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Evidence that organic farming promotes pest control

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Ecological intensification of agro-ecosystems, based on the optimization of ecological functions such as biological pest control, to replace agrochemical inputs is a promising route to reduce the ecological footprint of agriculture while maintaining commodity production. However, the performance of organic farming, often considered as a prototype of ecological intensification, in terms of pest control remains largely unknown. Here, using two distinct meta-analyses, we demonstrate that, compared to conventional cropping systems, (i) organic farming promotes overall biological pest control potential, (ii) organic farming has higher levels of overall pest infestations but (iii) that this effect strongly depends on the pest type. Our study shows that there are lower levels of pathogen infestation, similar levels of animal pest infestation and much higher levels of weed infestation in organic than in conventional systems. This study provides evidence that organic farming can enhance pest control and suggests that organic farming offers a way to reduce the use of synthetic pesticide for the management of animal pests and pathogens without increasing their levels of infestation.

Increased crop production over the past decades has relied on the use of synthetic agrochemicals, as well as cropland expansion, both of which have strong negative impacts on the environment and human health[1,2]. Such unsustainable models need to shift towards agricultural systems that combine low ecological footprints with commodity production to ensure long-term food security[3]. One approach that promises synergies between high yields and reduced environmental externalities is the concept of ecological intensification[4]. It is based on optimizing the ecological functions that support ecosystem services to increase the productivity of agro-ecosystems[5]. Among the ecosystem services supported by biodiversity, biological pest control is a critical service that impacts crop productivity and that could significantly contribute to the reduction in use of agrochemicals. However, large-scale implementation of farming systems that enhance ecological processes and services requires the identification of beneficial practices and assessment of the performance of such systems[6].

Organic farming is a certified production system based on the principle of using farming practices that are expected to enhance ecological processes while prohibiting the use of external synthetic inputs[7]. It is currently one of the most widespread and rapidly growing alternative farming systems often considered as a prototype of ecological intensification[6,8]. However, even though certification of organic farming has obligations around practices, it has no obligations with respect to ecological processes or environmental impacts. Whereas provisioning services[9,10], as well as some regulating services such as carbon sequestration[11] and pollination[12] are well studied in organic cropping systems, other important ecological functions and ecosystem services supported by biodiversity in organic farming remain poorly explored[13]. Quantifying the actual performance of organic farming in terms of regulating services such as biological pest control is crucial to understand the potential of ecological intensification to reduce pesticide use[14].

Substantial evidence indicates that organic farming has generally positive but context-dependent impacts on local biodiversity[15–18]. This suggests that organic farming systems most likely support higher biodiversity-mediated ecosystem services such as pollination or soil organic matter decomposition[12,19]. However, the lower productivity of organic agriculture[9,10] suggests that such farming systems may face several limiting factors, such as nutrient limitation, or may be plagued by ecosystem disservices, such as higher levels of pest infestation or weed competition.

It remains unclear how organic farming affects the balance between biological control potential and pest infestation. On the one hand, it has been suggested that farming systems under organic management experience higher pest pressures than conventional ones using pesticides due to lower efficiency of organic pest control practices[20]. On the other hand, several studies have found lower levels of pest infestation in organic farming systems due to either farming practices that limit pest establishment and development (for example, crop rotation) and/or positive impacts of organic management on natural enemies[18,21,22]. Analysing the balance between ecosystem services and disservices for organic agriculture, and specifically between biological pest control and pest infestation, is thus needed to inform agricultural policies, land use management and farmer decision-making[6,23]. Here, we hypothesized that, on average, organic farming promotes biological control of pests owing to higher abundance or diversity of natural enemies[15–18]. However, we expected higher levels of pest infestations in fields under organic farming compared to conventional farming because the positive effects of organic practices on biological pest control were expected to be insufficient to compensate for the negative effects of synthetic pesticides on pests in conventional systems.

Our study provides the first comprehensive synthesis of the performance of organic and conventional farming systems in

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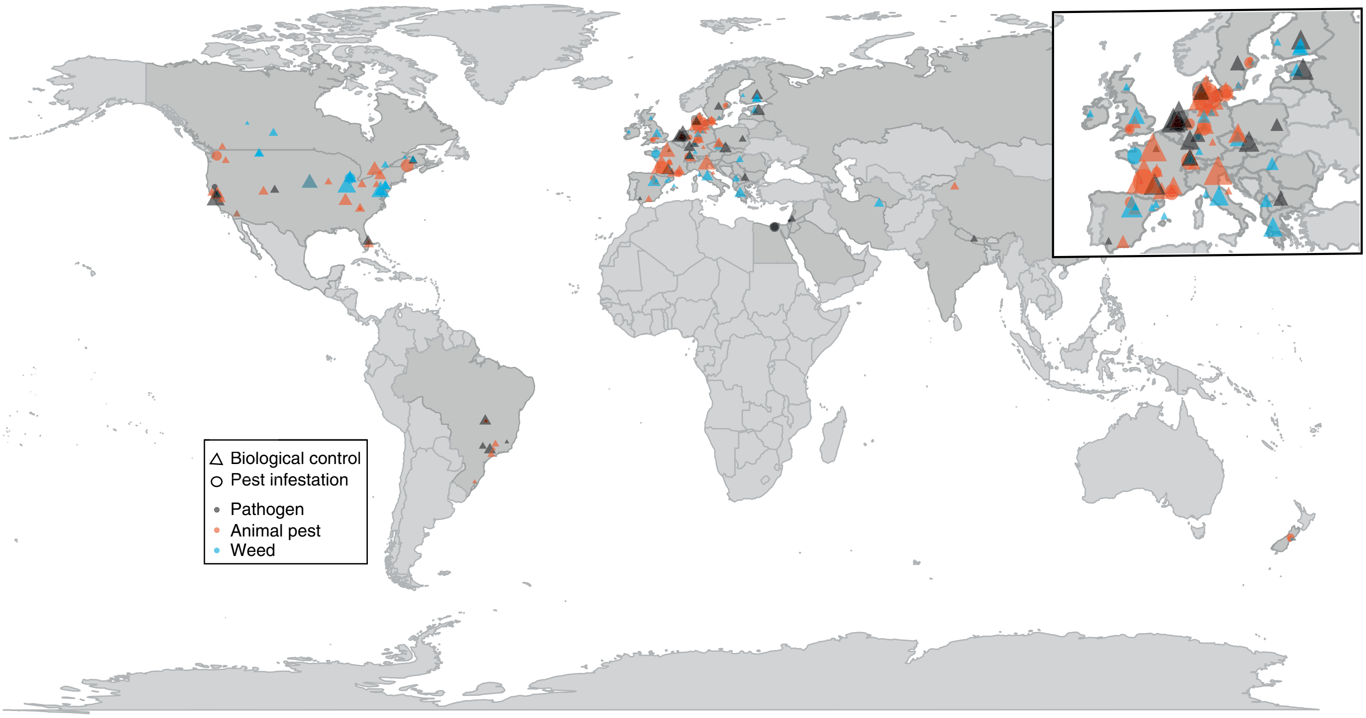

Fig. 1 | Overview of all the study sites included in the meta-analysis where primary studies comparing pest infestation and/or biological control levels between organic and conventional farming systems have been conducted. When the study area was wide, we reported the centroid of the study area. Triangles represent studies about biological control and dots represent studies about pest infestation. Black symbols represent studies about pathogens, red symbols represent studies about animal pests and blue symbols represent studies about weeds. The size of the symbols represents the number of effect sizes provided by each study site.

terms of biological pest control services and pest infestation levels. We address these questions using two distinct meta-analyses, a meta-analysis on biological control potential based on 43 studies including 194 comparisons, and a meta-analysis on pest infestation based on 134 studies including 594 comparisons between organic and conventional farming systems (Fig. 1; Supplementary Table 1). Data collected for the biological control potential meta-analysis included metrics measuring predation rate, parasitism rate and soil-suppressiveness (that is, soil ability to suppress pathogens following their inoculation), whereas data collected for the pest infestation meta-analysis included metrics such as disease severity or incidence, pest abundance or pest density, weed soil cover, weed biomass or weed density (Supplementary Tables 2 and 3). Even though organic farming encompasses several definitions and varied regulations[24], farming systems were considered organic when their management followed the organic farming guidelines of their countries. All organic farming guidelines excluded the use of synthetic agrochemicals. Here, we refer to non-organic farming systems using the terms 'conventional farming systems'. Conventional farming systems aggregated various farming systems ranging from low- to high-input systems and were considered as the control group. We only considered studies from which we could report the mean, the sample size and a measure of variance from both organic and conventional treatments. Comparisons were computed as effect sizes using a standardized mean differences index (that is, the Hedges' d). In addition, we extracted information useful to identify the biological and contextual variables driving the relative performance of organic farming in terms of biological control and pest infestation (see various hypotheses related to these contextual variables, Supplementary Tables 4 and 5).

Our study demonstrates that organic farming promotes overall biological pest control potential and that organic farming practices are able to match or outperform the abilities of conventional farming practices to limit pathogen and animal pest infestations. Indeed, organic farming systems had, generally, lower levels of pathogen infestation, similar levels of animal pest infestation and much higher levels of weed infestation relative to conventional farming systems. Thus, our results provide evidence that organic farming can lead to ecological intensification of agro-ecosystems and can contribute to replace the use of synthetic inputs for the management of animal pests and pathogens. This should encourage policymakers and practitioners to allocate more resources to the development of agricultural systems that rely more heavily on the ecosystem services provided by biodiversity.

Results

Higher biological control services in organic than in conventional fields. Overall, the average level of biological control services was higher in organic than in conventional fields (standardized mean difference Hedges' $d_{\text{grand mean}} = 0.31 \pm 0.30$ ($\pm$95% confidence interval), Fig. 2, see Methods for interpretation of this index). After accounting for confounding moderators (see Supplementary Table 6) the analysis of the number of pest species shows that, on average, there is a significantly higher level of biological control in organic than in conventional fields for individual pests ($d_{\text{single}} = 0.42 \pm 0.26$). However, no differences between organic and conventional fields were found for studies examining pest communities ($d_{\text{community}} = 0.18 \pm 0.32$, Fig. 2). The positive effect of organic management on biological control was detected both for perennial ($d_{\text{perennials}} = 0.56 \pm 0.52$) and annual crops ($d_{\text{annuals}} = 0.43 \pm 0.41$, Fig. 2; see Supplementary Table 7). All categories of pest type and study type had confidence intervals that included zero, meaning that the level of biological control within each category of these two moderators is not significantly greater in organic than in conventional fields (Supplementary Table 7).

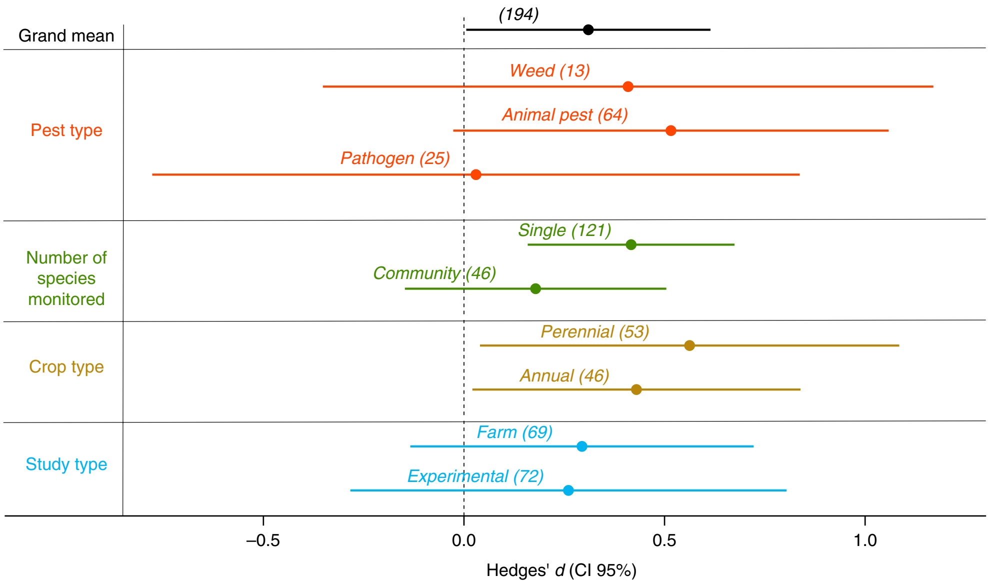

Fig. 2 | Impact of organic management on biological control, as influenced by pest type, number of pest species monitored, experimental conditions of the study and crop type. A Hedges' *d* positive value indicates a higher level of biological control in organic than in conventional fields. For all moderators, the mean effect size ± 95% confidence interval is shown for each category. Numbers indicate numbers of effect sizes. The top box contains the grand mean of Hedges' *d* for biological pest control; the model was fitted with the intercept only.

Contrasting responses of weed, pathogen and animal pest infestation levels to organic farming. Overall, organic fields exhibited higher pest infestation levels than conventional fields ($d_{\text{grand mean}} = 0.23 \pm 0.16$; Fig. 3). However, this effect was highly dependent on the pest type. We found no difference in the levels of animal infestation ($d_{\text{animal pests}} = 0.08 \pm 0.21$) between conventional and organic farming systems, but weed infestation was much higher ($d_{\text{weed}} = 1.02 \pm 0.22$) and pathogen infestation lower ($d_{\text{pathogen}} = -0.38 \pm 0.23$) in organic than in conventional fields (Fig. 3; Supplementary Table 8). In addition, our results showed that studies considering multiple pest species found higher pest infestation levels in organic than in conventional fields, whereas studies considering only one pest species reported similar levels of pest infestation between organic and conventional fields (Fig. 3). The higher infestation level in organic fields in studies that considered multiple pest species was found to be independent of the pest type (Supplementary Fig. 1; Supplementary Table 8). Studies conducted in annual crops or on experimental sites always exhibited higher levels of pest infestations in organic than in conventional farming (Fig. 3, Supplementary Table 8). However, no significant difference in levels of pest infestation was found between organic and conventional for studies conducted in perennial crops or in studies carried out on farmers' fields (Fig. 3; Supplementary Table 8). Pest attack location on the plant and the number of years since conversion to organic farming did not explain a significant proportion of the variability in effect sizes (Fig. 3; Supplementary Table 8). Studies conducted under tropical latitudes were too scarce to allow for an assessment of the effect of climate on the difference in pest infestation levels (see Supplementary Table 3). Specifically for animal pest infestations, the levels of both nematode and insect infestations were similar between organic and conventional fields ($d_{\text{nematode}} = -0.27 \pm 0.28$; $d_{\text{insect}} = 0.06 \pm 0.15$), whereas acari infestation was lower in organic than in conventional fields ($d_{\text{acari}} = -0.48 \pm 0.34$, Supplementary Fig. 2A; Supplementary Table 9). In addition, we found that differences in insect pest infestation levels in organic and conventional fields did not significantly vary with the experimental conditions, crop type, monitored insect order or insect biological features (Supplementary Table 10; Supplementary Fig. 2B).

Robustness. We checked for publication bias using funnel plots but detected no significant bias. We also performed three types of sensitivity analyses for both meta-analyses. We evaluated the impact of including the most uncertain effect sizes and effect sizes from studies providing more than 2.5% of the datasets. We also assessed the impact of including time series data using a bootstrap approach (see Methods section and Supplementary Figs. 3 and 4). We found no impact of temporal dependency and study dependency on the results of both meta-analyses. In one case, including effect sizes of weed infestation having a within-year dependence reduced the magnitude of the positive effect (that is, higher weed infestation) of organic farming (Supplementary Fig. 4). However, this did not change the overall positive effect of organic farming on weed infestation levels, indicating strong robustness of our results.

Discussion

While the concept of organic farming theoretically relies on ecological intensification, no consensus exists about the actual performance of organic farming in terms of pest control. This study shows, using two large meta-analytical datasets, that organic farming promotes pest control to a level able to compensate, or even outperform, the effects of conventional practices on pathogens and animal pests, but not weeds. Our results therefore confirm our initial hypothesis that organic farming enhances biological control potential. However, despite overall higher levels of pest infestations, our study does not validate the hypothesis that organic farming experiences higher levels of pest infestation for all pest types, since we found that organic farming has lower pathogen infestation, similar levels of animal pest infestation and much higher levels of weed infestation relative to conventional farming.

Once established, pest populations within agro-ecosystems are affected, to varying degrees, by three ecological processes: bottom-up effects mediated by soil or plant communities involving, for instance, plant quality or habitat structure[25,26], horizontal processes within a given trophic level such as competition for resources between individuals or populations[27,28], and top-down control by natural antagonists such as predation or parasitism[29,30]. In addition, pest populations are directly affected by farming practices

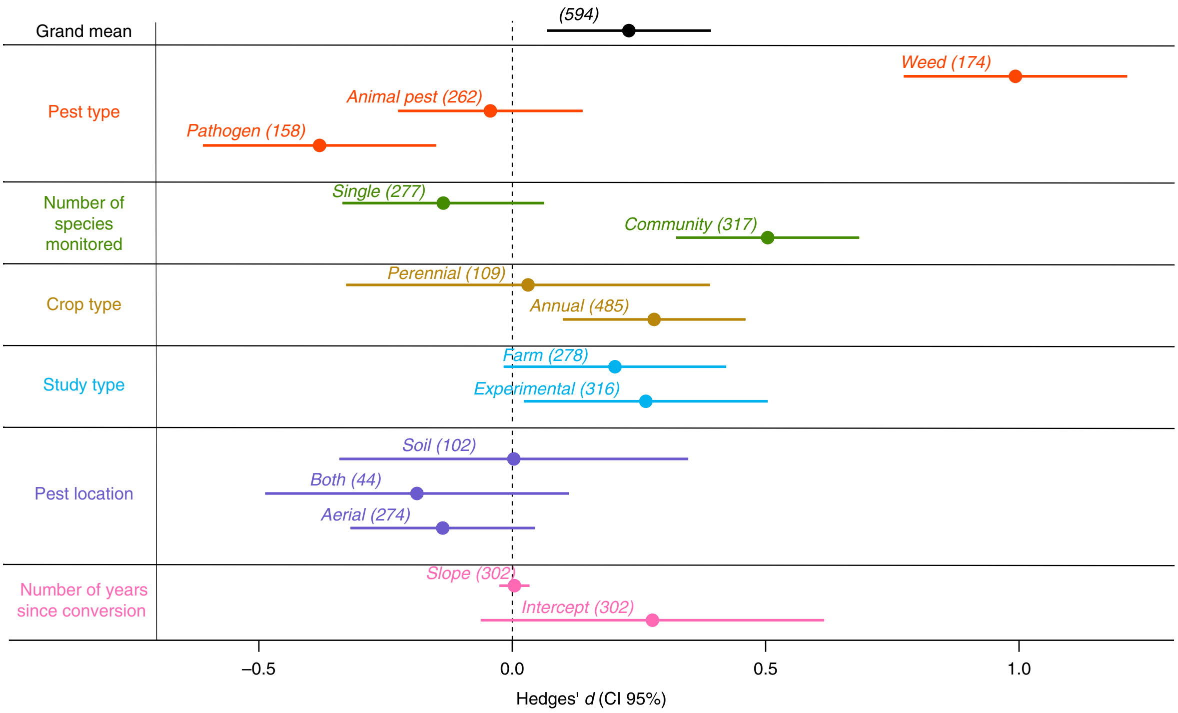

Fig. 3 | Impact of organic management on pest infestation, as influenced by pest type, number of pest species monitored, experimental conditions of the study, crop type, location of the pest attack and number of years since the conversion to organic farming. A Hedges' *d* positive value indicates a higher level of infestation in organic than in conventional fields. For all moderators, the mean effect size ± 95% confidence interval is shown for each category. Numbers indicate numbers of effect sizes. The top box contains the grand mean of Hedges' *d* for pest infestation level; the model was fitted with the intercept only. The coefficients displayed here are the outputs of single moderator, minus-intercept models because this allows clearer representations of the individual effect of each moderator on the variability of effect sizes.

implemented to limit their development. Our results show various responses of different organism groups to organic farming and thus allow development of hypotheses about how these different ecological processes shape pest infestation in organic agro-ecosystems.

Our analysis shows that organic farming results in much higher weed infestation. This result is supported by previous studies that have shown higher abundance and diversity of plant communities within organic arable fields[16,31]. We assume that this higher weed infestation, in turn, most likely influences animal pest and pathogen populations. These bottom-up effects of plant communities on higher trophic levels have been demonstrated[25] and more abundant or diverse plant communities have been found to limit insect and disease infestation through direct and indirect mechanisms[26,32] because of higher structural complexity or lower habitat quality under increased plant diversity[26,33]. Although this needs further investigation, the observed performance of organic farming on animal pest and pathogen infestation may result from bottom-up effects generated by the higher weed infestation levels in organic cropping systems. Additionally, the favourable performance of organic farming found in our study may also result from higher plant diversity (including crop and non-crop vegetation) of organic farms at the landscape scale[34,35]. Other known indirect bottom-up effects resulting from modifications of soil physical, chemical and biological properties under organic management can also explain the observed ability of organic farming to limit animal pest and pathogen infestations[33].

Horizontal pest control processes are also most likely involved in the observed effect of organic farming. Competition for resources is an important biotic factor shaping patterns of distribution, abundance and diversity in ecological communities[36]. Organic farming practices increase the abundance and richness of animal and microbial species[16,33], and this could result in higher competition for resources between pests and other non-problematic species of the same trophic level, resulting in lower pest infestation levels. For instance, the higher organic matter content found in organically managed soils enhances the activity and diversity of primary decomposers, such as bacteria and fungi, that can suppress pathogenic strains due to strong competition for nutrients[33]. Similar evidence of competition between phytophagous insects have also been reported[37] and could help explain the lower insect pest infestation levels we observed in organic cropping systems.

Finally, top-down ecological processes through natural enemies are also probably shaping pest populations under organic management. Organic farming can benefit natural enemies both directly, through farming practices limiting negative impacts on their populations[38], and indirectly, through the positive effect of the diversity and abundance of plant communities (including crop and non-crop vegetation at the field, farm and landscape scales) on the diversity and abundance of predators[25,26]. The positive effect of organic farming on biological control potential that we found indicates that the enhanced abundance and diversity of natural enemies in organic fields that has previously been observed[15–18] probably result in the provision of higher levels of biological control services. The ecological mechanisms driving this effect have been highlighted previously and include niche partitioning and sampling effects[21].

It is important to highlight that we cannot rule out that the high pest control potential under organic management revealed by our study partly results from a similar or even higher effectiveness of organic pesticides compared to synthetic pesticides. However, pesticide use is typically much lower in organic than conventional farming[31], and involves very different types of chemicals of typically lower toxicity[39].

At first glance, our results show that controlling weed infestations is one of the main challenges in organic farming and that weeds could be a potential driver of the yield gap between organic and conventional farming systems[40]. However, the relationships between infestation levels and yield losses for a large majority of pest groups remain poorly known. Moreover, recent studies have disputed the relationship between weed infestation and yield loss in organic systems, highlighting that weeds can also be seen as a crucial biodiversity component that could benefit several ecosystem functions including biological pest control or pollination[41,42]. In line with these studies, our results indicate that the performance of organic farming in terms of animal pest and pathogen control could result from bottom-up effects mediated by the high levels of weed infestation in organic cropping systems. These simultaneous positive and negative effects of weeds in agricultural systems highlight the need for further research to analyse the multifunctional role of weeds in agricultural systems and their effects on the performance of organic farming systems.

Understanding the context-dependency of the performance of organic farming is crucial to address shortcomings and adopt organic management under the conditions where it performs best[8]. We explored how several moderators including number of pest species monitored, crop type, number of years since conversion to organic farming, pest attack location and study type could explain variabilities in the performances of organic farming (see the Supplementary Material for hypotheses and discussion related to all moderators). Our analyses showed that the number of pest species considered in primary studies as well as crop type were important moderators of the performance of organic farming in terms of biological control and pest infestation. Our findings suggest that the positive effect of organic farming on biological control services can efficiently lead to reduced mono-specific pest infestation but not necessarily to lower levels of infestation at the pest community level. A sampling effect may be one possible explanation of this result as organic farming is known to enhance species richness and abundance at different trophic levels (including plant and phytophagous species)[16]. Hence, the probability of including species that significantly benefit from organic farming practices is expected to be higher in organic than in conventional fields where the pest communities are much less diverse and abundant. In addition, our study shows that organic farming practices in perennial crops limit pest infestations to similar levels as conventional farming practices, whereas in annual crops organic farming practices lead to higher pest infestation levels compared to conventional farming (Fig. 2). This occurs despite higher levels of biological control services in both organic perennial and annual crops compared to conventional farming (see Figs. 2 and 3 and the Supplementary Discussion for discussion about these moderators). Such effects could result from differences in the intensity of pesticide use between annual and perennial organic crops. On average, almost no pesticide is used in organic annual crops whereas pesticide use intensity is usually high in organic perennial crops (using certified organic products)[43]. This result highlights the fact that the relative performance of organic farming in controlling pests is dependent on the type of crop and on the farming practices used in each system.

Unfortunately, we could not fully explore the context-dependency of the performance of organic farming because of a lack of information in the primary studies. Factors driving the positive or negative performance of organic farming in terms of pest management thus need to be further explored, especially how specific management practices, landscape and climate context may affect these outcomes[16]. The substantial variability sometimes observed in the response of biological pest control and pest infestation to organic and conventional managements (Figs. 2 and 3) suggests that for some organism groups the binary organic versus conventional management categories might not adequately capture the variation in management that is important for pest regulation. This binary classification allows us to explore effects at the farming system level but examining the effects of specific farming practices independently of the broader farming system is a key research gap. Moreover, pest infestation might be driven by other important variables that we were not able to analyse. For instance, populations of both pests and natural enemies are strongly influenced by the landscape surrounding agricultural fields[43,44], and the relative impact of organic management on pest control might differ depending on landscape context[16]. As organic farms are usually associated with heterogeneous landscapes[34], it is possible that some of the effects of organic farming found in our study are driven by landscape context. In addition, specific management practices, such as the types and quantities of pesticides applied, crop rotations, different cultivars, levels of diversification or fertilization levels, could potentially be more important drivers of pest infestation levels than organic and conventional management categories[10,45]. Analyses of such moderators will provide important insights into how to effectively and successfully implement ecological intensification strategies based on organic farming in agro-ecosystems.

Our study demonstrates that organic farming globally experiences higher levels of pest infestation but this effect highly depends on the pest type. Our findings in particular show that organic farming practices are able to match or outperform conventional pest control practices against pathogens and animal pests whereas weeds are much more abundant in organic than in conventional systems. Thus, ecological intensification based on organic farming can contribute to the control of animal pests and pathogens by enhancing biological control services and limiting their infestation levels. However, we acknowledge that our analysis did not integrate the consequences of these pest control effects on yield gain or loss. We therefore advocate for more detailed analyses of the relationships between pest infestation levels and yield losses to clearly quantify the impact of pest control differences on yield gaps between farming systems. To reach a desirable state in the provisioning of bundles of ecosystem services we also need to identify and manage trade-offs and synergies between different desirable and undesirable ecological functions. Similar studies considering other key ecological functions and services such as organic matter decomposition are now needed to fully assess the multifunctionality of organic farming systems. Our findings demonstrate that ecological intensification strategies based on the adoption of organic farming practices can contribute to management action reducing the environmental impacts of agriculture.

Methods

Literature search. To perform our two meta-analyses, we collected studies evaluating the effect of organic farming on either pest infestation levels (weeds, pathogens and pests) or biological control services. We used two sets of keywords for study collection to identify the relevant articles in the Institute for Scientific Information Web of Knowledge: (i) 'organic AND conventional AND (pest OR disease OR pathogen OR weed)' and (ii) 'organic AND conventional AND (parasitism OR predation OR 'infestation rate' OR 'predation rate' OR biocontrol OR 'natural regulation' OR mortality OR survival OR 'biological control' OR 'natural pest control' OR 'weed control' OR 'seed predation'. The literature search included studies published between 1956 and April 2017. We screened the bibliography from related reviews[16,46–48]. We also added four unpublished datasets provided by the authors (from three different experiments).

Study selection. To be included in the dataset, studies had to report data comparing either pest infestation levels or biological control services between organic and conventional farming systems. Organic farming was defined by the exclusion of synthetic fertilizers and pesticides, and took into account both organic as well biodynamic farming systems. Biodynamic agriculture is similar to organic farming as synthetic fertilizers, chemical plant protection agents and artificial additives during processing are prohibited but it also integrates various esoteric concepts such as considering moon cycles or soil energy. It also has a certification system, which is close to organic certification but more restrictive in the list of authorized products. In contrast, conventional farming allowed for synthetic inputs even if the intensity of pesticide use highly varied across the dataset, ranging from 'integrated pest management' systems to 'high-input' systems. Data from both organic and conventional farming systems had to be original and strictly comparable in the study to be considered. We incorporated different kinds of response variables quantifying biological control services (predation rate, parasitism rate or soil disease-suppressiveness; Supplementary Table 2) and pest pressure (severity, incidence, abundance, biomass, density, soil cover or occurrence; Supplementary Table 3). To be included in the dataset about biological control, studies had to quantify natural pest control by antagonistic organisms, and whether or not this followed pest inoculation or introduction by the experimenter. The studies had to clearly indicate the mean, any measure of variance (that is, standard deviation, standard error of the mean or confidence interval) and the sample size (a minimum of three observations was tolerated) of both organic and conventional treatments to be included. In the case of partial or unclear information reported, we contacted the authors. We did not include studies that explored pest infestation or biological control before and after conversion from conventional to organic farming because of their mismatched study design (that is, the comparison of pest infestation levels across years in a given farm).

Data extraction procedure. We considered the conventional treatment as the control. Hence, if a study evaluated the effect of several conventional as well as organic treatments, we computed an effect size for each pair of most comparable treatments (for example, same dates, equal tillage intensity). If several conventional treatments were compared to one single organic, all the conventional treatments were considered as variants and we randomly selected one to calculate an effect size. We only selected 'low input systems' and 'integrated pest management' as control when there was no other variant of conventional treatment. If there were several organic compared to one conventional treatment, we included them all in the dataset and compared each organic treatment to the same conventional treatment. This dependence was then taken into account in the models (see below in the 'Statistical analysis' section). When several pest stages were examined in a primary study, we extracted one measure for each pest stage at a given date because we assumed that they could lead to different damages and they were probably controlled by several natural enemy species. When the data reported weed infestation through weed soil cover, density and biomass, we extracted the weed soil cover values. As a second choice, we extracted data as weed biomass followed by weed density. In addition, if the authors reported results of a time series survey, we calculated as many effect sizes as was possible. However, when an error term for each time point was not available, we calculated the mean as well as the standard deviation across time. We extracted data from graphics using Image J software, texts or tables, and we additionally received many datasets from authors. We were not able to directly examine the relationship between biological control potential and pest infestation levels due the low number of studies (that is, 16 studies) that jointly measured comparable data on these two aspects. Moreover, these studies were largely unbalanced considering the moderators we examined, as they were dominated by studies on parasitism rates of insects in annual crops, which strongly limited the scope of the potential analysis.

Effect size calculation. For each comparison between one organic and one conventional farming system, we calculated the standardized mean difference using the Hedges' d index[49] (that is, the effect size called 'd'). It is a well-known index that requires the mean, the standard deviation and the sample size of both treatments (see the formula given in Supplementary Methods). This index was chosen as the effect size measure because it has the benefit of being unbiased by small sample sizes and it allows comparisons having the mean of the control equal to zero. Positive values of d indicate that organic farming experiences a higher level of either biological control services or pest infestation than conventional farming (that is, the control group), whereas negative values indicate that organic farming experiences a lower level of biological control or pest infestation than conventional farming. We consider Hedges' $d < 0.2$ as small effects, 0.2–0.8 as medium effects and >0.8 as large effects[50].

Potential causes of variation between effect sizes. We extracted much information from the original studies and the literature related to the biology of the studied organisms and the experimental design to explain the variability within the effect sizes (Supplementary Tables 2, 3, 11 and 12). First, to describe the data structure, we collected (i) the study location and the authorship dependence to take the between-study dependence into account and (ii) the temporal dependence between the effect sizes to deal with the within-study dependence[51]. Studies reporting results from the same long-term experiment as well as studies sharing the first and/or the last author were also considered dependent. Within studies, the temporal dependence between the effect sizes can be either within year or between years, and these dependences were coded independently. Second, beyond the description of the data structure, we also collected various biological moderators for the two different meta-analyses (see Supplementary Tables 4 and 5 for details of the underlying hypotheses). For both the pest infestation and the biological control section, we collected the type of pest considered ('pathogen', 'weed' or 'animal pest' and specific taxonomic information, if available), the number of pest species that had been monitored ('community', that is, more than one species, or 'single'), the study type (that is, whether the study has been conducted in experimental sites 'experimental' or in commercial farms 'farm'), the crop type ('annual' or 'perennial'; see the distribution of the effect sizes among moderators in the Supplementary Figs. 7, 10 and 12). Note that the strawberry and the cotton production were considered as annual crops due to the management they are subjected to. We also collected climatic data, the coordinates and the minimal number of years since the conversion to organic farming when it was reported. For the pathogens and the animal pests, we noted the location of the pest attack on the host plant ('aerial', 'soil' or 'both'; see Supplementary Figs. 5 and 6 to observe the distribution of effect sizes among categories for each moderator analysed).

Statistical analysis. For each meta-analysis, we created multiple contingency tables, crossing the number of effect sizes for all pairs of potential moderators. Based on these contingency tables, we identified a high dependency between moderators (that is, confounded effects) when the distribution of their effect sizes was largely unbalanced across categories of the considered moderator (see Supplementary Methods for a detailed example). This step allowed the selection of the datasets that were used to fit the models while avoiding models containing confounding effects (that is, including dependent moderators in the same model; Supplementary Table 6). Hence, several moderators extracted from the literature were excluded at this step, such as the climate. After this step, we searched the best random structure to include in our models because we assumed that the effect sizes were not independent in each dataset (Supplementary Tables 13 and 14). Hence, we used linear multilevel models to analyse our datasets[52]. To identify the random effect structure that best fits the datasets, several models with different random effect structures were compared. We tested all the credible combinations of the four following variables as random terms: (i) the 'Case ID' (that is each comparison between one conventional and one organic treatment from a given primary study is a singular case study); (ii) the 'Study ID' (that is, observations coming from the same study); (iii) the long-term experiment dependence 'Experimental site' (that is, temporal dependence); and (iv) the authorship dependence 'Authors dependence' (that is, observations coming from the same primary or last author). For each meta-analysis, we fitted several models including all the moderators and each credible random effect structure using the larger dataset (Supplementary Table 6). We retained the random effect structure from the models providing the lower BIC (Bayesian Information Criterion) value (see the Supplementary Methods for details). The retained random effect structures were different for the pest infestation and the biological control meta-analysis but they were consistent across all the datasets for each meta-analysis (Supplementary Tables 13 and 14). We used the BIC, which is more conservative than the AIC (Akaike Information Criterion) and favours the simplest models[53]. Moreover, to take into account the correlation between the effect sizes sharing the same control (that is, the conventional treatment), we added a variance-covariance matrix describing the dependence among the effect sizes on all the models[50] before the selection of the random structure. Effect sizes were considered significantly different from zero if their confidence interval (95%) did not include zero. The quantification of the heterogeneity among the effect sizes was quantified with τ^2 and the I^2 statistics[50,51]. They indicate how the variation among the effect sizes can be attributable to the true effect sizes (without the variation that is due to sampling error). τ^2 is an absolute value, varying with the magnitude of the Hedges' d value. It corresponds to the sum of the between-study ID variance and the within-study ID variance. I^2 is a percentage, which corresponds to the ratio between the variance explained by the true effect sizes and the observed variance[54]. It allows for comparison across different meta-analyses of the percentage variance in the observed effect size estimates that is contributed by the variance in the true effect sizes. We also reported Q_m, which is a test statistic from the omnibus test of moderators, where the null hypothesis is that the coefficients of all non-intercept predictors is equal to zero, that is, $b_1 = b_2 = \ldots = b_k = 0$, where k is the index of the last coefficient.

Sensitivity analysis. We checked for publication bias using funnel plots and no biases were detected (Supplementary Figs. 7 and 8). We tested the robustness of the analysis on biological control by removing the 10 most variable effect sizes from the full dataset ($N = 194$), all of which were positive (Supplementary Fig. 7), and fitting the intercept-only model on this new dataset. Removing these effect sizes did not affect the results of the analysis ($d_{\text{grand mean}} = 0.25 \pm 0.23$). We also tested the robustness of the analysis by removing individually the studies providing more than 2.5% of each dataset (7 studies for the pest infestation meta-analysis and 13 studies for the biological control meta-analysis). Removing these studies did not significantly change the model outputs. Finally, we tested how the temporal dependence between effect sizes affected the results of our analyses by using a bootstrap approach for each selected model in both separate meta-analyses (with $N = 100$). We then computed estimates of the coefficients and their confidence intervals based on the bootstrap outputs. We considered that if the mean and the confidence interval of the estimate from the bootstrap is included in the confidence interval of estimate for each coefficient of the retained model (having the lowest BIC), then the model outputs are robust (Supplementary Figs. 3 and 4).

All analyses were carried out with the 'metafor' package[55], which is implemented in R software[56].

Data availability. The data that support the findings of this study are available from the Dataverse repository https://doi.org/10.15454/DV8LMF.

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Authors contributions

L.M., E.A.D., S.A., J.P., M.P., D.T. and A.R. conceived the work and designed the study. M.M. and V.S. contributed to data analysis and interpretation of the results. L.M. and A.R. collected the data, analysed the data, interpreted the results and led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

Competing interests

The authors declare no competing interests.

Additional information

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