Effects of cover crops on multiple ecosystem services: ten meta-analyses of data from arable farmland in California and the Mediterranean

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Abstract

Cover crops are considered to be beneficial for multiple ecosystem services, and they have been widely promoted through the Common Agricultural Policy (CAP) in the EU and Farm Bill Conservation Title Programs, such as the Environmental Quality Incentives Program (EQIP), in the USA. However, it can be difficult to decide whether the beneficial effects of cover crops on some ecosystem services are likely to outweigh their harmful effects on other services, and thus to decide whether they should be promoted by agricultural policy in specific situations. We used meta-analysis to quantify the effects of cover crops on five ecosystem services (food production, climate regulation, soil and water regulation, and weed control) in arable farmland in California and the Mediterranean, based on 326 experiments reported in 57 publications. In plots with cover crops, there was 13% less water, 9% more organic matter and 41% more microbial biomass in the soil, 27% fewer weeds, and 15% higher carbon dioxide emissions (but also more carbon stored in soil organic matter), compared to control plots with bare soils or winter fallows. Cash crop yields were 16% higher in plots that had legumes as cover crops (compared to controls) but 7% lower in plots that had non-legumes as cover crops. Soil nitrogen content was 41% lower, and nitrate leaching was 53% lower, in plots that had non-legume cover crops (compared to controls) but not significantly different in plots that had legumes. We did not find enough data to quantify the effects of cover crops on biodiversity conservation, pollination, or pest regulation. These gaps in the evidence need to be closed if cover crops continue to be widely promoted. We suggest that this novel combination of multiple meta-analyses for multiple ecosystem services could be used to support multi-criteria decision making about agri-environmental policy.

Keywords

catch crops; conservation agriculture; Conservation Evidence; conservation practices; evidence synthesis; green manures

1. Introduction

Cover crops are grown as an alternative to leaving the soil bare or fallow, often over the winter, and often in rotation with cash crops that are grown over the summer. In spring, the remains of cover crops are often retained on the surface of the soil, and the soil is only minimally tilled or is not tilled at all. Cover crops are also referred to as “green manures” when they are used to increase soil fertility (incorporating organic carbon and nitrogen into the soil), or as “catch crops” when they are used to retain nitrogen (“catching” nitrate before it leaches out of the soil), but they are most strictly referred to as “cover crops” when they are used to cover bare soil and thus to reduce erosion and control weeds (Pieters 1927; Pieters & McKee 1938; Thorup-Kristensen, Magid & Jensen 2003). Here, we refer to all of the above as “cover crops”.

Cover crops have a long history that goes back over 2,000 years in Europe, where legumes were ploughed into the soil by the ancient Greeks and Romans (Pieters 1927). Recently, there has been an increase in the area planted to cover crops in the United States of America (USA), and an increase in payments to farmers for growing cover crops as part of the Environmental Quality Incentives Program (EQIP) of the Natural Resources Conservation Service (NRCS) (Dunn *et al.* 2016; GAO 2017). Cover cropping was among the most popular conservation practices funded through the EQIP in 2009–2015, and payments for cover cropping increased from $15 million US Dollars in 2009 to $56 million in 2015 (GAO 2017). In the European Union (EU), cover cropping has been an option for Ecological Focus Areas (EFAs), as part of the compulsory greening measures that were introduced through the Common Agricultural Policy (CAP) in 2015. Farmers with over 15 ha of arable land have had to devote 5% of their farmed area to EFAs to qualify for full direct subsidy payments, and cover crops were grown on 28% of the land under EFAs in 2015 (Pe’er *et al.* 2017). However, a survey of ecologists suggested that cover crops may not be as effective for biodiversity conservation as other agri-environment measures, such as buffer strips or fallows (Pe’er *et al.* 2017), even though biodiversity conservation is among the objectives of EFAs (Dicks *et al.* 2014). Recent policy developments suggest that EFAs will not be retained in the CAP after 2020, but will be incorporated into required standards for good agricultural and environmental condition of land, known as “GAEC” conditions (European Commission

2018a). The new GAEC 7 requires “No bare soil in most sensitive period(s)” (European Commission 2018b). Cover crops will be an important strategy for meeting this requirement.

Reviews of the literature on cover crops have a relatively long history that goes back over 100 years (e.g., Pieters 1917; Alvarez, Steinbach & De Paepe 2017). In recent years, reviews have begun to use meta-analysis, which is a method of averaging the results from multiple experiments (Hedges, Gurevitch & Curtis 1999). Meta-analyses have shown that, on average, cover crops cause an increase in organic matter, carbon, and nitrogen in the soil, a decrease in nitrate leaching from the soil, and an increase in root colonization by mycorrhizae, but also an increase in greenhouse-gas emissions from the soil, and they have variable effects on the yields of subsequent cash crops (Miguez & Bollero 2005; Tonitto, David & Drinkwater 2006; Aguilera *et al.* 2013; Quemada *et al.* 2013; Basche *et al.* 2014; Poeplau & Don 2015; Vicente-Vicente *et al.* 2016; Bowles *et al.* 2017; Alvarez, Steinbach & De Paepe 2017).

It can be difficult to determine whether the benefits of cover crops are likely to outweigh the harms, especially when considering their effects on multiple criteria, such as soil fertility and water availability (Snapp *et al.* 2005; Roper *et al.* 2012). Moreover, cover crops can have different effects in different situations (Unger & Vigil 1998; Snapp *et al.* 2005; Vicente-Vicente *et al.* 2016). For example, water use by cover crops can be beneficial in an overly-wet climate (making the soil more workable in spring) but harmful in an overly-dry climate (competing with cash crops for water) (Unger & Vigil 1998; Vincent-Caboud *et al.* 2017). In spite of these interactions with climate, most meta-analyses of cover crops have taken a global perspective on a narrow range of ecosystem services across multiple climate types (e.g., Tonitto, David & Drinkwater 2006; Basche *et al.* 2014). In contrast, we used meta-analysis to quantify the effects of cover cropping on a wide range of ecosystem services (food production, climate regulation, soil and water regulation, and weed control) in one climate type and one farming system (arable fields in Mediterranean climates). This complements the narrative review by Shackelford *et al.* (2017). We present the results as a “dashboard” (a simple visualization of important information (Few 2006)) that could be used by decision makers to get an evidence-based overview of the effects of cover crops on multiple ecosystem services. Dashboards have recently begun to be used in sustainable development, notably in monitoring progress towards the Sustainable Development Goals (Sachs *et al.* 2016).

Five regions of the world have a Mediterranean climate: California, central Chile, southwest Australia, southwest South Africa, and much of the land around the Mediterranean Sea (Aschmann 1984; Olson *et al.* 2001). Mediterranean climates have hot, dry summers and cool, wet winters. There is at least two times as much rainfall in winter as in summer, but rainfed farming is possible in most years (Aschmann 1984). Our objective was to give an overview of the average effects of cover crops across all experimental conditions in Mediterranean arable fields. Thus, we did not explore the effects of specific species of cover crops or other variables that could moderate the effects of cover crops (e.g., soil organic carbon at different depths in the soil or after different amounts of time). However, there are other sources of information, such as the *Cover Crops Database* (Auburn & Bugg 1991) and *Cover Cropping for Vegetable Production* (Smith *et al.* 2011), both of which provide more detailed information on the agronomic effects of specific cover crops in California. For an example of multi-criteria decision making involving cover crop species, see Ramírez-García (2015). There are already some narrative reviews of the effects of cover crops on soil nitrogen and crop yields in Mediterranean climates (Shennan 1992; Roper *et al.* 2012). There are also some meta-analyses of the effects of cover crops on soil carbon in Mediterranean climates, but these meta-analyses used data from orchards or vineyards (Vicente-Vicente *et al.* 2016; Winter *et al.* 2018) or a combination of orchards and arable fields (Aguilera *et al.* 2013), whereas we isolated the data from arable fields.

2. Material and methods

Based on a recent review of farming practices and ecosystem services in Mediterranean climates (Shackelford *et al.* 2017), we expected to find data on the effects of cover crops on several ecosystem-service metrics: *soil water content* (as a measurement of water regulation); *soil nitrogen content* (as a measurement of soil regulation); *soil organic matter*, *soil microbial biomass*, and *carbon dioxide emissions* from the soil (soil and climate regulation); *soil nitrate leaching* (soil, water, and climate regulation); *food crop yields* (food production); *food crop damage* due to weeds and other pests and diseases, *weed abundance*, and *weed diversity* (weed control). We did not expect to find much data on crop *pollinators*, *natural enemies* of crop pests, or other forms of *biodiversity* (as measurements of crop pollination, pest regulation, and biodiversity conservation), but we looked for these data anyway, because these ecosystem services are targets of agri-environment schemes that include cover cropping and we wanted to systematically assess the scarcity of data on these services as a gap in our knowledge.

We searched for relevant data in the publications from a wider review of Mediterranean farming practices (not only cover cropping) (Shackelford *et al.* 2017). On 7 April 2017, we also searched the Web of Science for publications from 1900–2016 with titles, abstracts, or keywords that included "cover crop*" or "catch crop*" or "green manure" and "Mediterranean" or the name of a country that intersects with the Mediterranean Forests, Woodlands, and Scrub biome (Figure 1 and Olson *et al.* 2001). We substituted "California" for the "United States of America" and "Mexico" (Baja California), to reduce the number of irrelevant results from the non-Mediterranean parts of these countries. We also searched the bibliographies of publications that we included (see below for inclusion/exclusion criteria).

We included/excluded publications on cover crops firstly based on their titles and abstracts and secondly based on their full texts (only if the titles and abstracts were relevant). Although our search for publications was systematic, this review should be seen as a “rapid review” rather than a “systematic review” (Abou-Setta *et al.* 2016). However, we think a rapid review was more appropriate here, for the purpose of informing time-sensitive decision making about the reform of agri-environment policy (e.g., the Common Agricultural Policy).

We included and extracted data from a publication if (1) it reported the results of an experiment in the Mediterranean Forests, Woodlands, and Scrub biome (Figure 1) or the Central Valley of California, (2) it compared a winter cover crop with a winter fallow, followed by a food crop in spring or summer (annual food crops in arable fields, including cereals, fruits, and vegetables, but not perennial food crops in orchards or vineyards), and (3) it reported the mean effect on an ecosystem-service metric (Table 1).

We did not extract data for plots that were amended with green manures not grown on the same plots; plots that were inoculated with pathogens, pests, or weeds; comparisons in greenhouses or laboratories; or comparisons that were confounded by something other than tillage, mowing, herbicide, or fertilizer (the “conventional” management practices in fallow fields, to which cover crops are compared as the “alternative” management practice). For example, we did not extract data from comparisons in which compost was added only to plots with cover crops and not to plots with fallows. All comparisons were replicated, but we did not set a minimum number of replications or a minimum plot size. We did not review publications written in languages other than English or publications that were not available to us online.

We extracted data from tables and figures, using *WebPlotDigitizer* (Rohatgi 2017). If an error bar was covered by a plotting symbol, then we assumed that the height of the error bar was half of the height of the plotting symbol. Unless an overall comparison was reported, we extracted data for all comparisons between cover crops and fallows (with and without tillage, mowing, herbicide, or fertilizer), or at least the first and last comparisons in a time series (for example, multiple measurements of nitrogen in spring). We excluded duplicated data (on the same metric, in the same plots, in the same year, in different publications), if it seemed reasonable to assume that it was indeed duplicated (but differences in data reporting between publications made this difficult in some cases).

For each comparison between cover crops and fallows, we calculated the response ratio (R), using the equation $R = X_E / X_C$, where X_E was the mean value in plots with cover crops (hereafter, "experimental plots") and X_C was the mean value in plots with fallows (hereafter, "control plots"). We then calculated the natural logarithm of the response ratio (L) and its variance (v) from the standard deviations in experimental plots (SD_E) and control plots (SD_C) and the numbers of experimental plots (n_E) and control plots (n_C), using the equation $v = (SD_E^2 / (n_E * X_E^2)) + (SD_C^2 / (n_C * X_C^2))$ (Hedges, Gurevitch & Curtis 1999). If the SD was not reported, then we calculated the SD from the standard error (SE), using the formula $SD = SE * \sqrt{n}$.

If the SD and the SE were not reported, and if a P-value was reported, then we used the Z-score for that P-value (for example, if $P = 0.05$, then $Z = 1.96$) to calculate the variance, using the equation $|L| - (Z * \sqrt{v}) = 0$. In other words, we used the equation for the confidence interval, $CI = L \pm Z * \sqrt{v}$ (Hedges, Gurevitch & Curtis 1999), to set the lower or upper bound of the $(1 - P) * 100\%$ confidence interval to zero, and then we calculated v from this equation (which is conservative, because it overestimates v and thus it reduces Type I errors). If the P-value was reported as "significant" or "$P < 0.05$", then we assumed $P = 0.025$. If the P-value was reported as "not-significant" or "$P > 0.05$", then we assumed $P = 0.525$ (the midpoint of $0.05 < P < 1$). If we could not calculate the variance, using any of the above methods, then we imputed the variance, using the mean variance of all other comparisons (for that metric).

It has been suggested that it is better to include studies with missing data, by approximating or imputing the missing data, than it is to exclude these studies from meta-analyses, and it is possible to test the effects of these approximations and imputations using sensitivity analyses (Lajeunesse 2013). To test the effects of our assumptions about *P*-values, we used different combinations of *P*-values in different sensitivity analyses: $P = 0.145$ or $P = 0.905$ (the lower and upper deciles of $0.05 < P < 1$) and $P = 0.005$ or $P = 0.045$ (the lower and upper deciles of $0 < P < 0.05$). We then calculated the percentage of these sensitivity analyses that were inconsistent with the main analysis. We considered them to be inconsistent if they had effects in different directions ($R < 1$ vs $R > 1$) or of different significances ($P < 0.05$ vs $P > 0.05$). We also did a sensitivity analysis that excluded the data points with imputed variances.

For each metric (Table 1), if we had data from more than two publications, then we used the log response ratio (*L*) and its variance (*v*) as inputs into a random-effects meta-analysis, using the *metafor* package in R (Viechtbauer 2010; R Development Core Team 2017) and weighting the log response ratio by the inverse of its variance. We included random effects to account for non-independent comparisons within a publication (for example, multiple comparisons between the same plots at different time points or soil depths), using the rma.mv function from *metafor*. To report the results, we transformed the effect sizes and confidence intervals from the log response ratio (*L*) to the response ratio (*R*).

We considered plots with different species of cover crops to be independent. We also considered plots with different species of food crops, and experiments in different fields or different sites, to be independent. We used the formula “random = ~ 1 | publication/experiment” to model the non-independence of data points within publications/experiments using random effects (not to be confused with “random-effects” vs “fixed-effects” meta-analysis, and all of our models were “random-effects” models in this sense, using the rma.mv function). An “experiment” was a unique combination of cover crop species, food crop species, and field or site. We used the same random effects formula when imputing variance and assessing publication bias. We used fail-safe numbers, funnel plots, and regression tests for assessing publication bias (see File S2 for methods). We also tested for the effects of influential experiments or outliers by removing experiments, one at a time, refitting the models, and comparing the results with the those of the full model.

The effects of cover crops are likely to vary by crop type, climate type, soil type, soil depth, fertilization, irrigation, tillage, herbicide usage, and countless other variables. Our focus on arable fields in Mediterranean climates should place limits on some of this variation, and our objective here was to provide a simple synthesis of the effects of cover crops on each ecosystem-service metric, rather than a more complicated analysis of the variation in these effects (e.g., “meta-regression” using model selection to identify significant predictor variables). However, as well as calculating effect sizes across all experiments, we also calculated effect sizes for selected subgroups of experiments (experiments with different types of cover crops, different levels of tillage, or different levels of nitrogen fertilizer usage). For cover crop type, we split the dataset into three subsets: experimental plots in which the cover crops were legumes, non-legumes, or mixtures of legumes and non-legumes. For tillage, we split the dataset into four subsets: tillage in all plots (experimental and control plots), no tillage in any plots, tillage in control plots only (no tillage in plots with cover crops), or tillage in some but not all plots (e.g., split-plot experiments with aggregated results for tilled and untilled plots that could not be disaggregated). For fertilizer, we split the dataset into four subsets: fertilizer in all plots, no fertilizer in any plots, fertilizer in control plots only (to compensate for nitrogen addition in cover crops), or fertilizer in some but not all plots (e.g., split-plot experiments). We then repeated the meta-analysis for each of these subgroups for which we had data. These subgroup analyses are not intended as comprehensive analyses of heterogeneity in this dataset, but instead as “filters” for readers with different interests. For example, readers who are interested in legumes can see the effects of legumes in isolation from the effects of non-legumes (but see the Discussion for limitations).

3. Results

We analysed data from 57 publications that included data from 326 experiments and 1,062 comparisons (Table 2): 26 publications from a wider review of Mediterranean farming practices (Shackelford *et al.* 2017) and 31 publications from our new searches (see File S3 for a list of included publications and a modified PRISMA flow diagram). The data came from approximately 50 species or mixtures of cover crops, 12 food crops, and 5 countries: Italy (24 publications), the United States of America (20 publications), Spain (9 publications), France (2 publications), and Greece (2 publications).

We analysed the effects of cover crops on five ecosystem services: food production, soil regulation, water regulation, climate regulation, and weed control. We did not analyse the effects of cover crops on several other ecosystem services, because we did not find enough data. Two or fewer publications had relevant data on pollination, pest regulation, soil biodiversity, soil erosion, sediments in water, pathogens or pesticides in water, or other forms of biodiversity (other than weed diversity, which we categorized as a measurement of weed control, but which could also be considered a measurement of biodiversity conservation). The most common cash crops were maize (21 publications), tomatoes (18 publications), sweet peppers (5 publications), and lettuce (4 publications).

The results of ten meta-analyses are shown in Figure 2 (one meta-analysis for each of ten ecosystem-service metrics). Compared to plots without cover crops, plots with cover crops had 9% more organic matter (R = 1.09) and 41% more microbial biomass (R = 1.41).

However, plots with cover crops also had 13% less water (*R* = 0.87), measured in spring, before the food crops were planted. Despite these differences in soil and water, food crop yield was not significantly different between plots with or without cover crops. Weeds were 27% less abundant in plots with cover crops (*R* = 0.73). This included measurements of weed biomass, cover, and density. Weed diversity and food crop damage were not significantly different between plots with or without cover crops, but 15% more carbon dioxide was emitted by plots with cover crops (*R* = 1.15).

We had to make assumptions about the *P*-values for 78% of the comparisons in these meta-analyses (Table 2), because they were not reported in the publications. When we changed these assumptions, to analyse the sensitivity of the results, the average effect sizes did not change from significant to insignificant, from positive to negative, or *vice versa*, for any of the metrics reported above (or in the sensitivity analyses in which we excluded data points with imputed variances). Therefore, the above results were robust to these assumptions. However, the results for soil nitrogen content were not robust to these assumptions. Although plots with cover crops had 22% less inorganic nitrogen (*R* = 0.78) in the main analysis, there was no significant difference in soil nitrogen content in 50% of the sensitivity analyses in Table 2, or in the sensitivity analysis in which we excluded data points with imputed variances. The results for soil nitrogen content could also be sensitive to publication bias, since the fail-safe number was relatively low (File S2). Thus, the results for soil nitrogen content should be seen as inconclusive, and so should the results for soil nitrate leaching (plots with cover crops had significantly less nitrate leaching than plots without cover crops in 50% of the sensitivity analyses in Table 2).

None of the results for any of the meta-analyses changed from significant to non-significant when we removed experiments, one at a time, and refit the models, except for carbon dioxide emissions and weed abundance. Thus, the results seem to be insensitive to the effects of individual experiments, except for carbon dioxide emissions and weed abundance. For carbon dioxide emissions, 15% of experiments had influential effects (the results changed from significant to non-significant when we removed these experiments). For weed abundance, 3% of experiments had influential effects. We note also that there was significant heterogeneity between experiments (File S4), and this suggests that cover crops have different effects in different situations, even when considering only Mediterranean climates.

Legumes and non-legumes had opposite effects on food crop yield (Figure 3). Compared to plots without cover crops, food crop yield was 16% higher ($R = 1.16$) in plots with cover crops that were legumes. In contrast, food crop yield was 7% lower ($R = 0.93$) in plots with cover crops that were non-legumes, compared to plots without cover crops. Soil nitrogen content was 42% lower ($R = 0.58$), and soil nitrate leaching was 53% lower ($R = 0.47$) in plots with non-legume cover crops, compared to plots without cover crops, but soil nitrogen content and soil nitrate leaching were not significantly different between plots with legume cover crops and plots without cover crops. Mixtures of legumes and non-legumes had intermediate and non-significant effects on food crop yield and soil nitrogen content.

Fertilizer and tillage did not change the direction of the effects that cover crops had on ecosystem-service metrics. Subsets of the data with different levels of tillage (Figure S1) had effect sizes that were in a consistent direction (i.e. all positive or all negative, if they were significant), as did subsets of the data with different levels of fertilizer (Figure S2). However, the effect sizes were significant in only some of these subsets. For example, weed abundance was significantly lower in plots with cover crops, compared to plots without cover crops, but only in experiments with “no N added”. Furthermore, some effect sizes that were non-significant in the main analyses were significant in some subgroup analyses. For example, soil nitrate leaching was significantly lower in plots with cover crops, compared to plots without cover crops, in experiments with “N added to all plots” or “tillage in all plots”.

Several of the subgroups had data from only one or a few experiments, and the effect sizes for these subgroups should be considered inconclusive.

The funnel plots for many of the meta-analyses were significantly asymmetrical (File S2). However, for studies with missing data on variance, our formula for approximating variance (see above) could have created a spurious correlation between effect size and variance. For example, for effect sizes with approximate *P*-values (e.g., those reported as “significant” or “$P < 0.05$”), our formula would have created a perfect correlation between effect size and variance. Therefore, the funnel plots and regression tests, which are conventionally used to test for publication bias, are not necessarily very informative for these meta-analyses. Although they could suggest publication bias, it is unlikely that this bias would have changed the significances of the mean effect sizes in these meta-analyses, based on the fail-safe numbers that we calculated, with the exception of the meta-analysis on soil nitrogen content (File S2). Therefore, we note that many of the funnel plots were significantly asymmetrical, but we do not think the results of most of these meta-analyses should be seen as sensitive to publication bias.

4. Discussion

4.1 Trade-offs between ecosystem services

We found several trade-offs between and within ecosystem services, as a consequence of growing winter cover crops in in arable fields with Mediterranean climates: trade-offs between soil regulation and water regulation (more organic matter and microbial biomass but less water), trade-offs between weed control and water regulation (fewer weeds but less water), trade-offs within water regulation (less water but less nitrate leaching), trade-offs within soil regulation (more organic matter and microbial biomass but less inorganic nitrogen), and trade-offs within climate regulation (more organic matter, but more carbon dioxide and less inorganic nitrogen).

Some of these trade-offs could be minimized by identifying and implementing the best management practices. For example, by suppressing cover crops at the optimal time in spring—late enough to reduce nitrate leaching in the spring rains, but early enough to reduce competition with the cash crop for water—the trade-off between soil water content and soil nitrate leaching could be minimized (Kaye & Quemada 2017). However, if trade-offs cannot be minimized through management practices, then decision makers will need to prioritize some ecosystem services above others, when deciding whether or not cover crops should be grown in specific situations. Our objective here was to give a simple overview of the effects of cover crops on multiple ecosystem services, but future research could focus on other management practices in combination with cover crops, and move towards a more complex and mechanistic synthesis (not necessarily for policy makers) that would consider the optimal selection of cover crop species and management practices (e.g., Storkey *et al.* 2015; White *et al.* 2017).

4.2 Trade-offs could be masked by management practices

When we analysed all cover crops together, we found that cover crops did not significantly change the yields of the food crops that followed them. On average, this suggests that cover crops could be used to provide additional ecosystem services, without causing significant trade-offs between food production and these additional services. However, when we analysed leguminous and non-leguminous cover crops separately, we found that legumes increased food crop yields and non-legumes decreased food crop yields (but also decreased nitrate leaching). Thus, legumes and non-legumes could cause opposite trade-offs between food production and nitrate leaching.

In one meta-analysis, Miguez *et al.* (2005) also found that leguminous cover crops increased the yields of food crops (maize), but in another meta-analysis Tonitto *et al.* (2006) did not. Tonitto *et al.* only included data from control plots that were fertilized and experimental plots (with legumes) that were not fertilized (i.e. experimental plots that used legumes to reduce or replace fertilizer use). Miguez *et al.* found that leguminous cover crops increased maize yields in plots with less than about 150 kg N/ha from fertilizer but decreased yields in plots with more than that. This suggests that the effects of cover crops on food crops might be masked by other management practices, such as using legumes to reduce or replace fertilizer use. In almost all of the experiments in our analysis, cover crops were not used to replace synthetic fertilizer (fertilizer was added to both experimental and control plots; see Figure S2).

Because food crop yields are limited by water shortages in Mediterranean climates (Austin *et al.* 1998), it would seem remarkable that we found a decrease in soil water content but not a decrease in food crop yield. However, of the 38 publications from which we extracted data on food crop yield, only two publications reported that the food crops were not irrigated. This suggests that the effects of cover crops on food crops (through their effects on soil water content) might also be masked by other management practices (irrigation that could have compensated for water use by the cover crops). However, we extracted data on soil water content in spring only (before irrigation), and so we cannot comment on the effect of cover crops on soil water content throughout the growing season.

We also found a decrease in weed abundance (and a decrease in food crop damage in some analyses), but not an increase in food crop yield. In 10 of the 13 publications from which we extracted data on weed abundance, weeds were controlled through herbicide usage or tillage over the summer. This suggests that, after herbicide usage or tillage, weed abundance was not high enough to affect food crop yield, whether or not the cover crops provided additional weed control.

Thus, we found three examples of effects on food crop yields that could potentially be masked by other management practices. Whereas cover crops might decrease food crop yields in the absence of irrigation (by competing for water), they might also increase food crop yields in the absence of fertilization (by increasing soil organic matter and nitrogen content) and increase food crop yields in the absence of herbicide-usage or other forms of weed control. Therefore, in evaluating the trade-offs between multiple ecosystem services, decision makers should consider not only the explicit trade-offs (those that we analysed) but also the implicit trade-offs that might be masked by other management practices, such as an implicit trade-off between irrigation and fertilization. Policies for cover cropping might need to be integrated with policies for other management practices.

4.3 Limitations of the results on climate regulation

We found that cover crops increased carbon dioxide emissions, but this result should be interpreted with extreme caution and considered in the context of other effects on climate regulation, such as an increase in soil carbon storage in organic matter. A meta-analysis by Basche *et al.* (2014) found that cover crops increased nitrous oxide emissions. However, a meta-analysis by Han *et al.* (2017) found that cover crops decreased nitrous oxide emissions while the cover crops were growing, and might also have decreased them throughout the growing season, when considering the total amounts of nitrogen that were added (in many studies, the amount of nitrogen fertilizer was not reduced to compensate for the nitrogen in the cover crops, and the amount of nitrogen in the cover crops was positively correlated with nitrous oxide emissions).

A careful calculation of the net-effects of cover crops on climate regulation is beyond the scope of this publication, but Kaye *et al.* (2017) concluded that cover crops could help to mitigate climate change though several mechanisms: reducing fertilizer usage (fertilizer production is energy intensive and thus it increases greenhouse-gas emissions, but it could be reduced or replaced by leguminous cover crops), increasing the reflectiveness of the soil (reducing heat absorption), increasing soil carbon storage, and reducing greenhouse-gas emissions from the soil. In their calculations, the most important variables were fertilizer usage and carbon storage, not greenhouse-gas emissions.

Therefore, our results on carbon dioxide emissions should not be seen as evidence that cover crops are counterproductive for climate regulation. On the contrary, we found an increase in soil organic matter in plots with cover crops, which could be seen as evidence of an increase in carbon sequestration (most organic matter is carbon, and carbon accumulates only when inputs exceed outputs). We also found a decrease in inorganic soil nitrogen, which could be seen as a trade-off between climate regulation and soil fertility regulation, if it leads to an increase in fertilizer use (and indeed this effect was significant only for “N added to all plots” in Figure S2). However, nitrogen is stored not only in the soil but also in the cover crops, and nitrogen becomes available to other plants as the cover crops decompose. Thus, a decrease in inorganic soil nitrogen in the spring could be counterbalanced by an increase in the summer (as cover crops decompose), and there could be no need to increase fertilizer use (unless the food crop needs a lot of nitrogen at the beginning of the growing season). However, we extracted data on soil nitrogen content in spring only (like soil water content), and so we cannot comment on the effect of cover crops on the nitrogen cycle throughout the growing season.

4.4 Other limitations of these results

There are also other limitations that should be considered when using these results. For example, readers may only be interested in results from experiments with specific management practices or local conditions (e.g., cover crops grown in combination with inorganic fertilizer usage or tillage). Where there is enough data, we show how different management practices can interact with the effects of cover crops (e.g., Figures S1–S2). For example, if readers are interested in the effects of cover crops in experiments that used inorganic fertilizer, they can refer to the relevant subgroup in Figure S2 (e.g., “N added to all plots”). However, if readers are only interested in combinations of subgroups that we do not show here (e.g., experiments that both used inorganic fertilizer and also used no tillage), then these meta-analyses may not be relevant to them. Readers should also consider the limitations in the quantity and quality of the data (e.g., few data points for some ecosystem services, such as weed diversity; many assumptions about missing data, such as those shown in Table 2; and limitations in the time of data collection, such as soil water content in spring only).

With these limitations in mind, if readers are interested in “conventional” agriculture (with inorganic fertilizer and conventional tillage), then the subgroups for “N added to all plots” and “tillage in all plots” are likely to be the most relevant (Figures S1–S2). Likewise, if readers are interested in “conservation” agriculture (with cover crops and no tillage), then the subgroups for “no tillage” and “tillage in control plots” are likely to be the most relevant, and if they are interested in using legumes to replace inorganic fertilizer, then the subgroup for “N in control plots” is likely to be the most relevant (e.g., “organic” agriculture). Nevertheless, meta-analyses are always generalizations, and decision makers should consider the relevance of these generalizations to their specific situations. If their interests are very specific, then meta-analyses may not be relevant to them at all. We can envision an interactive database that would allow decision makers to filter the data for a meta-analysis and automatically recompute the results, using only the data that are relevant to their decisions (e.g., selecting data points by cover crop type, fertilizer usage, tillage, etc.). Such a database is beyond the scope of our work here, but it may be available in the near future (www.metadataset.com). Our analyses of a few selected subgroups are a small step towards this vision, but it is not practical for us to show all possible combinations of subgroups in the present format.

4.5 Cover crops and wildlife

The effects of cover crops on pollinators, natural enemies, and other forms of biodiversity have only rarely been studied in Mediterranean climates (Shackelford *et al.* 2017), and we did not find enough data to analyse these outcomes. We would argue that this is a wide gap in the evidence base, and field experiments should be designed to test the effects of cover crops on wildlife, especially if cover crops are to be promoted through agricultural policy. Crop pollinators and natural enemies of crop pests are more abundant on farms with higher plant and habitat diversity (Shackelford *et al.* 2013). Therefore, if cover crops increase the plant or habitat diversity of a field, whether in space or in time, then they might also increase the biodiversity of the farm. Cover crops are grown for more of the year than cash crops in some fields (Campiglia, Mancinelli & Radicetti 2011), and therefore cover crops could be more representative of the habitats that are available for wildlife in some fields. Crop diversification has been suggested as a high priority for wildlife conservation in the Mediterranean (Sokos *et al.* 2013).

4.6 Comparison of meta-analysis and expert assessment as decision-support tools

We summarized the results of ten meta-analyses (Figure 2) in a simple dashboard (Figure 4). This dashboard complements the information from a wider review of Mediterranean farming practices that is freely available through Conservation Evidence at www.conservationevidence.com (Shackelford *et al.* 2017). Conservation Evidence provides information about agricultural practices in Mediterranean farmland (not only cover cropping), in the form of short summaries of scientific studies that have tested the effects of these practices. The website also provides expert assessments of the effectiveness of each practice, based on the interpretation of the evidence in these short summaries by a group of experts, using a modified Delphi method (Sutherland *et al.* 2018). By comparison, this meta-analysis provides information about only one practice (cover cropping), but at a higher level of resolution (e.g., effects of cover crops on "soil water content" and "soil nitrate leaching" vs effects on "water") and in the form of average effect sizes (e.g., +9% soil organic matter).

In the expert assessment, cover crops in arable fields were assessed as "likely to be ineffective or harmful" for food production, which agrees with "no significant difference" in food production in the meta-analysis. They were assessed as "beneficial" for soil regulation, which agrees with the increase in soil organic matter and soil microbial biomass in the meta-analysis. They were assessed as "likely to be beneficial" for climate regulation, which is difficult to compare to the meta-analysis (more organic matter [potentially stored carbon] and less nitrogen [potentially less nitrous oxide] but higher carbon dioxide emissions). They were assessed as a "trade-off between benefits and harms" for water regulation, which agrees with the decrease in water content but also the decrease in nitrate leaching in the meta-analysis. They were "likely to be beneficial" for pest regulation, which agrees with the decrease in weed abundance and food crop damage in the meta-analysis.

Thus, there was good agreement between the meta-analysis and the expert assessment (even though the expert assessment was based on less than half as many publications). However, we think these two decision-support tools will be useful to different people for different purposes, and each of them has its own comparative advantages. For example, the effect sizes that were output by the meta-analysis could be used as inputs into a model that optimizes the trade-offs between multiple ecosystem services (e.g., Storkey *et al.* 2015). Effect sizes at a higher resolution (e.g., +9% soil organic matter) could be more useful for this purpose than expert assessments at a lower resolution (e.g., “beneficial” for “soil”).

Combined with effect sizes for other agricultural practices (e.g., adding compost to the soil, or planting hedgerows), these effect sizes could be used to decide which combination of practices are the “best management practices” for a field, farm, or landscape. In other words, the results of multiple meta-analyses could be used as inputs into a multi-criteria decision analysis (Langemeyer *et al.* 2016). Indeed, we can imagine an evidence-based tool for deciding which agri-environment measures should be prioritized, based on multiple meta-analyses of the effects of multiple agri-environment measures on multiple ecosystem services.

4.7 Other assessments of multiple ecosystem services from cover crops

Our method of using multiple meta-analyses is not the only method of assessing the multifunctionality of cover cropping. For example, multiple ecosystem services are beginning to be studied simultaneously in field trials of cover crops (Finney *et al.* 2017). Although it was not done in the Mediterranean, this study found that cover crops promoted weed suppression and nitrogen retention as a “bundle” of ecosystem services, which agrees with our results. Another study of the same farming system (in Pennsylvania) used a combination of simulation modelling, literature reviewing, and expert opinion to assess the multifunctionality of cover crops (Schipanski *et al.* 2014). These other methods of assessing multifunctionality seem useful, but an advantage of our method—using evidence synthesis and meta-analysis—is that it is already an accepted method of informing policy that is rigorous and transparent (Donnelly *et al.* 2018), and it can be generalized to any subject that can be quantitatively reviewed.

5. Conclusions

We used multiple meta-analyses to provide evidence of the effects of one management practice (growing cover crops) on multiple ecosystem services, in the form of an information dashboard that can be used to inform agri-environmental policy. This evidence could be used when reforming the Common Agricultural Policy (CAP) in the EU and Farm Bill Conservation Title Programs in the USA. For some of these ecosystem services, we found trade-offs (e.g., soil and water regulation). For others, we found co-benefits (e.g., soil regulation and weed control). However, some of the effects of cover crops may have been masked by the effects of other management practices that were used in combination with cover crops (e.g., using inorganic fertilizer, herbicide, or irrigation water). Other effects may have been biased by the time they were measured (e.g., soil water content and soil nitrogen content were measured in spring, but not in summer). Moreover, we found almost no data on the effects of cover crops on wildlife, pollination, erosion control, and several other ecosystem services. These are conspicuous gaps in our knowledge, and field experiments should be designed (or long-term experiments should be modified) to close these gaps. Nevertheless, we are optimistic about the prospect of using the outputs of multiple meta-analyses as inputs into decision-support tools (together with meta-analyses of other agricultural practices and other ecosystem services) to identify the "best management practices" for a set of ecosystem services, or to identify practices that should be prioritized through agri-environment schemes, based on the best available evidence.

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Figures

Figure 1. The Mediterranean Forests, Woodlands, and Scrub biome from the Terrestrial Ecoregions of the World (Olson *et al.* 2001) are shown in red (File S1). Parts of the following countries intersect with the Natural Earth (www.naturalearthdata.com) map of the countries of the world: Albania, Algeria, Australia, Bosnia and Herzegovina, Bulgaria, Chile, Croatia, Cyprus, Egypt, France, Greece, Iraq, Israel, Italy, Jordan, Kosovo, Lebanon, Libya, Macedonia, Malta, Mexico, Monaco, Montenegro, Morocco, Palestine, Portugal, San Marino, Slovenia, South Africa, Spain, Syria, Tunisia, Turkey, and the United States of America.

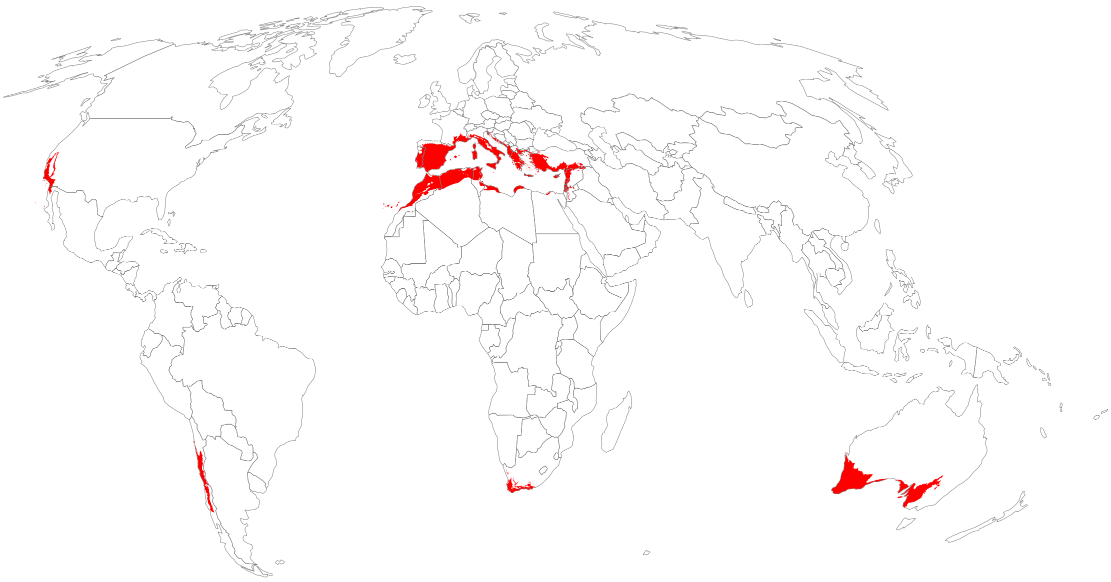
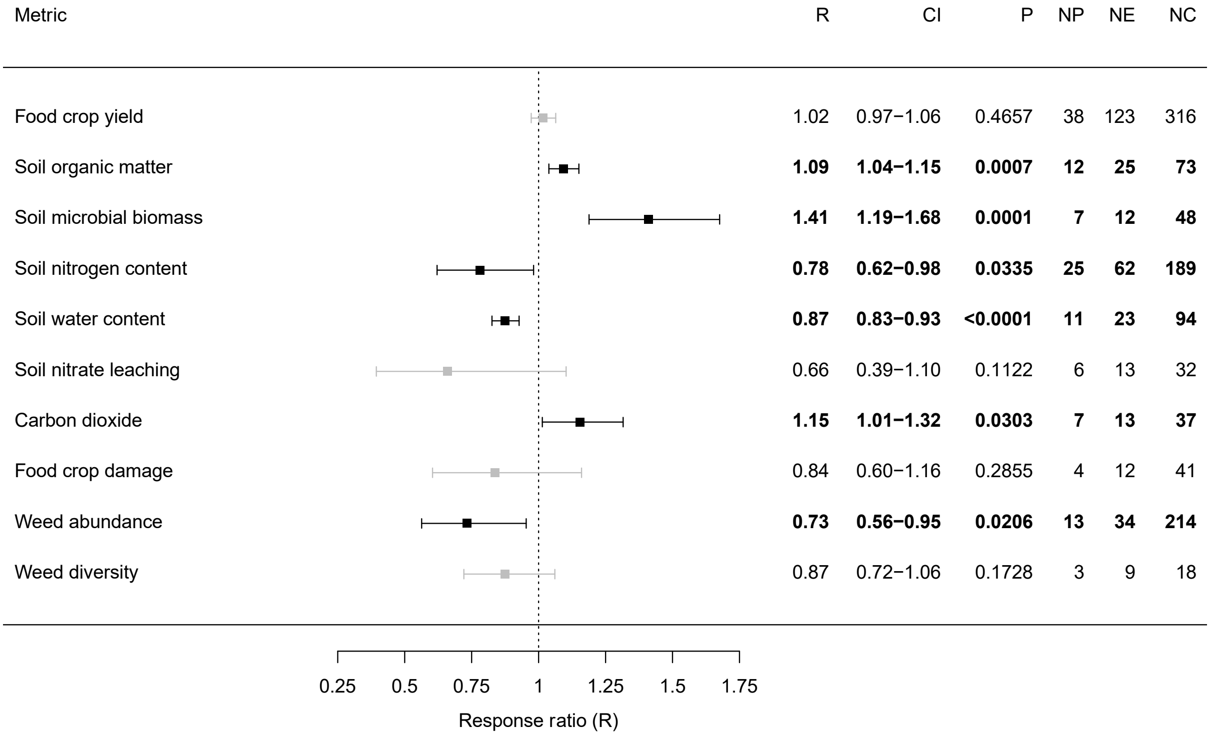
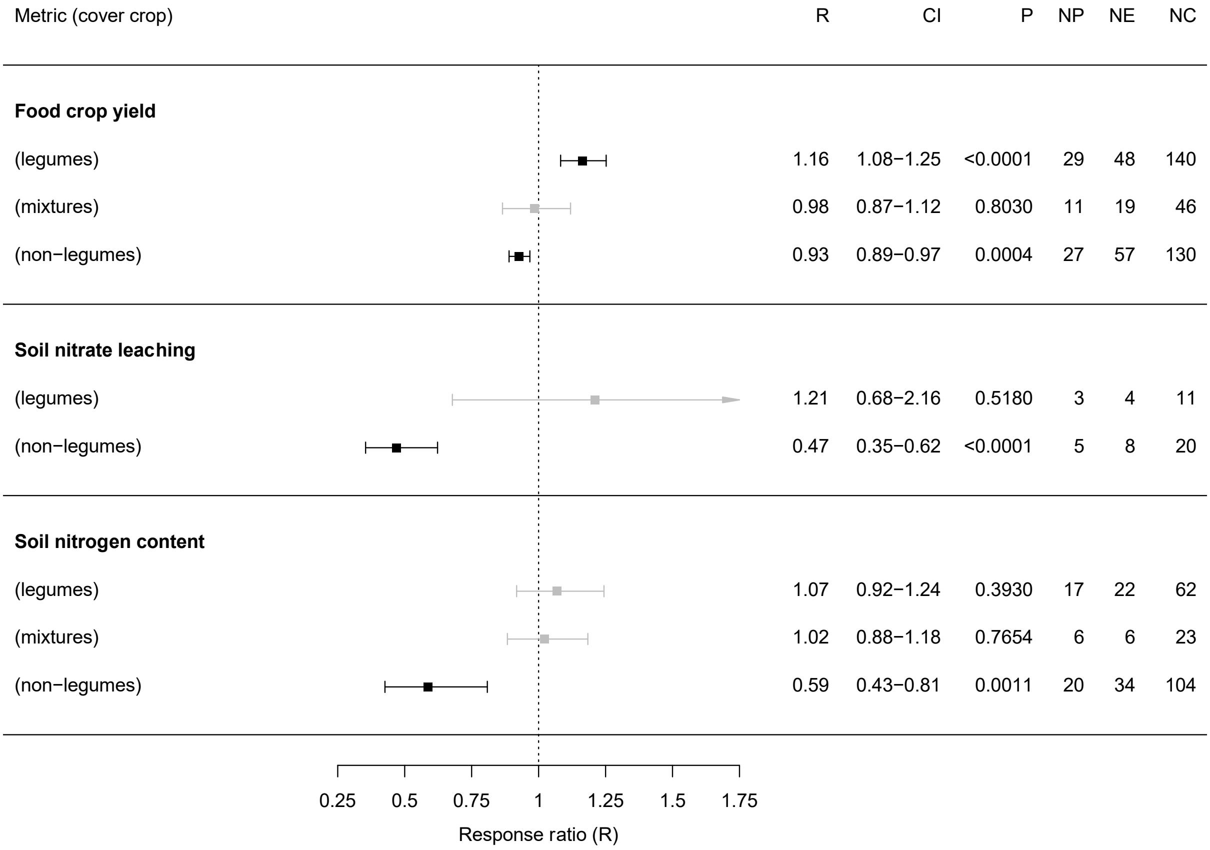


Figure 2. Effects of winter cover crops in arable fields with Mediterranean climates. The effect size is the response ratio (*R*), where *R* = the mean value in plots with cover crops divided by the mean value in plots without cover crops. An effect is significant ($P < 0.05$) if its 95% confidence interval (CI) does not include 1. The confidence intervals are not symmetrical around the effect sizes, because they were back-transformed from the log response ratio (*L*). NP is the number of publications, NE is the number of experiments, and NC is the number of comparisons for each metric. The symbols are black for significant effects and grey for non-significant effects.



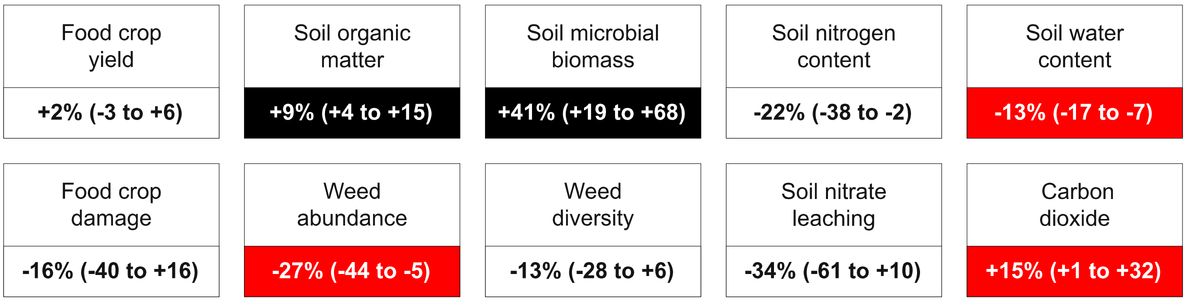
Metric	R	CI	P	NP	NE	NC
Food crop yield	1.02	0.97−1.06	0.4657	38	123	316
Soil organic matter	**1.09**	**1.04−1.15**	**0.0007**	**12**	**25**	**73**
Soil microbial biomass	**1.41**	**1.19−1.68**	**0.0001**	**7**	**12**	**48**
Soil nitrogen content	**0.78**	**0.62−0.98**	**0.0335**	**25**	**62**	**189**
Soil water content	**0.87**	**0.83−0.93**	**<0.0001**	**11**	**23**	**94**
Soil nitrate leaching	0.66	0.39−1.10	0.1122	6	13	32
Carbon dioxide	**1.15**	**1.01−1.32**	**0.0303**	**7**	**13**	**37**
Food crop damage	0.84	0.60−1.16	0.2855	4	12	41
Weed abundance	**0.73**	**0.56−0.95**	**0.0206**	**13**	**34**	**214**
Weed diversity	0.87	0.72−1.06	0.1728	3	9	18

Figure 3. Effects of leguminous and non-leguminous winter cover crops on the yield of food crops, the nitrogen content of the soil (measured in in spring), and the amount of nitrogen that was leached from the soil (measured at any time) in arable fields with Mediterranean climates. Please see Figure 2 for more information.



Metric (cover crop)	R	CI	P	NP	NE	NC
Food crop yield						
(legumes)	1.16	1.08−1.25	<0.0001	29	48	140
(mixtures)	0.98	0.87−1.12	0.8030	11	19	46
(non−legumes)	0.93	0.89−0.97	0.0004	27	57	130
Soil nitrate leaching						
(legumes)	1.21	0.68−2.16	0.5180	3	4	11
(non−legumes)	0.47	0.35−0.62	<0.0001	5	8	20
Soil nitrogen content						
(legumes)	1.07	0.92−1.24	0.3930	17	22	62
(mixtures)	1.02	0.88−1.18	0.7654	6	6	23
(non−legumes)	0.59	0.43−0.81	0.0011	20	34	104

Figure 4. Effects of winter cover crops in arable fields with Mediterranean climates: a dashboard for decision making. Effects are shown as percent increases or decreases (±X%), compared to not growing a cover crop (100%). Statistically significant effects are on a black background if they are “good” outcomes or a red background if they are “bad” or “complicated” outcomes for farming and the environment in Mediterranean ecosystems (in our opinion). Statistically non-significant effects are on a white background (as is soil nitrogen content, which was not robust to sensitivity analysis). Note that climate regulation is not only a function of carbon dioxide emissions, but also carbon storage (soil organic matter), fertilizer usage, and other factors.



Food crop yield	Soil organic matter	Soil microbial biomass	Soil nitrogen content	Soil water content
+2% (-3 to +6)	**+9% (+4 to +15)**	**+41% (+19 to +68)**	**-22% (-38 to -2)**	**-13% (-17 to -7)**
Food crop damage	Weed abundance	Weed diversity	Soil nitrate leaching	Carbon dioxide
-16% (-40 to +16)	**-27% (-44 to -5)**	**-13% (-28 to +6)**	**-34% (-61 to +10)**	**+15% (+1 to +32)**

Tables

Table 1. Ecosystem-service metrics (based on Shackelford *et al.* (2017)). We searched for publications that tested the effects of winter cover crops on any of these metrics. The metrics for which we found relevant data in more than two publications are underlined.

Ecosystem service	**Metric**
Biodiversity conservation	Taxa not reported in other metrics (e.g., not microbes, which are reported in "Soil microbial biomass"): abundance, species richness, and other diversity metrics (e.g., evenness, beta diversity)
Food production	**Food crop yield** by area (e.g., t ha^{-1})
Climate regulation	**Carbon dioxide** (CO$_2$) emitted from the soil or measured in the soil (including soil respiration)
Pest and weed regulation	Pest regulation by natural enemies (e.g., parasitism rates)
Pest and weed regulation	**Food crop damage** by pests and diseases (e.g., plants killed by to weeds or diseases)
Pest and weed regulation	Pest numbers: abundance and diversity (including **weed abundance** and **weed diversity**)
Pest and weed regulation	Natural enemy numbers: abundance and diversity
Pollination	Pollination: changes in the yield or 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 regulation	**Soil organic matter** (including soil organic carbon)
Soil regulation	**Soil nitrogen content** (inorganic/mineral nitrogen): nitrate (NO$_3$), or ammonium (NH$_4$), measured in spring, when the cover crop was suppressed or anytime thereafter, but before the food crop was planted
Soil regulation	Other soil nutrients: phosphorus (P), phosphate (PO$_4$), potassium (K), and pH, measured in spring, before the food crop was planted
Soil regulation	**Soil microbial biomass**: microbial biomass carbon or nitrogen
Soil regulation	Other soil organisms: abundance and diversity (including earthworms, mites, nematodes, and springtails)
Soil regulation	Soil erosion and aggregation: soil lost to wind or water, and aggregate stability
Water regulation	**Soil water content**: measured in spring, when the cover crop was suppressed or anytime thereafter, but before the food crop was planted
Water regulation	**Soil nitrate leaching** (e.g., nitrate content in the leachate, in lysimeters)
Water regulation	Pathogens and pesticides in water or leaching from the soil
Water regulation	Sediments in water

Table 2. The number of publications, experiments (independent data), and comparisons (independent and non-independent data), and the percentage of comparisons for which the variance was imputed ("V imputations") or the *P*-value was assumed ("P assumptions"). Missing variance values were imputed from the mean variance and missing *P*-values were assumed to be different values in different sensitivity analyses (e.g., $P = 0.025$ if reported as "significant"). "Sensitivity" is the percentage of four sensitivity analyses in which the significance of the effect size (R) differed from that shown in Figure 2 for that metric. The direction of the effect ($R > 1$ or $R < 1$) did not differ between any of the sensitivity analyses and that shown in Figure 2. The sensitivity analyses tested the effects of our assumptions about *P*-values that were not reported as exact values ("P assumptions").

Metric	Publications	Experiments	Comparisons	V imputations	P assumptions	Sensitivity
Food crop yield	38	123	316	2%	85%	0%
Soil organic matter	12	25	73	3%	75%	0%
Soil microbial biomass	7	12	48	0%	67%	0%
Soil nitrogen content	25	62	189	1%	60%	50%
Soil water content	11	23	94	21%	47%	0%
Soil nitrate leaching	6	13	32	16%	75%	50%
Carbon dioxide	7	13	37	0%	51%	0%
Food crop damage	4	12	41	0%	100%	0%
Weed abundance	13	34	214	1%	99%	0%
Weed diversity	3	9	18	6%	94%	0%
Totals	57	326	1062	4%	78%	

Supplementary material

File S1. The Mediterranean Forests, Woodlands, and Scrub biome as a KML file (Keyhole Markup Language) for use in Google Earth.

File S2. Assessment of publication bias (fail-safe numbers, funnel plots, and regression tests).

File S3. Modified PRISMA diagram and list of publications from which we extracted data for meta-analysis.

File S4. Assessment of heterogeneity (Q-values).

File S5. Data used for meta-analysis.

Figure S1. Meta-analyses for subgroups with different levels of tillage in spring, before planting the cash crop.

Figure S2. Meta-analyses for subgroups with different levels of nitrogen fertilizer.