods:** Two pastures in each of three streams were assigned to either moderate or intensive grazing (reducing stubble to 2–3 and less than 2 inches, respectively). Half of each were grazed in the dry season, and half in the wet season (July–October and October/November–May, respectively). Plant cover was measured in June on 10 transects running across the streams.

A replicated, controlled study in 1998–2000 in north-central California, USA (8), found no differences in purple needlegrass *Nassella pulchra* survival or density in lightly, compared to heavily, grazed areas. In one of three years, plants in lightly grazed plots had more reproductive stems and were taller than those in heavily grazed plots. **Plants:** Needlegrass mortality and density did not vary between grazed and ungrazed plots (data reported as model results). Plants in lightly grazed plots had more reproductive stems, compared to those in heavily grazed plots in one of three years (4 vs 2). Plants were also taller in lightly grazed, compared to heavily grazed, plots in one of three years (data not provided). Plant stem diameter did not vary between lightly and heavily grazed plots (data not provided). **Methods:** Twenty 20 x 20 m plots were rotationally grazed from January (in 1998) or December (1999, 2000) until May at a stocking density of 0.75 animal units/ha. Plots were grazed until 25% (lightly grazed) or 50% (heavily grazed) of plant biomass was removed and then rested for 35 days. Thirty individual plants were measured each year and plant density was estimated using 3–5, 1 x 1 m quadrats in each plot.

A controlled study in 1976–1983 in wood pasture (Espinal) in central Chile (9) found fewer species of native plants, more species of non-native plants, more grasses, fewer composites, and more plant biomass in paddocks with lower stocking rates of sheep. Plants had different traits with different stocking rates. **Plants:** Fewer native species were found in paddocks with lower stocking rates, in three of four years (e.g., with 1 vs 3.5 sheep/ha, in the 8th year: 2.5 vs 8 native species), and more non-native species were found in one of four years (e.g., with 1 vs 3.5 sheep/ha, in the 6th year: 9.5 vs 7.5 non-native species). In two of four years, the highest numbers of non-native species were found with intermediate stocking rates (e.g., in the 3rd year, with 1 vs 2.5 sheep/ha: 11 vs 7.5 non-native species). Overall, fewer plant species (native and non-native) were found in paddocks with lower stocking rates (e.g., with 1 vs 3.5 sheep/ha, in the 8th year: 12 vs 15 species). More grasses, and fewer plants in the daisy family (composites), were found in paddocks with lower stocking rates (e.g., with 1 vs 3.5 sheep/ha, in the 8th year: 75% vs 25% relative frequency, for grasses; 10% vs 65% for composites), but similar numbers of legumes were found at different stocking rates (1–3%). More plant biomass was found in paddocks with lower stocking rates (e.g., with 1 vs 3.5 sheep/ha, in the third season: 850 vs 150 kg dry biomass/ha). Lower stocking rates were associated with taller, more palatable plants with fibrous roots and animal-dispersed seeds, whereas high stocking rates were associated with shorter plants that grow in rosettes and produce fewer wind-dispersed seeds (data reported as locations of morpho-functional traits in ordination space). **Methods:** The study area (32 ha) was grazed with 1 sheep/ha for at least 20 years before the study began. In 1976, seven paddocks were established with fences (2.5–10 ha/paddock, 10 sheep/paddock), each with a different stocking rate (1, 1.5, 2, 2.5, 3, 3.5, or 4 sheep/ha). In paddocks with 1–3.5 sheep/ha, plants were sampled in spring (October–November, five 4 m transects/plot), and plant biomass was measured in exclusion cages at the end of the growing season (one 1 m^2 cage/paddock from May to December), in 1978, 1979, 1981, and 1983.

A replicated, randomized controlled study in 1993–2002 in wetlands in central California, USA (10), found lower plant diversity in one of two habitats in lightly, compared to moderately, grazed plots. Herbaceous plant cover increased in lightly, but decreased in moderately, grazed plots. Species composition of plant communities differed, but variability did not, between lightly and moderately grazed plots for one of two habitats. **Plants:** Two measures of plant diversity were lower in lightly, compared to moderately, grazed plots alongside creeks, but not at springs (data reported as model results). Herbaceous plant cover increased over time in lightly grazed plots, but decreased in moderately grazed plots (data reported as model results). The species composition of plant communities varied between lightly and moderately grazed plots (data reported as ordination results). Plant community variability did not differ between lightly and moderately grazed plots (data presented as coefficients of variation). **Methods:** In 1993, three wetlands in each of three watersheds were assigned to either light grazing (reducing dry matter to 250 g/m^2) or moderate grazing (reducing dry matter to 150 g/m^2). Plots of 2–5 ha were established at springs and creeks in each wetland. Vegetation biomass was sampled each year in 1993–1998 from three 0.0625 m^2 quadrats in each plot and plant communities sampled with transects in 1993–2002.

A replicated, randomized, controlled study in 2008–2010 in grasslands in northern California, USA (11), found that plant diversity did not vary between plots grazed at different intensities, but that cover of native species was higher in plots grazed at lower intensities, compared to those grazed at higher intensities, for one of three plant assemblages. **Plants:** Plant diversity did not differ between plots with different grazing intensities (results reported as Shannon diversity). Cover of native species was higher in plots with medium, rather than high, grazing intensity in plots sown with native perennial grasses (17% vs 22% cover), but there was no difference in plots sown with two types of non-native assemblages (2–3%). **Methods:** In 2007 four experimental blocks were established across two pastures. Each block was split into three areas, sown with one of three vegetation types: native perennial grasses, non-native annual forage grasses, or a non-native, non-edible annual weed. These were then divided into six plots, which were subjected to one of three treatments, each replicated twice: no manipulation, mowing and trampling by cattle to simulate medium cattle grazing, or mowing and trampling by cattle to simulate heavy cattle grazing. Plants were surveyed in a 1 m^2 quadrat in May 2008–2010.

A replicated, randomized, controlled study replicated study in 1993–2012 in grassland in north-eastern Israel (12) (same study as (5)) found no difference in plant diversity in plots grazed by cattle at moderate, compared to heavy, intensities. The cover of three of five plant functional groups varied between moderately and heavily grazed plots. **Plants:** Plant diversity did not differ between moderately and heavily grazed plots (data not reported). Cover of tall annual grasses was higher in moderately, compared to heavily, grazed plots for two out three grazing timings (7–52% vs 2–23% cover, no difference for early-grazed plots). Cover of short grasses was lower in moderately, compared to heavily, grazed plots (1–30% vs 3–41%), with the biggest differences in continuously, rather than seasonally, grazed plots. Cover of tall perennial grasses was lower under moderately, compared to heavily, grazed plots for one of three grazing timings, but this difference had gone by the end of the study. There were no differences in cover of perennial or annual non-grass plants between grazing intensities. **Methods:** In 1993 eight plots were established with half grazed continuously (January–October) and half grazed seasonally. In seasonal plots, half the plot was grazed early (January–April/May) and half late (April/May–October). In addition, half the plots were subject to moderate grazing (0.55 or 1.1 cow-calf pairs/ha for continuous and seasonal respectively) and half to heavy (1.1 or 2.2 cow-calf pairs/ha). Plants were surveyed every spring every two steps along permanent transects.

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7.11. Use grazers to manage vegetation: Other biodiversity (18 studies)

- Amphibians (0 studies)
- **Birds (1 study):** One replicated, randomized, controlled study in grasslands in the USA[8] found higher densities of dabbling duck nests, but similar nesting success, in cattle-grazed plots, compared to ungrazed plots.
- **Invertebrates (4 studies):** Two replicated studies (one controlled, one site comparison) in grasslands in the USA[10] and Spain[12] found more invertebrates in sheep-, goat-, or cattle-grazed plots, compared to ungrazed plots, in some or all comparisons. One before-and-after study in grassland in the USA[1] found that a threatened, endemic butterfly species did not recolonize a site after grazing was reintroduced. One replicated, randomized, controlled study in grasslands in the USA[16] found fewer invertebrates in plots with simulated grazing, compared to ungrazed plots, but found similar numbers of invertebrate species. One replicated site comparison in forested grasslands in Spain[12] found higher beetle diversity in grazed plots, compared to ungrazed plots, in one of two beetle groups. Two replicated studies (one randomized and controlled) in grasslands in the USA[16] and Spain[12] found different invertebrate communities in grazed and ungrazed plots.

- **Mammals (2 studies):** Two replicated, controlled studies (one randomized before-and-after study) in grasslands in the USA[6,10] found that abundances of some or all rodents were higher, or increased more, on sheep- or cow-grazed plots, compared to ungrazed plots. However, they also found that some species were less abundant or monthly survival was lower on grazed plots.
- **Plants (15 studies)**
  - Abundance (14 studies): Eight studies (two meta-analyses; two replicated, randomized, and controlled) from grasslands, shrublands, and forests in the USA[1,4,5,13,15,17], Spain[11], and France[18] found higher cover or higher abundance of some groups of plants (or lower cover of undesirable plants[4,15,17,18]), on cattle-, sheep-, or goat-grazed plots, compared to ungrazed plots. Six studies (five replicated; one randomized and controlled) from grasslands in Spain[9] and the USA[1,4,5,10,14] found lower cover or lower abundance of some groups of plants on cattle-, sheep-, or goat-grazed plots, compared to ungrazed plots (or after grazers were reintroduced[1]). Three replicated, controlled studies (two randomized) from grasslands in the USA[2,7,16] found similar cover or biomass on grazed or ungrazed plots.
  - Diversity (7 studies): Three studies (one meta-analysis; two replicated site comparisons) from grasslands in the USA[4,5,13] found more plant species on grazed plots, compared to ungrazed plots, in some or all comparisons. One of these studies[5] also found fewer species of some plant groups on grazed plots, and two of these stuides[4,13] also found more non-native species on grazed plots, compared to ungrazed plots. Two replicated, controlled studies (one randomized) in grasslands in the USA[16] and France[18] found no difference in the number of plant species between cattle- or sheep-grazed plots and ungrazed plots. Two replicated controlled studies (one randomized) from grasslands in the USA[14] and France[18] found no difference in plant diversity between cattle- or sheep-grazed plots and ungrazed plots. One replicated, randomized, controlled study grasslands and woodlands in the USA[15] found that plant community composition varied between cattle-grazed and ungrazed plots.
  - Survival (3 studies): Of two studies on purple needlegrass mortality from grasslands in the USA[3,7], one replicated, randomized, controlled study[3] found lower mortality on sheep-grazed plots, compared to ungrazed plots, in some comparisons, but found higher mortality in other comparisons, and one replicated, controlled study[7] found no difference in mortality between cattle-grazed plots and ungrazed plots. One replicated, randomized, controlled study from grasslands in the USA[2] found lower germination rates in purple needlegrass seeds from sheep-grazed plots, compared to ungrazed plots, in some comparisons.
- **Reptiles (1 study):** One replicated, controlled study in grasslands in the USA[10] found that the abundance of some lizard species increased at a greater rate on cattle-grazed plots, compared to ungrazed plots.
- **Implementation options (1 study):** One study from the USA[16] found more invertebrates on plots with simulated grazing, compared to ungrazed plots, when these plots were planted with non-native plants. One study in shrublands in Spain[9] found lower gorse cover in plots grazed by goats, compared to sheep, as well as other differences in plant biomass and cover.

A before-and-after study in 1995–1998 in a serpentine grassland in the San Francisco Bay Area, California, USA (1), found that grass cover decreased and forb cover increased after grazers were reintroduced, but the threatened, endemic, Bay checkerspot butterfly *Euphydryas editha bayensis* did not recolonize the site. **Invertebrates:** Populations of the

Bay checkerspot butterfly did not increase in the three years after grazers were reintroduced. **Plants:** In 1995, after cattle had been excluded for five years, grass cover was 75%. In 1998, after cattle had grazed for three years, grass cover was 45%. Cover of *Plantago erecta* (a host plant of the Bay checkerspot butterfly) did not increase after cattle were reintroduced, but cover of forbs (non-grass herbs) increased from 10% to 30%. **Methods:** Grazers were reintroduced to one site in Silver Creek in 1995. Postdiapause butterfly larvae and plant cover were sampled in 1995–1998 (sampling methods not reported).

A replicated, randomized, controlled study in 1988–1999 in central California, USA (2), found that purple needlegrass *Nassella pulchra* seeds were less likely to germinate when they came from sheep-grazed plots, compared to ungrazed plots. **Plants:** Seeds were less likely to germinate if they came from grazed, unburned plots, compared to ungrazed, unburned plots (12% vs 23% germination). In burned plots, there was no difference in germination between grazed and ungrazed plots (26–32%). Seeds of similar sizes were found in grazed or ungrazed plots (0.6–0.8 vs 0.7 mg). **Methods:** In 1989, needlegrass seeds were collected from approximately 18 plants in each of 12 plots that had been either ungrazed or grazed by sheep in summer, since 1988. Half of the plots were burned in September 1988. In 1999, 5–10 seeds from each of 185 plants were germinated on germination paper.

A replicated, randomized, controlled study in 1988–1995 in grassland in central California, USA (3), found no consistent differences in mortality or basal area of purple needlegrass *Nassella pulchra* plants in sheep-grazed plots, compared to ungrazed plots. **Plants:** Needlegrass mortality was lower in spring-grazed plots, compared to ungrazed plots, for one combination of burning and topography (5% vs 15% annual mortality), and was higher in summer-grazed plots, compared to ungrazed plots, for another combination (3% vs 0%). Density of plants did not differ between grazed and ungrazed plots (0.3–1.0 plant/m^2). The basal area of plants increased less in summer-grazed plots, compared to ungrazed plots (0% vs 110% increase), but there was no difference between spring-grazed and ungrazed plots (86–110% increase). **Methods:** In 1988–1995, six 20 x 20 m plots were ungrazed, six were grazed by sheep in spring, and six were grazed in summer. Half of the plots were burned in 1988, 1991, and 1994. The survival of 629 needlegrass plants was monitored annually (except for 1993), and 126–130 plants were measured in 1992 and 1995.

A replicated site comparison in 1998–2001 in grasslands in northern California, USA (4), found that the effects of cattle grazing on native and exotic plants depended on soil type. **Plants:** More native plant species were found in grazed sites, compared to ungrazed sites, on serpentine soils (22 vs 19 species/5 m^2), but fewer native species were found in grazed sites on non-serpentine soils (11 vs 12). The same number of non-native species were found in grazed, serpentine sites, compared to ungrazed sites (4–5), but more were found in grazed, non-serpentine sites (10 vs 7). The abundances of one native and one non-native species were lower in grazed plots, compared to ungrazed plots (native: 0–3.0 individuals/m^2; non-native: 1–2 vs 2–4), and another native species had lower abundances in grazed plots on serpentine soils (0–1). Four other species did not differ between grazed and ungrazed plots. **Methods:** Vegetation in 80 sites across two soil types was sampled in April-May 1998–2001 using five 1 m^2 quadrats. An additional 20 sites were sampled in 2000–2001. Forty-three of the sites were grazed at an intensity of 1 cow-calf pair/10 ha, and 57 were ungrazed (having previously been grazed until 1985).

A replicated, paired site comparison in 2000–2001 in coastal grasslands in central California, USA (5), found more plant species in cattle-grazed sites, compared to ungrazed sites, in three of eight groups, in at least one year, but found fewer plant species in two groups in one year. Cover of five groups varied between grazed and ungrazed sites. **Plants:** More species of native and non-native annual non-grass plants were found in grazed sites, compared to ungrazed sites (native: 6–8 vs 1–4 species/site; non-native 12–16 vs 7–12). More species of non-native annual grasses were found in grazed sites, compared to ungrazed sites, in one of two years (9 vs 7). Fewer species of native perennial non-grass and grass plants were found in grazed sites, compared to ungrazed sites, in one of two years (non-grass: 11 vs 16; grass: 4 vs 5). Three other groups showed no differences. Cover of three groups was higher in grazed sites (native annual non-grasses: 9–14 vs 1–3 m^2/ha; non-native annual non-grasses: 73–76 vs 54–62 intercepts/250 sampling points; non-native perennial non-grasses: 45–77 vs 32–54), and cover of another group was higher in one of two years (non-native annual grasses: 170 vs 130). One group had lower cover in grazed sites (25–26 vs 41–52). Cover of three other groups did not vary. Vegetation height was lower in grazed sites (13–15 vs 25–27 cm). **Methods:** Between 17 (2000) and 25 (2001) pairs of sites were studied along the coast (670 km). One site in each pair had been grazed by cattle for at least 10 years, and the other had not been grazed for five years. Vegetation was sampled in March–June (five transects/site).

A replicated, randomized, controlled before-and-after study in 1996–2000 in grasslands in southern California, USA (6), found that Stephen's kangaroo rat *Dipodomys stephensi* increased in numbers on sheep-grazed plots, but not on ungrazed plots. Monthly survival was lower on grazed plots. **Mammals:** Similar numbers of kangaroo rats were found in grazed and ungrazed plots after two grazing sessions (13–38 individuals/ha), but fewer were found after one grazing session and in six of eight surveys before grazing (1–19 vs 21–39). Similar numbers were found in plots that were mown and then grazed, compared to ungrazed plots, after grazing (18–38), but fewer were found before grazing, in 14 of 15 surveys (3–14 vs 21–38). Monthly survival was lower on grazed plots, compared to ungrazed plots (data not provided). **Methods:** Eight 80 x 80 m plots were established in December 1996. Three were grazed in June 1998 (1,500 sheep for four hours) and 1999 (200 sheep for three days), three were mown in 1998 and grazed in 1999, and two were neither mown nor grazed. Kangaroo rats were trapped in 24 periods of three nights each.

A replicated, controlled study in 1998–2000 in north-central California, USA (7), found no differences in purple needlegrass *Nassella pulchra* survival or density in grazed areas, compared to ungrazed areas. Plants had fewer reproductive stems and were shorter in grazed areas, compared to ungrazed areas. **Plants:** Needlegrass mortality and density did not differ between grazed and ungrazed plots (data reported as model results). Needlegrass plants in grazed plots had fewer reproductive stems, compared to in ungrazed plots (1.5–5.2 vs 0.4–4.1). Plants were shorter in grazed plots, compared to ungrazed plots (data not provided). Stem diameter did not differ between grazed and ungrazed plots (2.6–3.6 cm). **Methods:** Forty 20 x 20 m plots were either ungrazed, continuously grazed, or rotationally grazed from January (1998) or December (1999, 2000) until May, at a stocking density of 0.75 animal units/ha. Continuous grazing maintained animals on the plots at all times, whilst rotational grazing removed either 25% or 50% of plant biomass, with 35 days rest between rotations. Thirty individual plants were measured each year and plant density was estimated using 3–5 quadrats/plot (1 x 1 m).

A replicated, randomized, controlled study in 1995–1997 in pastures in central California, USA (8), found that more dabbling ducks *Anas* sp. nested in rotationally grazed fields, compared to ungrazed fields, in one of two years. **Birds:** Nesting densities were higher in grazed fields, compared to ungrazed fields in 1996 (2.2 nests/ha vs 0.6, 4 replicates) but not in 1997 (0.7 vs 0.4). Nest success did not differ between grazed and ungrazed fields (5% success vs 3%). **Methods:** Half of each field (10–14 ha) was grazed by 70 cows and calves for 7–15 days at a time in July–November 1995–1996, after the duck nesting period. Fields were also mown at various times outside the nesting period to control milk thistles *Silybum marianum* and star thistles *Centaurea solstitialis*.

A replicated study in 2001–2004 in shrublands in northwest Spain (9) found that plant biomass decreased in plots grazed by sheep or goats. **Plants:** Cover of herbaceous vegetation declined in years three and four under both goat and sheep grazing (goat grazing: decline from 35% to 21%; sheep grazing: 34% to 11%). **Implementation options:** After two years of grazing, there was no difference in total biomass in plots grazed by goats, compared to sheep (9,000–14,400 kg dry matter/ha), but, after four years, less biomass was found on plots initially grazed by goats, irrespective of current grazers (10,900–11,400 vs 14,200–14,400 kg/ha). More biomass was herbaceous in plots grazed by goats, compared to those grazed by sheep, after both two and four years, and the biggest difference was between plots consistently grazed by goats or sheep (27% vs 14% after two years; 37% vs 14% after four). After both two and four years, cover of herbaceous vegetation was higher in plots grazed by goats in the first two years, compared to those grazed by sheep (42% vs 27% after two years; 21–35 vs 17–19% after four). Heather contributed more biomass after two years on goat grazed, compared to sheep grazed plots (23% vs 13%), but there was no difference after four years (9% in all). Cover of heather did not vary between goat and sheep grazed plots (1%). Less western gorse *Ulex gallii* was found in plots grazed by goats, after two and four years (the biggest differences between plots consistently grazed by goats, compared to sheep: 14% vs 20% cover after two years; 24% vs 44% cover after four years). Gorse was a smaller percentage of plant biomass in plots grazed by goats, compared to sheep, in the first two years (46% vs 70% after two years) but not in the last two years (73% vs 53% after four years). **Methods:** Four plots (1.2 ha each) in a gorse-dominated shrubland were burned in May 2001 and then grazed by either Gallega sheep or Cashmere and local-breed goats (two plots each, 12 animals/plot). Plots were grazed in two periods: first in October 2001–January 2002 and May–November 2002, and second in May–November 2003 (at a lower stocking density) and June–October 2004. In the second seasons the plots were split in half: one half received the same treatment and the other half was grazed by the other species. Vegetation cover was measured eight times/plot (six 13 m transects). Biomass was measured at six points in 2003 and 2004 (five 0.2 m^2 transects).

A replicated, controlled study in 1997–2006 in scrub and grassland in central California, USA (10), found more ground-dwelling invertebrates in cattle-grazed plots, compared to ungrazed plots. The abundances of one of five mammals and one of three reptiles increased faster in grazed plots, compared to ungrazed plots. The abundance of one mammal species was lower in grazed plots, in some years. Less vegetation was left in grazed plots. **Invertebrates:** Fewer ground-dwelling invertebrates were found in grazed plots, compared to ungrazed plots, in six of nine years (data not provided). Abundances of grasshoppers did not differ between grazed and ungrazed plots (8–1,600 individuals/count). **Mammals:** Abundances of giant kangaroo rats *Dipodomys ingens* increased by 1.6 individuals/year in grazed plots, but did not increase in ungrazed plots. The changes in abundances of four other species did not differ between grazed and ungrazed plots. Heermann's kangaroo rats *Dipodomys heermanni* were less abundant in grazed plots in some years (0–3 vs 0–22 individuals). Abundances of San Joaquin pocket mice *Perognathus inornatus inornatus* differed between grazed and ungrazed plots, but not consistently. The abundances of three other mammals did not differ between grazed and ungrazed plots. **Reptiles:** The abundance of blunt-nosed leopard lizards increased at a greater rate in grazed plots (6.8 vs 1.4 extra individuals/year). The change in abundances of two other species, and the overall abundances of all three species did not differ between grazed and ungrazed plots. **Plants:** At the end of the grazing season, less vegetation was left in grazed plots, in eight of ten years (20–2,100 vs 900–4,000 kg/ha). **Methods:** Four 2.6 km^2 plots were established and grazed from December to leave approximately 560 kg dry matter/ha by April. Therefore, grazing intensity varied over time, and plots were not grazed at all in 2002–2004. Within each plot, a 25 ha plot was left ungrazed. Mammals were surveyed using 64 traps in each plot for six days and six nights in July–September each year. Grasshoppers and day-active lizards were surveyed visually within 9 ha grids, on ten days in May–July each year. Ground-dwelling invertebrates were monitored with pitfall traps. Vegetation was monitored on the same grids as lizards and clipped to assess biomass.

A replicated, randomized, controlled study in 1997–2006 in former farmland in central Spain (11) found that the cover of three of seven functional groups of plants differed between sheep-grazed and ungrazed plots. **Plants:** Grazed plots had lower perennial cover than ungrazed plots (14–36% perennial cover vs 26–47%). Grazed plots had lower cover of spring annuals than ungrazed plots, but only with one of three irrigation treatments (year-round irrigation: 71–79% vs 100%). This pattern was driven by large-seeded annuals, which also had lower cover with a combination of spring grazing and no irrigation (29% vs 50% for ungrazed). There were no differences in cover for the other four functional groups investigated. **Methods:** Eighteen 162 m^2 plots were established in 1997, with a combination of three grazing regimes (spring grazing in April, autumn grazing in November, or no grazing) and three irrigation regimes (none, spring and autumn, or year-round). Plots were grazed for one week each year, at 5.2 or 4.3 sheep/ha in spring and autumn, respectively. Plants were surveyed in six 50 x 50 cm quadrats in each plot, in May and September each year.

A replicated site comparison in 2007 in montane forested pastures in northwest Spain (12) found more ground beetles, and a higher diversity of ground beetles, in goat-grazed or sheep-grazed pastures, compared to ungrazed pastures. **Invertebrates:** Beetle diversity was higher in grazed pastures, compared to ungrazed pastures, in one of two groups (ground beetles, but not rove beetles: data reported as effective number of species). More ground beetles were found in grazed pastures, compared to ungrazed pastures (19–510 vs 9–220 individuals), but similar numbers of rove beetles were found (56–240). Similar communities of ground beetles, but different communities of rove beetles, were found in grazed and ungrazed sites (data reported as statistical results). **Methods:** In 2007, three grazed sites and three abandoned sites were selected (abandoned at least 20 years previously). Invertebrates were collected in June–October (10 pitfall traps/site).

A meta-analysis from 2013 of 15 studies in coastal and interior grasslands in California, USA (13), found that native grasses had higher cover in grazed grasslands, and native forbs had higher cover in grazed interior grasslands but lower cover in grazed coastal grasslands, compared to ungrazed grasslands. More species of native forbs were found in grazed grassland, compared to ungrazed grassland, but so were more species of exotic grasses, and higher cover of exotic forbs. **Plants:** More species of native forbs were found in grazed grasslands, compared to ungrazed grasslands (data reported as the response ratio of grazed to ungrazed plants: 0.14), but similar numbers of native grass species were found. Native grasses had higher cover in grazed grasslands, compared to ungrazed grasslands (response ratio: 0.13), but native forbs did not. More species of exotic grasses were found in grazed grasslands, compared to ungrazed grasslands (data reported as the response ratio of grazed to ungrazed plants: 0.11), but similar numbers of species of exotic forbs were found. Exotic forbs had higher cover in grazed grasslands, compared to ungrazed grassland (response ratio: 0.43), but exotic grasses did not. **Implementation options:** Native forbs had higher cover in grazed interior grasslands, compared to ungrazed interior grasslands (response ratio: 0.66), but they had lower cover in grazed coastal grasslands, compared to ungrazed coastal grassland (response ratio: –0.38). **Methods:** The Web of Knowledge and Google Scholar databases were searched for publications from 1923 to 2011, using the keywords, "California" and "grassland" or "prairie", or "grazing" or "livestock", and 15 replicated studies from 1997 to 2009 were meta-analysed.

A replicated, randomized, controlled study in 2008–2010 in lowland grasslands in northern California, USA (14), found that plant diversity did not differ between plots with simulated grazing and ungrazed plots. The cover of native species was lower in plots with simulated grazing, compared to ungrazed plots, for one of three plant assemblages. **Plants:** Plant diversity did not differ between plots with simulated grazing and ungrazed plots (results reported as Shannon diversity). Cover of native species was lower in plots with simulated grazing, compared to ungrazed plots, when plots were sown with native perennial grasses (17–22% vs 59% cover), but there was no difference in plots sown with two types of non-native assemblages (1–3%). **Methods:** In 2007, four experimental blocks were established across two pastures. Each block was split into three areas, sown with one of three vegetation types: native perennial grasses, non-native annual forage grasses, and a non-native, non-edible annual weed. These were then divided into six plots, which were subjected to one of three treatments, each replicated twice: no manipulation, mowing and trampling by cattle to simulate medium grazing, or to simulate heavy grazing. Plants were surveyed in a 1 m^2 quadrat in May 2008–2010.

A replicated, randomized, controlled, before-and-after study, in 2006–2011 in grasslands and oak woodlands in northern California, USA (15), found differences in the abundance of some plant species, and differences in the plant community, between grazed and ungrazed plots. One of two non-native plant species declined in grazed plots, compared to ungrazed plots, in dry years. **Plants:** One desirable forage species increased in grazed plots, but not ungrazed plots (change from 0% to 17% cover vs 1% to 0%). Another desirable forage species increased in both (change from 1% to 5–10% cover). By the end of the experiment, but not at the beginning, the plant community differed between grazed and ungrazed plots (results reported as ordination results). Cover of medusahead *Elymus caput-medusae* decreased in three dry years in grazed plots, but not in ungrazed plots (decrease from 48% to 22% cover vs increase from 44% to 52%). Overall, it decreased to similar levels in grazed and ungrazed plots (25–26%). Cover of yellow starthistle *Centaurea solstitialis* did not differ between grazed and ungrazed plots (8–18%). Two other non-native species that are poor forage increased in ungrazed plots, but not in grazed plots (ungrazed: increase from 0% to 5% and 0% to 8% cover; grazed: decrease from 2% to 0% and 1% to 0%). **Methods:** In 2006, rotational grazing at moderate stocking densities was started in 11 paddocks of 80–600 acres. Paddocks were grazed for up to two weeks in November–February and March–June. Paired 8 x 8 foot plots were established in each paddock and the plant community monitored in June 2006, 2009, and 2011.

A replicated, randomized, controlled study in 2008–2009 in pastures in northern California, USA (16), found fewer arthropods in plots with simulated grazing, compared to ungrazed plots. **Invertebrates:** Similar numbers of arthropod species were found in plots with or without simulated grazing (data not reported). Overall, fewer arthropods were found in plots with simulated grazing (data not reported). More herbivorous arthropods were found in plots with simulated grazing (79% higher volume), but more predatory arthropods were found in ungrazed plots (13% higher in ungrazed plots). Similar numbers of parasitoids or decomposers were found in plots with or without simulated grazing (data reported as log volumes). **Plants:** Similar numbers of plant species (14 species/plot), and similar amounts of plant biomass (data not reported), were found in plots with or without simulated grazing. **Implementation options:** In plots that were planted with non-native plants, the volume of arthropods was higher in plots with simulated grazing (380 vs 190 mm^3). **Methods:** In 2006, two tilled plots were planted with native bunchgrass species, and two tilled plots were sown with non-native annual grasses. In 2008–2009, simulated heavy grazing (30–45 minutes of disturbance by 40–42 cattle each spring/summer, and mowing the plots to 2 cm height, 2–3 times) was used on some sections of the plots (each 3 x 10 m). Arthropods and plants were sampled in May 2009 (suction sampling and visual surveys, respectively).

A meta-analysis from 2015 of four studies from annual rangelands in California, USA (17), found that grazing decreased the abundance of medusahead *Taeniatherum caput-medusae*. **Plants:** The abundance of medusahead was lower in plots that were grazed, compared to ungrazed, one year after grazing (reported as the response ratio of grazed to ungrazed plots: –0.7 log response ratio), but not 2–4 years after grazing. **Methods:** The Web of Knowledge, Agricola, and Digital Dissertations databases (and others managed by the University of California) were searched for publications from 1960 to 2013 (keywords not reported). Five studies from 1969 to 2011 were meta-analysed. There were four studies from California (response ratios from –2.4 to 0.4) and one study from Oregon (response ratios from 0.17 to 0.48: all positive, and so grazing decreased the abundance of medusahead only in California). Sheep or cattle were used for grazing, for 5–180 days, with an average stocking rate of 5.6 animal unit months (AUMs). The average plot size was 0.21 ha.

A replicated, controlled study in 2010–2013 in grasslands in southern France (18) found that grazing by sheep had little effect on plant communities or elmleaf blackberry *Rubus ulmifolius*. **Plants:** Similar numbers of plant species and similar plant diversity were found in grazed and ungrazed plots (17–51 species; diversity reported as Shannon indices). Bramble cover was lower in grazed plots, compared to ungrazed plots, under one of four conditions, when plots were also cut and drained (25% vs 49% cover). Bramble height was lower in grazed plots, under two of four conditions, when plots were also cut (13–14 vs 35–38 cm). Vegetation height was lower in grazed plots, under one of four conditions, when they were also cut and drained (13 vs 36 cm). **Methods:** In 2010, 48 plots (10 x 10 m) were established in two areas of grassland grazed by sheep and goats. Half of the plots were fenced to prevent grazing. Half of the plots were also cut, and half were drained using drainage ditches. The grazers were a flock of 1,100 sheep and 20 goats, for 30 days in March–April and 15 days in May–June in 2011–2013 (2.7 days/sheep/ha/year). Vegetation was monitored in May (one 5 x 5 m quadrat/plot).

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7.12. Use rotational grazing: Other biodiversity (2 studies)

- Amphibians (0 studies)
- Birds (0 studies)
- Invertebrates (0 studies)

- Mammals (0 studies)
- **Plants (2 studies):** One before-and-after study in grasslands in the USA[2] found a higher cover of native plants after the adoption of rotational grazing. One replicated, controlled study in grasslands in the USA[1] found that the density and mortality of a native plant species did not differ between plots with rotational or continuous grazing, but plants had more reproductive stems in plots with rotational grazing, in two of three years. This study also found that plants were larger under rotational grazing, in some comparisons, but smaller in other comparisons.
- Reptiles (0 studies)
- Implementation options (0 studies)

A replicated, controlled study in 1998–2000 in grasslands in north-central California, USA (1), found no difference in purple needlegrass *Nassella pulchra* mortality or density between plots with rotational grazing or continuous grazing, but there were some differences in plant size and reproduction. **Plants:** Needlegrass mortality and density did not differ between plots with rotational grazing or continuous grazing (data reported as model results). Plants in rotationally-grazed plots had more reproductive stems than plants in continuously-grazed plots, in two of three years (1.3–1.8 vs 0.4–0.5). Plants were taller under light rotational grazing, but shorter under heavy rotational grazing, compared to continuous grazing, in one of three years (data not provided). There were no differences in plant stem diameter. **Methods:** Thirty 20 x 20 m plots were grazed from January (in 1998) or December (1999, 2000) until May at a stocking density of 0.75 animal units/ha. Rotationally-grazed plots were grazed until 25% (lightly grazed) or 50% (heavily grazed) of the plant biomass was removed, and then they were rested for 35 days. Continuously-grazed plots had animals at all times. Thirty individual plants were measured each year and plant density was estimated using 3–5 quadrats/plots (1 x 1 m quadrats).

A before-and-after study in 2011–2013 in grasslands in central California, USA (2), found that native grasses increased in cattle pasture after the adoption of rotational grazing. **Plants:** More survey units had native grasses, two years after rotational grazing was adopted, compared to before (80% vs 8%). Average percentage cover increased to 3%, two years after rotational grazing was introduced, compared to 0% before (0–20% vs 0–10%). **Methods:** In 2011, cattle density in 74 plots (1–10 ha) was increased to 110–170 t/ha, with fields grazed for 1–7 days and rested for 70–120 days (depending on the time of year and pasture quality). Previously, larger fields were grazed for longer periods, with little rest between grazing periods. Vegetation cover was estimated each July, using transects of variable lengths.

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7.13. Use seasonal grazing: Other biodiversity (8 studies)

- Amphibians (0 studies)
- Birds (0 studies)
- **Invertebrates (1 study):** One replicated, randomized, controlled before-and-after study in wet grasslands in the USA[5] found more aquatic invertebrate species in continuously grazed plots, compared to seasonally grazed plots, in some comparisons.
- Mammals (0 studies)
- **Plants (8 studies)**
    - Abundance (7 studies): Five studies (one meta-analysis; four replicated, randomized, and controlled studies) in grasslands in Israel[2,8] and the USA[3,5,7] found that the cover of native or non-native plants, or the abundance of plants, differed between sites grazed at different times, in some comparisons. Two replicated, randomized, controlled studies from forested pastures in the USA[4] and former farmland in Spain[6] found no difference in plant cover between areas grazed at different times.
    - Diversity (2 studies): Two replicated, randomized, controlled studies in grasslands in Israel[2] and the USA[5] found differences in the number and/or diversity of plant species between plots that were grazed at different times, in some comparisons.
    - Survival (2 studies): One replicated, randomized, controlled study in grasslands in the USA[1] found differences in tree survival between plots grazed at different times. Another one[3] found no difference in bunchgrass survival between plots grazed at different times.
- Reptiles (0 studies)
- Implementation options (0 studies)

A replicated, randomized, controlled study in 1989–1991 in grasslands in north-central California, USA (1), found higher survival of, and less damage to, oak seedlings in plots grazed in winter, compared to plots grazed in spring or summer. **Plants:** More blue oak *Quercus douglasii* seedlings survived in winter-grazed plots, compared to spring- or summer-grazed plots (46–50% vs 7–29% survival). Seedlings in winter-grazed plots were less likely to be damaged by browsing or trampling, compared to those in spring- or summer-grazed plots (12–52% vs 40–93% of seedlings damaged). **Methods:** In December 1989, oak seedlings were planted in three pastures, each containing nine plots grazed for a week each in winter (January–February), spring (April), or summer (June–July), at one of three grazing intensities. Each plot received 24 seedlings (720 in total), of which half had the area around them treated with glyphosate herbicide to reduce competition from grass.

A replicated, randomized, controlled study in 1993–1997 in grassland in north-eastern Israel (2) (same study as (8)) found that the number of plant species and community composition varied between plots grazed by cattle in different seasons. **Plants:** Fewer plant species were found in seasonally-grazed plots, compared to continuously-grazed plots, in three of four years (28–50 vs 49–66 species/plot). Fewer plant species were found in late-grazed plots, compared to early-grazed, at moderate, but not heavy, stocking rates (28–42 vs 42–49 species/plot). Cover of annual thistles was higher for three out of four years in continuously grazed and early-grazed, compared to late-grazed plots (continuous: 4–20% cover; early: 5–18%; late: 1–11%). This effect was stronger at heavy, compared to moderate, stocking rates. Cover of crucifers was lower in late-grazed, compared to continuously grazed plots at heavy stocking rates (6–11% vs

11–20%). Other contrasts and eight other functional groups did not differ between treatments. **Methods:** In 1993, eight plots were established. Half were grazed continuously (January–October), and half were grazed seasonally. In seasonal plots, half of the plot was grazed early (January–April/May), and half was grazed late (April/May–October). In addition, half of the plots were moderately grazed (0.55 or 1.1 cow-calf pairs/ha for continuous and seasonal, respectively) and were heavily grazed (1.1 or 2.2 cow-calf pairs/ha). Plants were surveyed every spring, every two steps along permanent transects.

A replicated, randomized, controlled study in grassland in central California, USA (3), found no difference in purple needlegrass *Nassella pulchra* mortality in plots grazed by sheep in spring, compared to summer. Needlegrass density was higher in spring-grazed plots in some comparisons, and needlegrass size increased by more in spring-grazed plots, compared to summer-grazed plots. **Plants:** There was no difference in mortality between spring- and summer-grazed plots (0–15% annual mortality for all). Needlegrass density was greater in spring-grazed plots, compared to summer-grazed, when the plots were also burned (0.8–0.9 vs 0.3 plants/m^2), but not when they were unburned (0.5–0.9 plants/m^2). Average basal area of needlegrass plants increased by more in spring-grazed plots, compared to summer-grazed (86% increase vs no increase). **Methods:** In 1988–1995, eighteen 20 x 20 m plots were maintained. One-third were ungrazed, one-third were grazed by sheep in spring, and one-third were grazed in summer each year. Half of the plots were also burned in 1988, 1991, and 1994.

A replicated, randomized, controlled study in 1995–1998 in forested pastures in central California, USA (4), found no difference in plant cover on stream banks or in grassy areas in pastures grazed by cattle in the dry season, compared to the wet season. **Plants:** There was no difference in plant cover on stream banks or in the surrounding grassy areas between pastures grazed in the dry season, compared to the wet season (31–84%). **Methods:** Two pastures in each of three streams were assigned to either dry- or wet-season grazing (July–October and October/November–May, respectively). Half of each were grazed at moderate intensity, and half at high intensity (reducing stubble to 2–3 and <2 inches, respectively). Plant cover was measured in June, on 10 transects running across the streams.

A replicated, randomized, controlled before-and-after study in 2000–2003 in wet grassland in central California, USA (5), found that the number of aquatic invertebrate species and native plant species, and the cover of native and exotic plants, varied between plots grazed at different times, in some comparisons. **Invertebrates:** There were more aquatic invertebrate species in pools in continuously-grazed plots, compared to seasonally-grazed plots, in one of three years (14 vs 11–12 species). **Plants:** The number of native plant species in pool edges declined more in 2001–2003 in wet-season grazed, compared to continuously or dry-season grazed plots (pool edges: 0.5 fewer species vs 1–1.8 more species). Changes within pools and on the surrounding dry land did not differ between plots with different grazing timings. There was a higher relative cover of native species in pool edges and surrounding dry land in continuously grazed plots, compared to seasonally grazed plots (pool edges: 72% vs 53–58%; dry land: 31% vs 17–18%). There was no difference in relative coverage of native species within pools between grazing timings. There was lower cover of exotic grasses in continuously grazed plots compared to dry- and wet-season grazed plots in dry land but not in other habitats (52% vs 69–84%). **Methods:** Eighteen plots were established in 2000, each with three pools (70–1,130 m^2) and nine times more dry land than pool. Areas were grazed continuously or seasonally (dry-season: October–November; wet-season: April–June). Before the experiment, the area had been grazed for at least 100 years.

A replicated, randomized, controlled study in 1997–2006 in former farmland in central Spain (6) found that the plant cover varied between plots grazed by sheep in the spring and autumn, and this effect varied with irrigation, for two of seven functional groups of plants. **Plants:** Spring-grazed plots had lower cover of spring annuals than autumn-grazed plots, for two of three irrigation treatments (100–105% vs 81–91% cover). Spring-grazed plots had lower cover of large-seeded spring annuals, for all irrigation treatments (30–62% vs 17–51% cover). There were no differences in cover for five of seven functional groups. **Methods:** Twelve plots were established in 1997 (162 m^2 plots), with a combination of either spring grazing (April) or autumn grazing (November) and one of three irrigation regimes (none, spring and autumn, or year-round). Plots were grazed for one week each year at 5.2 or 4.3 sheep/ha for spring and autumn, respectively. Plants were surveyed in six 50 x 50 cm quadrats in each plot in May and September each year.

A meta-analysis from 2013 of 15 studies in coastal and interior grasslands in California, USA (7), found that seasonal grazing increased the cover of native plants, but continuous grazing decreased the cover of some native plants, compared to no grazing. Wet-season grazing decreased the cover of exotic grasses, compared to dry-season or continuous grazing. **Plants:** Native grasses and native forbs had higher cover with wet-season grazing, compared to no grazing (data reported as the response ratio of grazed to ungrazed plants: 0.96 for grasses; 0.44 for forbs). Native forbs also had higher cover with dry-season grazing, compared to no grazing (response ratio: 1.24), but native grasses did not. Native forbs had lower cover with continuous grazing, compared to no grazing (response ratio: −0.31), but native grasses did not. Lower cover of exotic grasses was found with wet-season grazing, compared to dry-season or continuous grazing (data not reported), but no differences were found in the cover of exotic forbs. **Methods:** The Web of Knowledge and Google Scholar databases were searched for publications from 1923 to 2011, using the keywords, “California” and “grassland” or “prairie”, or “grazing” or “livestock”, and 15 replicated studies from 1997 to 2009 were meta-analysed.

A replicated, randomized, controlled study in 1993–2012 in grassland in north-eastern Israel (8) (same study as (2)) found that plant diversity and cover varied between plots grazed by cattle in different seasons, for four of five plant functional groups. **Plants:** Plant diversity was higher under early or continuous grazing, compared to late grazing (data not reported). Cover of tall annual grasses was higher in late-grazed plots, compared to early-grazed (34% vs 14% cover), but only with moderate grazing, rather than heavy. Cover of tall perennial grasses was higher with one of six timing-intensity combinations, but this difference disappeared by the end of the study. Cover of short grasses was higher in early-grazed plots, compared to late-grazed (2–41% vs 1–24%), but similar to continuously grazed plots (1–37%). Cover of annual forbs was higher in early-grazed plots, compared to late-grazed, with moderate grazing, but not with heavy grazing (19–60% vs 4–39%). Cover of perennial forbs did not vary between grazing timings. **Methods:** In 1993, eight plots were established. Half were grazed continuously (January–October) and half were grazed seasonally. In seasonal plots, half of the plot was grazed early (January–April/May) and half was grazed late (April/May–October). In addition, half of the plots were moderately grazed (0.55 or 1.1 cow-calf pairs/ha for continuous and seasonal, respectively) and half were heavily grazed (1.1 or 2.2 cow-calf pairs/ha). Plants were surveyed every spring, every two steps along permanent transects.

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