GfÖ Ecological Society of Germany, Austria and Switzerland

Basic and Applied Ecology 63 (2022) 115–124

Basic and Applied Ecology

www.elsevier.com/locate/baae

REVIEW ARTICLE

A meta-analysis of biocontrol potential and herbivore pressure in olive crops: Does integrated pest management make a difference?

Sasha Vasconcelos[a,b,c,d,*], Mattias Jonsson[d], Ruben Heleno[e], Francisco Moreira[a,b,c], Pedro Beja[a,b,c]

[a]*CIBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, InBIO Laboratório Associado, Universidade do Porto, Campus de Vairão, Vairão 4485-661, Portugal*
[b]*CIBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, InBIO Laboratório Associado, Instituto Superior de Agronomia, Universidade de Lisboa, Campus de Vairão, Lisboa 1349-017, Portugal*
[c]*BIOPOLIS Program in Genomics, Biodiversity and Land Planning, CIBIO, Campus de Vairão, 4485-661 Vairão, Portugal*
[d]*Department of Ecology, Swedish University of Agricultural Sciences, PO Box 7044, Uppsala SE-750 07, Sweden*
[e]*Centre for Functional Ecology, TERRA Associate Laboratory, Department of Life Sciences, University of Coimbra, Calçada Martin de Freitas, Coimbra 3000-456, Portugal*

Received 30 November 2021; accepted 22 May 2022
Available online 25 May 2022

Abstract

Agricultural policies in the European Union (EU) are increasingly promoting organic management and integrated pest management (IPM) as environmentally friendly alternatives to high-input conventional management. While there is consensus that organic management is largely beneficial for biodiversity, including the natural enemies of crop pests, IPM has been much less scrutinized. We conducted a meta-analysis based on 294 observations extracted from 18 studies to compare the effects of conventional, IPM and organic management on biocontrol potential and herbivore pressure in olive, an important cash crop in the EU. Information about the management practices used was also compiled to assess differences in intensity between the three management strategies. Results suggest that IPM is predominantly based on intensive practices, employing chemical control rather than preventive measures as a first resort. Biocontrol potential and herbivore pressure were similar in conventional management and IPM. Moreover, biocontrol potential was higher in organic crops than in crops under IPM, especially when considering canopy-dwelling natural enemies. Although organic management enhanced biocontrol potential, it also benefitted some olive pests, and in both cases effects were more pronounced at warmer temperatures. Our results suggest that, in its current form, IPM might not significantly affect biocontrol potential or herbivore pressure when compared with conventional olive crop management. A shift to a more comprehensive implementation of IPM practices is thus needed, involving the use of proactive measures to promote natural enemies and regulate olive pests before resorting to chemical control. Moreover, greater use of non-chemical inputs might be required for effective regulation of olive pests in organic olive crops.

Keywords: Integrated pest management; Organic management; Olive farming; Biocontrol; Meta-analysis

*Corresponding author at: CIBIO, Instituto Superior de Agronomia, 1349-017 Lisboa, Portugal.
E-mail address: sasha.vasconcelos@cibio.up.pt (S. Vasconcelos).

https://doi.org/10.1016/j.baae.2022.05.009

Introduction

Global food production has doubled over the last 60 years to meet rising demands of the growing human population and the increasing per capita consumption (Wittwer et al., 2021). However, this has come at a high environmental cost, including in particular the strong negative impacts of synthetic pesticides and mineral fertilizers on non-target organisms, human health and food quality (Pimentel et al., 2005; Tilman et al., 2002). To counteract these impacts in the European Union (EU), where agriculture currently occupies 48% of the land (Rega et al., 2020), policies are increasingly promoting organic management and principles of integrated pest management (IPM) as more environmentally-friendly options. For instance, the EU directive on sustainable use of pesticides (Directive 2009/128/EC) required all countries to have plans to adopt principles of IPM by 2014. More recently, the EU Farm to Fork strategy aims at halving the risk and use of synthetic pesticides by 2030, largely by promoting the adoption of organic management and IPM (European Commission, 2020). However, while there is substantial evidence to support organic management as a less harmful alternative to conventional farming, with several quantitative syntheses providing consensus about its benefits for biodiversity (e.g., Bengtsson et al., 2005; Lichtenberg et al., 2017), the effects of IPM have been subject to far less scrutiny (but see Katayama et al., 2019).

IPM is a decision support system for crop protection in integrated farming, where the main goal is to reconcile ecological preservation with economic profitability through the balanced use of chemical, biological and cultural practices (Boller et al., 2004; Mili et al., 2017). There are, however, multiple definitions of IPM (Deguine et al., 2021), which ultimately boil down to two main approaches. One is the comprehensive form of IPM which prioritizes the enhancement of biodiversity and associated services, in particular biocontrol (i.e., conservation biocontrol, whereby resident natural enemies in an ecosystem are boosted by targeted human interventions; Stenberg et al., 2021), before any form of chemical control is used (Zalucki et al., 2009; Hokkanen et al., 2015; Lundin et al., 2021). It is typically represented as a pyramid, where priority is given to proactive actions (e.g., crop rotation, reduced or no tillage, fostering of natural enemies) at the base of the pyramid, while reactive actions (chemical pesticides) at the top of the pyramid should only be used when other measures fail to maintain pest densities below intervention thresholds (Hokkanen et al., 2015; Lundin et al., 2021). The other approach, which is prevailing, is more limited as it simply resorts to chemical control when predefined intervention thresholds are exceeded (Deguine et al., 2021; Hokkanen et al., 2015). This latter approach likely prevails as farmers tend to opt for the less labor-intensive option of chemical control, which is potentially more effective in the short term and perceived to ensure fewer crop losses (Deguine et al., 2021). These decisions can partly stem from a poor farmer involvement in IPM development, as they are often unaware of practices compatible with IPM (Deguine et al., 2021), or of the ecological concepts underpinning its principles (Wyckhuys et al., 2019). Organic management differs from IPM by prohibiting or strictly limiting the use of synthetic inputs, fostering instead natural enemies and limiting the use of pesticides to those produced from natural sources (e.g., organic insecticides and bacterial biological control agents). Productivity tends to be lower though, as this management strategy usually generates lower yields as synthetic fertilizers are not used (Seufert et al., 2012; Wittwer et al., 2021), but profitability can be comparable or even higher due to higher product pricing (Wittwer et al., 2021).

While various individual scientific studies have compared conventional, organic and IPM in terms of their biodiversity impacts (e.g., Campos-Herrera et al., 2008; Krauss et al., 2011; Meng et al., 2016; Pekár, 1999), meta-analyses have focused mainly on comparisons between conventional and organic management. These quantitative syntheses point to largely positive effects of organic management for biodiversity, particularly on service-providing organisms such as natural enemies of crop pests (Bengtsson et al., 2005; Garratt et al., 2011; Katayama et al., 2019; Lichtenberg et al., 2017; Tuck et al., 2014). Natural enemies are organisms that can exert top-down control on herbivores, which in turn can be considered pests or non-pests depending on the damage they produce to crops. Herbivorous insects (including pests) on the other hand have shown both positive or no responses to organic management (e.g., Bengtsson et al., 2005; Lichtenberg et al., 2017). Muneret et al. (2018) explicitly examined the effects of organic management on biocontrol potential and pest infestation relative to conventional management, revealing a higher level of biocontrol potential, but also of pest infestation, though only when the pests in question were weeds. To date, the effects of IPM on biodiversity have only been addressed in one meta-analysis (Katayama et al., 2019). Considering vertebrate, invertebrate and microbial taxa in perennial crops around the world, these authors found that overall species richness, but not abundance, was higher in systems under integrated farming than in those managed conventionally. The similar abundance was attributed to higher natural enemy and lower herbivore abundance in integrated farming. Moreover, no differences in overall species richness or abundance in relation to organic management were found, although specific effects on natural enemies and herbivores were not assessed. However, the magnitude and direction of effect sizes varied greatly with the crop studied. This suggests that while the inclusion of multiple crops in meta-analyses is important to detect general trends, it is equally important to evaluate the effects of IPM on specific crops, as these might be obscured in global analyses.

We performed a meta-analysis comparing conventional, IPM and organic management in terms of their effects on biocontrol potential and on herbivore pressure in olive crops. Olive was selected because it is a widely cultivated perennial crop in EU Mediterranean countries, which alone account for 54% of global olive production (FAOSTAT, 2020). We focused on arthropods as they play a key role in the provision of biocontrol services, but also as crop pests. In the particular case of olive orchards, the most damaging and widespread pests across the Mediterranean region are the olive fruit fly (*Bactrocera oleae*) and olive moth (*Prays oleae*) (Daane & Johnson, 2010; Gonzalez et al., 2015). Given that the limited form of IPM currently prevails in many agricultural systems, we also characterized the three management strategies in terms of the management practices used. Specifically, we sought to determine (i) the differences in management intensity between management strategies; and (ii) whether biocontrol potential (measured as natural enemy abundance, diversity, parasitism and predation rates) and herbivore pressure (measured as herbivore abundance and damage) differ between strategies.

Materials and methods

Study selection and data extraction

We conducted a literature search by adopting a Population-Intervention-Comparator-Outcome (PICO) framework (Koricheva et al., 2013) to select keywords, defining olive orchards as the Population, IPM/organic management as the Intervention (treatment groups), conventional/IPM as the Comparator (control groups) and biocontrol potential/herbivore pressure as the Outcome. The search was carried out on Web of Science (last update in February 2022) and yielded 499 records using the search string: (“olea europaea” OR “olive farm*” OR “olive orchard*” OR “olive grove*” OR “olive plantation*”) AND (organic* OR non-organic* OR integrated* OR extensive* OR conventional* OR traditional*) AND (biodiversity OR pest* OR herbiv* OR phytophag* OR damage* OR infest* OR “biological control” OR “pest control” OR natural enem* OR beneficial* OR controller* OR parasit* OR predat*). In addition, we found nine records in the reference lists of the studies (papers) obtained through the search, yielding a total of 508 records.

The studies were screened by sequentially reading the title and abstract, with 47 studies read in full to determine whether they met the following criteria: (i) the study provided a pairwise comparison of the management strategies, for at least two of the three management strategies (conventional, IPM, organic); (ii) comparisons between strategies involved a measure of biocontrol potential (natural enemy abundance, diversity, parasitism and/or predation) and/or herbivore pressure (herbivore abundance and/or damage); only pairwise comparisons were used to ensure more similar climatic and soil conditions in the compared orchards; (iii) the study reported the mean, a measure of variance (i.e., standard deviation, standard error, or 95% confidence interval) and sample size for the response variables. When only standard errors or 95% confidence intervals were reported, they were converted to standard deviations. We contacted the authors of six studies that included the necessary data except for the mean and/or a measure of variance by email and received information for two of the studies. Overall, 18 studies met the criteria for inclusion in the meta-analysis (see Appendix A: Table 1 and Fig. 1).

For each study, the means, measures of variance and sample sizes were extracted directly from the text or tables (n = 7), from graphs (n = 9) using WebPlotDigitizer 4.2 (Rohatgi, 2015), or were provided by the authors (n = 2). We separately compiled the natural enemy and herbivore data, assembling three datasets for each trophic group, involving comparisons between: (i) conventional and IPM management (conventional set as the control); (ii) conventional and organic management (conventional set as the control); and (iii) IPM and organic management (IPM set as the control). Whenever studies provided comparisons for more than one natural enemy and/or herbivore taxon, we calculated an effect size for each comparison. Likewise, when multiple temporal data points were provided, we calculated as many effect sizes as possible. We also compiled information about the farming practices used in each strategy to assess management intensity, and to check whether IPM consisted of either the limited or the more comprehensive approach: the use of synthetic insecticides, herbicides, synthetic fertilizers, organic insecticides, bacterial biocontrol agents, kaolin clay, copper, mass trapping, tillage, mowing and organic fertilizers (see Appendix A: Table 2).

Data analysis

Management intensity was explored with a heatmap illustrating the percentage of studies that reported the use (0/1) of the aforementioned farming practices in each of the three management strategies. In the meta-analysis, effect sizes for comparisons between the management strategies were calculated using the standardized mean difference (Hedges’ d) (Hedges & Olkin, 1985). We chose this index as it is frequently employed in ecological meta-analyses, it accounts for differences in sampling effort among studies and corrects for small sample sizes. It also allows for zero values in either the control or treatment groups (Rosenberg & Rothstein, 2013).

We used multi-level models with restricted maximum likelihood (REML) estimation (Cheung et al., 2014; Koricheva et al., 2013), as they allow for non-independence in the data. To account for dependence between observations (each comparison between two management strategies) obtained from the same study, we nested observations within studies (syntax: 1 | study/observation) (Nakagawa et al., 2017). Because most of the studies that shared some authors were conducted in the same locations and sometimes based on the same sampling designs, we also ran the models with author included as a random factor (syntax: 1 | author/study/observation). Studies were considered dependent when they shared a first and/or last author. The nested random structure that best fit the datasets was selected from the models with the lowest Akaike Information Criterion (AIC). In all cases the models where observations were nested within studies had the lowest AIC (see Appendix A: Table 3), and were thus retained in the analyses.

To assess heterogeneity among effect sizes within the three biocontrol potential and three herbivore pressure datasets, we used the Q statistic (Cheung et al., 2014). We then calculated the proportion of variance attributed to each level in our models, namely: within-observation heterogeneity/sampling error (level 1); within-study heterogeneity (level 2); and between-study heterogeneity (level 3) (Nagakawa & Santos, 2012). Significant heterogeneity was observed among effect sizes, in most cases due to variation within studies, followed by variation between studies and within observations (i.e., sampling error) (Table 1). In an attempt to explain part of this heterogeneity, we extracted information about the following moderator variables from each study: the sampling location (olive tree canopy/ground), the sampled arthropod order, years since conversion to IPM or organic management, the type of herbivore (olive-pest herbivore/other herbivores), the measure of biocontrol potential (abundance/diversity/predation/parasitism) and of herbivore pressure (abundance/damage). We also considered temperature, because it might vary markedly across studies carried out in different countries, years and months, and is known to strongly influence arthropod development (Logan et al., 2006). For each study location, we thus obtained mean minimum and maximum monthly temperatures available in WorldClim at a resolution of 2.5 min (~ 21 km^2). These data derive from the Climate Research Unit (CRU-TS-4.03; Harris et al., 2014) and are downscaled with WorldClim 2.1 for bias correction (Fick & Hijmans, 2017). The average of the mean minimum and maximum monthly temperatures was then used to approximate the mean monthly temperatures. The temperature data was matched with the study sampling periods as closely as possible, by extracting temperatures for the specific years and months in which study sampling was conducted. The temperature for each data point was then approximated as the average temperature of the months when data was collected. Of the moderators obtained, the measures of biocontrol potential and of herbivore pressure, as well as sampled arthropod order, were excluded from the analyses because of the very unbalanced distribution of effect sizes between their categories in most datasets. Because information about the number of years since conversion to IPM/organic management was not provided in most studies, this moderator was also excluded from the analysis. Sampling location was used in the biocontrol potential models, herbivore type in the herbivore pressure models, and temperature in both. We were unable to use sampling location in the herbivore pressure models due to limited ground sampling data for two of the three herbivore datasets.

Potential publication bias in the datasets was assessed through the inspection of contour-enhanced funnel plots (Peters et al., 2008) and by testing for funnel plot asymmetry using Egger's regression test (Egger et al., 1997). This test was extended to multi-level models by including the standard error of the effect sizes as a moderator. An intercept deviating significantly from zero indicates asymmetry in the funnel plot (Nagakawa & Santos, 2012), and asymmetry was considered at $P = 0.10$ (Egger et al., 1997). We also calculated fail-safe numbers to estimate how many unpublished, non-significant or missing studies would be needed to make significant results non-significant. If a fail-safe number exceeds the threshold of 5n + 10, where n = the number of observations, significant overall effects can be considered robust regardless of potential publication bias (Rosenberg, 2005).

We compared the models with and without outliers and influential observations, as they can affect the validity of meta-analytic findings (Viechtbauer & Cheung, 2010). The presence of outliers was assessed using quantile-quantile plots and boxplots (Wang & Bushman, 1998), while influential observations were identified using Cook's distance (Cook & Weisberg, 1982; Viechtbauer & Cheung, 2010).

Table 1. Cochran's Q statistic quantifying heterogeneity among effect sizes in the three natural enemy and three herbivore datasets. The distribution of variance in the models, attributable to within-observation heterogeneity (sampling error), and within- and between-study heterogeneity, is also provided.

Datasets	Q (*P*-value)	I^2		
		Level 1 (within-observation)	Level 2 (within-study)	Level 3 (between-study)
Biocontrol potential				
Conventional vs IPM	208.6 (<0.001)	19.8%	61.9%	18.2%
Conventional vs Organic	572.3 (<0.001)	6.9%	76.4%	16.8%
IPM vs Organic	842.3 (<0.001)	5.1%	82.3%	12.6%
Herbivore pressure				
Conventional vs IPM	71.5 (<0.001)	28.7%	27.8%	43.5%
Conventional vs Organic	381.9 (<0.001)	3.3%	70.8%	25.9%
IPM vs Organic	158.1 (<0.001)	8.7%	28.9%	62.4%

Following Muneret et al. (2018), we used a bootstrap approach to test whether our results were influenced by temporal dependence among effect sizes (both between-year and within-year dependence). Results were considered robust when the mean and 95% confidence intervals of the estimates resulting from the bootstrap were included in the confidence intervals of the global mean in each model. Analyses were performed with the ‘metafor’ package (Viechtbauer, 2010) in R (R Development Core Team, 2020).

Results

Study characteristics

Overall, we extracted 294 observations from 18 studies conducted in five of the nine olive-producing countries in the EU (see Appendix A: Table 1). The majority of studies was carried out in Spain (11 studies), while three studies were carried out in Italy, two in Portugal, and one study each in Croatia and Greece. Data on biocontrol potential was obtained from 15 studies, while only nine studies provided data on herbivore pressure. Most studies measured natural enemy and/or herbivore abundance, whereas natural enemy diversity, predation, parasitism and damage were the focus of only one study each. The natural enemy taxonomic groups that were sampled in the studies included spiders (Araneae), lacewings (Neuroptera), lady beetles (Coccinellidae), pirate bugs (Anthocoridae), a parasitoid wasp (*Psyttalia concolor*) and an ant (*Tapinoma nigerrimum*). The sampled herbivore taxa included butterflies/moths (Lepidoptera), aphids/scale insects/cicadas/leafhoppers (Homoptera), and four olive croppests: the olive moth (*Prays oleae*), olive psyllid (*Euphyllura olivina*), black scale (*Saissetia oleae*) and olive thrip (*Liothrips oleae*) (see Appendix A: Table 1). None of the studies provided comparisons between management strategies for the olive fruit fly (*Bactrocera oleae*).

Management intensity

The most prevalent management practices employed in IPM were largely similar to those used in conventional management, consisting mostly of synthetic pesticides and fertilizers, as well as tillage (Fig. 1; see Appendix A: Table 2). All studies assessing the effects of IPM reported that chemical pest control was used when intervention thresholds were exceeded. Organic management involved a wider range of practices, which were mostly non-chemical except for the use of kaolin clay and copper (Fig. 1). The organic insecticide pyrethrum, the bacterial biocontrol agent *Bacillus thuringiensis*, kaolin clay and mass trapping were exclusive to organic management, but were each reported in under 20% of the studies that assessed effects of organic management (Fig. 1; see Appendix A: Table 2). Synthetic insecticides were only used in IPM and conventional management, were

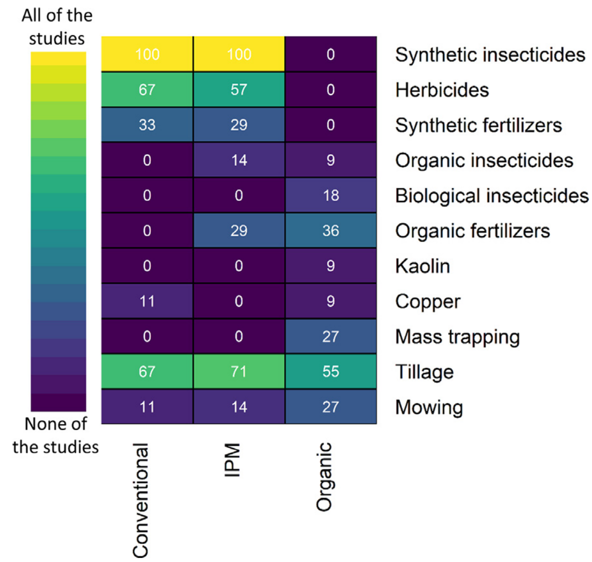

Fig. 1. Heatmap illustrating the percentage of studies (papers) that reported the use (0/1) of 11 main farming practices in each of the three management strategies.

reported in all studies (Fig. 1), mainly involving the broad-spectrum organophosphate insecticide, dimethoate. An organic insecticide (spinosad) was also used in IPM, but only reported in 14% of the studies in which IPM was assessed (Fig. 1; see Appendix A: Table 2). Herbicides were not used in organic management, while a slightly lower percentage of studies reported their application in IPM (57%) than in conventional (67%) management (Fig. 1). Synthetic fertilizers were only used in IPM (29% of studies) and conventional management (33%), though 29% of studies also reported the use of organic fertilizers in IPM. There were no reports of organic fertilization in conventional management (Fig. 1).

Biocontrol potential

Biocontrol potential, represented mainly by natural enemy abundance (see Appendix A: Table 1), did not differ between olive crops under conventional management and IPM (Hedges’ $d = 0.45$; 95% CI = −0.19, 1.1). This result did not differ depending on whether canopy- or ground-dwelling natural enemies were considered, and was not influenced by temperature (Fig. 2A). However, biocontrol potential was higher in IPM after the removal of outliers ($n = 2$), but not after removing influential observations ($n = 3$) (see Appendix A: Fig. 3A). No influence of between- or within-year temporal dependence among effect sizes was detected (see Appendix A: Fig. 3A). Biocontrol potential was higher in organic than in conventional olive crops (Hedges’ $d = 1.12$; 95% CI = 0.39, 1.86), both for canopy and ground-dwelling natural enemies, and particularly at warmer temperatures (Fig. 2A). This positive effect of organic management remained similar after excluding

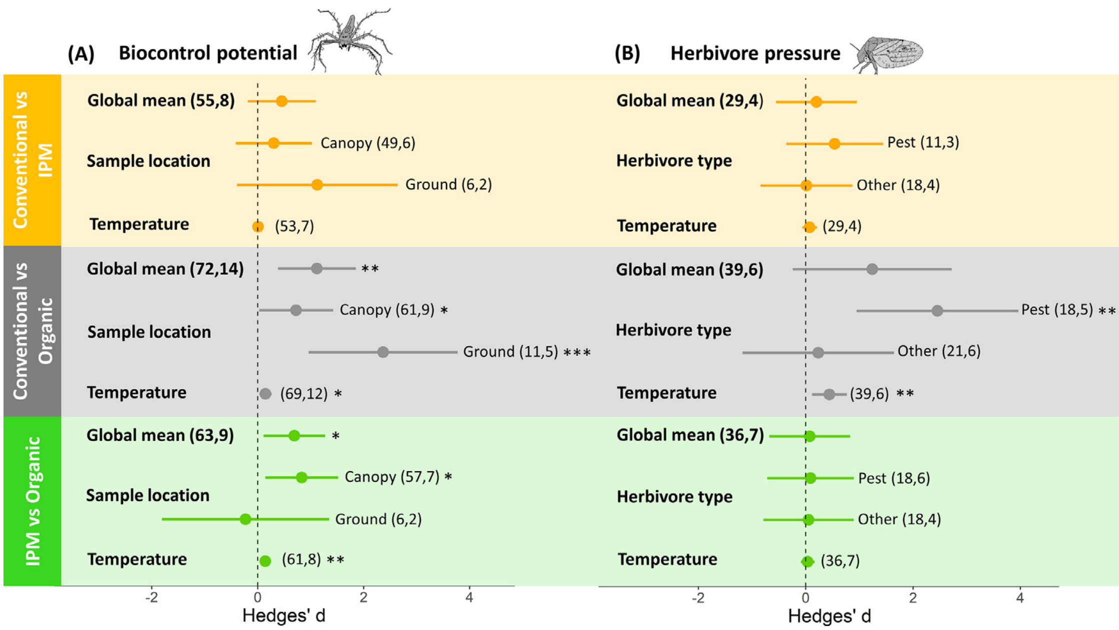

Fig. 2. Forest plots displaying effects of the three management strategies for (A) biocontrol potential and (B) herbivore pressure. A positive Hedges' d value indicates a higher level of biocontrol potential or herbivore pressure in a treatment group (IPM or organic management) relative to the control group (conventional or IPM). The mean effect size ± 95% CI is presented for the global mean (intercept-only model) and for the moderator variables: sampling location (canopy/ground), herbivore type (olive-pest herbivores/other herbivores) and temperature. The number of effect sizes and studies are provided in brackets. Significant differences are indicated (***$P < 0.001$; **$P < 0.01$; *$P < 0.05$).

outliers (n = 10) as well as influential observations (n = 3), and was robust to temporal dependence among effect sizes (see Appendix A: Fig. 3A). Biocontrol potential was higher in organic crops than in those under IPM (Hedges' $d = 0.69$; 95% CI = 0.11, 1.28) (Fig. 2A), though only for canopy-dwelling natural enemies (Fig. 2A). The positive effect also increased significantly with temperature (Fig. 2A). This result also remained similar after the sensitivity analyses (see Appendix A: Fig. 3A).

Herbivore pressure

Herbivore pressure, almost exclusively represented by herbivore abundance (see Appendix A: Table 1), did not differ between conventionally managed olive crops and those under IPM (Hedges' d = 0.2; 95% CI = −0.55, 0.95) (Fig. 2B). This result did not vary with the type of herbivore (olive-pest/other), or with temperature (Fig. 2B). The overall level of herbivore pressure was also similar between conventional and organically managed olive crops (Hedges' d = 1.24; 95% CI = −0.24, 2.72) (Fig. 2B). However, the abundance of olive-pest herbivores was higher in organic crops, whereas no significant differences were found for other herbivores (Fig. 2B). There was also a significant effect of temperature, with higher herbivore pressure in organic than in conventional crops at warmer temperatures (Fig. 2B). Herbivore pressure did not differ between crops under IPM and organic management (Hedges' d = 0.07; 95% CI = −0.68, 0.83) (Fig. 2B), regardless of herbivores being olive-pests or not (Fig. 2B). The result did not vary with temperature (Fig. 2B). Sensitivity analyses revealed that overall herbivore pressure remained similar among management strategies after excluding outliers, influential observations, and were robust to the temporal dependence among effect sizes (see Appendix A: Fig. 3B).

Publication bias

There was evidence of publication bias, as asymmetry was detected in all funnel plots, except for the comparison of biocontrol potential between conventional and organic management (see Appendix A: Fig. 2). This was supported by Egger's regression test for funnel plot asymmetry, although asymmetry was only marginal in the comparison of herbivore pressure between IPM and organic management (see Appendix A: Table 4). However, in all instances where significant differences were found between management strategies, the fail-safe numbers were far higher than the established threshold. This was the case for the higher level of biocontrol potential in organic compared with conventionally managed olive crops (1525 in relation to threshold of 370 (5n + 10 = 370, with n = 72 observations), and in organically managed crops relative to those under IPM (7202 in relation to threshold of 325 (5n + 10 = 325, with n = 63 observations)).

Discussion

Our meta-analysis highlights the need for more scrutiny of IPM practices, as it suggests that the limited form of IPM is currently prevailing in olive crops, and fails to boost levels of biocontrol potential relative to conventional management. Moreover, organic management increases biocontrol potential relative to IPM, though only when considering canopy-dwelling natural enemies, and particularly at warmer temperatures. No differences in herbivore pressure were found between conventionally managed crops and those under IPM. Lastly, we show that while organic management enhances biocontrol potential relative to IPM and conventional management, it also enhances some olive-pest herbivores, and more so at warmer temperatures.

Potential limitations and shortcomings

When interpreting the results of the meta-analysis, some limitations need to be considered, though they are unlikely to affect our main results and conclusions. The most important is the small number of studies that met the criteria for inclusion, particularly those providing herbivore responses, and which can limit the inferences drawn. We tried to circumvent this problem by maximizing the number of effect sizes gathered from each study, through the extraction of multiple temporal data points. Sensitivity analyses showed that the resulting temporal dependence among effect sizes did not significantly influence overall results. Apart from natural enemy and herbivore abundance, additional proxies of biocontrol potential (e.g., parasitism and predation rates) and of herbivore pressure (crop damage) were rare in the studies. Furthermore, only three studies provided information about yield, with no associated measures of variance, which prohibited its inclusion in the analyses. This information would be crucial to understand whether increases in biocontrol potential and reductions in herbivore pressure in olive crops actually translate to yield gains. We also found evidence of publication bias in most of the funnel plots and Egger's regression tests. However, in all the asymmetric funnel plots, the observations lay in areas of both significance and non-significance, very likely reflecting other sources of heterogeneity in the data rather than a real bias towards publishing significant results (Egger et al., 1997). Lastly, in all cases where a significant global effect of one management strategy was detected relative to another, the fail-safe numbers were far higher than the established thresholds. This further supports the validity of the significant effects detected.

Biocontrol potential

The apparently negligible effect of IPM on biocontrol potential relative to conventional management was supported by the majority of the sensitivity analyses and is likely due to the predominantly intensive practices used in IPM. For instance, insecticide and herbicide use were reported in 100% and 57% of the studies that assessed effects of IPM, respectively, and can negatively affect natural enemies in olive orchards (e.g., Cárdenas et al., 2006). Furthermore, all studies reported the implementation of a limited IPM approach which resorts to chemical pest control as soon as intervention thresholds are exceeded, rather than a comprehensive IPM approach where chemical use should be a last resource. Our single-crop meta-analysis thus reveals a negative impact of IPM on natural enemies, which contrasts with those detected in a global scale multi-crop meta-analysis (Katayama et al., 2019). The strong reliance on chemical control in olive crops under IPM likely contributed to the higher potential for biocontrol detected in the organic crops. This could explain why canopy-dwelling natural enemies were positively affected by organic management when compared with IPM, as the application of synthetic inputs on the tree canopies in organic management is very limited. Likewise, higher biocontrol potential in organic compared with conventional olive crops probably stems from the very limited use of synthetic inputs in favor of less harmful alternatives in organic crops. For instance, 36% of the studies reported the use of organic fertilizers in organic crops, which can enhance soil fauna and in turn benefit generalist natural enemies (Aguilera et al., 2021; Riggi & Bommarco, 2019). This positive response of natural enemies to organic compared with conventional management aligns with findings in broader meta-analyses (e.g., Bengtsson et al., 2005; Lichtenberg et al., 2017; Tuck et al., 2014), signaling the widespread benefits of more stringent limits on chemical control in organic management. Higher biocontrol potential in organic than in conventional and in IPM olive crops at warmer temperatures likely results from an acceleration of natural enemy population development at those temperatures. The fact that similar increases did not occur in IPM compared with conventionally managed crops, suggests that natural enemy populations were limited by the application of synthetic inputs in IPM.

Herbivore pressure

The similar level of herbivore pressure in olive crops under IPM and in those managed conventionally is probably due to the use of synthetic pesticides in both strategies, which can directly reduce herbivores, despite also compromising top-down control by natural enemies. Although organic management did not enhance herbivores relative to conventional management, it had a strong positive effect on olive pests (primarily the secondary olive crop pest, *Euphyllura olivina*, which accounted for 81% of the olive pest data points obtained). Therefore, despite greater biocontrol potential in organic olive crops, this appears to be insufficient to regulate at least some olive pests. Additional targeted measures, such as the use of organic/biological inputs and/or mass trapping, are thus likely needed, as they were only reported in under 20% of the studies. The positive effect of organic management on olive pests but not on other herbivores could explain why prior meta-analyses have found variable effects of organic management on herbivores, as most have not differentiated between pests and non-pests (e.g., Bengtsson et al., 2005; Lichtenberg et al., 2017; Tuck et al., 2014; but see Garratt et al., 2011). As with biocontrol potential, higher herbivore pressure in organic than in conventional olive crops at warmer temperatures was probably a consequence of faster population growth rates. The fact that the level of herbivore pressure in IPM and conventional crops did not differ, regardless of temperature, again points to restricted population development due to synthetic inputs.

Conclusions

In its current limited form, IPM in olive crops appears to represent a negligible improvement in relation to conventional management, both in terms of biocontrol potential and herbivore suppression. Furthermore, a higher level of biocontrol potential was found in organic olive crops than in those under IPM. This suggests that a shift to a more comprehensive implementation of IPM in olive crops is needed, prioritizing proactive actions at the base of the IPM pyramid to promote natural enemies of crop pests and relying on chemical use only as a last resource (Zalucki et al., 2009). This might involve, for instance, retaining herbaceous cover within olive orchards to boost natural enemy abundance and predation rates (e.g., Álvarez et al., 2021; Paredes et al., 2013), as well as maintaining complex landscapes with more natural/semi-natural habitat and less crop cover that can benefit natural enemies and contribute to reductions in olive pest abundance (e.g., Costa et al., 2020). However, the paucity of studies providing information about parasitism/predation, crop damage and/or yield, prohibits assessments of the contributions natural enemies make to olive pest suppression and to production levels across management strategies. The ongoing intensification of olive farming also presents a challenge to this needed shift in IPM, as agricultural intensification tends to increase the reliance on chemical control (Deguine et al., 2021; Flor et al., 2018). It thus remains to be determined if a more comprehensive form of IPM is feasible in light of the recent and expanding intensification of olive farming, which involves much higher tree densities and more intensive chemical control (Morgado et al., 2020). The positive response of olive-pest herbivores to organic management suggests that higher biocontrol potential in organic olive crops does not translate to reduced pest pressure, and therefore additional organic and/or biological inputs might be required to more effectively regulate pests in organic farming. Overall, our results highlight the need for further research on the impacts of alternative management strategies within crop systems, particularly those of IPM, as this could improve the effectiveness of implemented policy frameworks. Moreover, our results suggest that the EU Farm to Fork strategy may fall short of its key environmental objectives, unless more comprehensive models of IPM are widely implemented.

Declaration of Competing Interest

None

CRediT authorship contribution statement

Sasha Vasconcelos: Conceptualization, Data curation, Formal analysis, Writing − original draft, Writing – review & editing. **Mattias Jonsson:** Conceptualization, Writing – review & editing. **Ruben Heleno:** Writing – review & editing. **Francisco Moreira:** Conceptualization, Writing – review & editing. **Pedro Beja:** Conceptualization, Writing – review & editing.

Acknowledgements

We thank José M. Herrera for contributing to an initial discussion about the study; Lucille Muneret for suggestions about data extraction and for kindly providing the R code for the temporal dependence sensitivity analysis; Sérgio Timóteo for helpful discussions at an initial stage of data analysis; and Juan Pablo Cancela for the immense help extracting the temperature data and for making the arthropod illustrations. This research was funded by the Portuguese Foundation for Science and Technology (FCT) through a grant to SV (SFRH/BD/121388/2016) and contracts to RH (UID/BIA/04004/2020) and FM (IF/01053/2015). PB was supported by EDP Biodiversity Chair and MJ by SLU centre for Biological Control. The work was co-funded by the project NORTE-01-0246-FEDER-000063, supported by Norte Portugal Regional Operational Programme (NORTE2020), under the PORTUGAL 2020 Partnership Agreement, through the European Regional Development Fund (ERDF)

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.baae.2022.05.009.

References

Aguilera, G., Riggi, L., Miller, K., Roslin, T., & Bommarco, R. (2021). Organic fertilisation enhances generalist predators and suppresses aphid growth in the absence of specialist predators. *Journal of Applied Ecology*, *58*, 1455–1465.

Álvarez, H. A., Jiménez-Muñoz, R., Morente, M., Campos, M., & Ruano, F. (2021). Ground cover presence in organic olive orchards affects the interaction of natural enemies against *Prays oleae*, promoting an effective egg predation. *Agriculture, Ecosystems and Environment*, *315*, 107441.

Bengtsson, J., Ahnström, J., & Weibull, A. C. (2005). The effects of organic agriculture on biodiversity and abundance: A meta-analysis. *Journal of Applied Ecology*, *42*, 261–269.

Boller, E. F., Avilla, J., Joerg, E., Malavolta, C., Wijnands, F. G., & Esbjerg, P. (2004). *Integrated production. principles and technical guidelines* (3rd ed.). Zürich: OILB/WPRS Bulletin.

Campos-Herrera, R., Gómez-Ros, J. M., Escuer, M., Cuadra, L., Barrios, L., & Gutiérrez, C. (2008). Diversity, occurrence, and life characteristics of natural entomopathogenic nematode populations from La Rioja (Northern Spain) under different agricultural management and their relationships with soil factors. *Soil Biology and Biochemistry*, *40*, 1474–1484.

Cárdenas, M., Ruano, F., García, P., Pascual, F., & Campos, M. (2006). Impact of agricultural management on spider populations in the canopy of olive trees. *Biological Control*, *38*, 188–195.

Cheung, M. W. L. (2014). Modeling dependent effect sizes with three-level meta-analyses: A structural equation modeling approach. *Psychological Methods*, *19*, 211–229.

Cook, R. D., & Weisberg, S. (1982). *Residuals and influence in regression*. New York: Chapman and Hall.

Costa, A., Silva, B., Jiménez-Navarro, G., Barreiro, S., Melguizo-Ruiz, N., Rodríguez-Pérez, J., et al. (2020). Structural simplification compromises the potential of common insectivorous bats to provide biocontrol services against the major olive pest *Prays oleae*. *Agriculture, Ecosystems and Environment*, *287*, 106708.

Daane, K. M., & Johnson, M. W. (2010). Olive fruit fly: Managing an ancient pest in modern times. *Annual Review of Entomology*, *55*, 151–169.

Deguine, J. P., Aubertot, J. N., Flor, R. J., et al. (2021). Integrated pest management: Good intentions, hard realities. A review. *Agronomy for Sustainable Development*, *41*, 38.

Egger, M., Davey-Smith, G., Schneider, M., & Minder, C. (1997). Bias in meta-analysis detected by a simple, graphical test. *British Medical Journal*, *315*, 629–634.

European Commission (2020). A farm to fork strategy for a fair, healthy and environmentally-friendly food system. Communication from the commission to the European parliament, the council, the European economic and social committee, and the committee of the regions. COM(2020) 381 final. https://ec.europa.eu/info/sites/info/files/communication-annex-farm-fork-greendeal_en.pdf

FAOSTAT. (2020). *Food and agriculture organization of the United Nations*Statistics Division. Retrieved from https://www.fao.org/faostat/en/#data/QCL Accessed February 17, 2022.

Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: New 1km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, *37*, 4302–4315.

Flor, R.J., Chhay, K., Sorn, V., Maat, H., & Hadi, B.A.R. (2018). The technological trajectory of integrated pest management for rice in Cambodia. *Sustainability*, 10, 1−14.

Garratt, M. P. D., Wright, D. J., & Leather, S. R. (2011). The effects of farming system and fertilisers on pests and natural enemies: A synthesis of current research. *Agriculture, Ecosystems and Environment*, *141*, 261–270.

Gonzalez, D., Cabral, J. A., Torres, L., & Santos, M. (2015). A cohort-based modelling approach for managing olive moth *Prays oleae* (Bernard, 1788) populations in olive orchards. *Ecological Modelling*, *296*, 46–56.

Harris, I., Jones, P. D., Osborn, T. J., & Lister, D. H. (2014). Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset. *International Journal of Climatology*, *34*, 623–642.

Hedges, L. V., & Olkin, I. (1985). *Statistical methods for meta-analysis*. Orlando, FL: Academic Press.

Hokkanen, H. M. (2015). Integrated pest management at the crossroads: Science, politics, or business (as usual)? *Arthropod-Plant Interactions*, *6*, 543–545.

Katayama, N., Bouam, I., Koshida, C., & Baba, Y. G. (2019). Biodiversity and yield under different land-use types in orchard/vineyard landscapes: A meta-analysis. *Biological Conservation*, *229*, 125–133.

Koricheva, J., Gurevitch, J., & Mengersen, K. (2013). *Handbook of meta-analysis in ecology and evolution*. Princeton University Press.

Krauss, J., Gallenberger, I., & Steffan-Dewenter, I. (2011). Decreased functional diversity and biological pest control in conventional compared to organic crop fields. *PloS One*, *6*, e19502.

Lichtenberg, E. M., Kennedy, C. M., Kremen, C., et al. (2017). A global synthesis of the effects of diversified farming systems on arthropod diversity within fields and across agricultural landscapes. *Global Change Biology*, *23*, 4946–4957.

Logan, J. D., Wolesensky, W., & Joern, A. (2006). Temperature-dependent phenology and predation in arthropod systems. *Ecological Modelling*, *196*, 471–482.

Lundin, O., Rundlöf, M., Jonsson, M., Bommarco, R., & Williams, N. M. (2021). Integrated pest and pollinator management − expanding the concept. *Frontiers in Ecology and Environment*, *19*, 283–291.

Meng, J., Li, L., Liu, H., Li, Y., Li, C., Wu, G., et al. (2016). Biodiversity management of organic orchard enhances both ecological and economic profitability. *PeerJ*, *4*, e2137.

Mili, S., Júdez, L., & de Andrés, R. (2017). Investigating the impacts of EU CAP reform 2014-20 and developments in sustainable olive farming systems. *New Medit*, *16*, 2–10.

Morgado, R., Santana, J., Porto, M., Sánchez-Oliver, J. S., Reino, L., Herrera, J. M., et al. (2020). A Mediterranean silent spring? The effects of olive farming intensification on breeding bird communities. *Agriculture, Ecosystems and Environment*, *288*, 106694.

Muneret, L., Mitchell, M., Seufert, V., Aviron, S., Djoudi, E. A., Pétillon, J., et al. (2018). Evidence that organic farming promotes pest control. *Nature Sustainability*, *1*, 361–368.

Nakagawa, S., Noble, D. W. A., Senior, A. M., & Lagisz, M. (2017). Meta-evaluation of meta-analysis: Ten appraisal questions for biologists. *BMC Biology*, *15*, 18.

Nakagawa, S., & Santos, E. S. A. (2012). Methodological issues and advances in biological meta-analysis. *Evolutionary Ecology*, *26*, 1253–1274.

Paredes, D., Cayuela, L., & Campos, M. (2013). Synergistic effects of ground cover and adjacent vegetation on natural enemies of olive insect pests. *Agriculture, Ecosystems and Environment*, *173*, 72–80.

Pekár, S. (1999). Effect of IPM practices and conventional spraying on spider population dynamics in an apple orchard. *Agriculture, Ecosystems and Environment*, *73*, 155–166.

Peters, J. L., Sutton, A. J., Jones, D. R., Abrams, K. R., & Rushton, L. (2008). Contour-enhanced meta-analysis funnel plots help distinguish publication bias from other causes of asymmetry. *Journal of Clinical Epidemiology*, *61*, 991–996.

Pimentel, D. (2005). Environmental and economic costs of the application of pesticides primarily in the United States. *Environment, Development and Sustainability*, *7*, 229–252.

Rega, C., Short, C., Pérez-Soba, M., & Paracchini, M. L. (2020). A classification of European agricultural land using an energy-based intensity indicator and detailed crop description. *Landscape and Urban Planning*, *198*, 103793.

Riggi, L. G., & Bommarco, R. (2019). Subsidy type and quality determine direction and strength of trophic cascades in arthropod food webs in agroecosystems. *Journal of Applied Ecology*, *56*, 1982–1991.

Rohatgi, A. (2015). WebPlotDigitizer. URL. https://automeris.io/WebPlotDigitizer

Rosenberg, M. S. (2005). The file-drawer problem revisited: A general weighted method for calculating fail-safe numbers in meta-analysis. *Evolution; International Journal of Organic Evolution*, *59*, 464–468.

Rosenberg, M., & Rothstein, H. (2013). Effect sizes: Conventional choices and calculations. In J. Koricheva, J. Gurevitch, K. Mengersen (Eds.), *Handbook of meta-analysis in ecology and evolution*. Princeton University Press.

R Development Core Team. (2020). R: A Language and Environment for Statistical Computing. Vienna, Austria.

Seufert, V., Ramankutty, N., & Foley, J. A. (2012). Comparing the yields of organic and conventional agriculture. *Nature*, *485*, 229–232.

Stenberg, J. A., Sundh, I., Becher, P. G., Björkman, C., Dubey, M., et al. (2021). When is it biological control? A framework of definitions, mechanisms, and classifications. *Journal of Pest Science*, *94*, 665–676.

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature*, *418*, 671–677.

Tuck, S. L., Winqvist, C., Mota, F., Ahnström, J., Turnbull, L. A., & Bengtsson, J. (2014). Land- use intensity and the effects of organic farming on biodiversity: A hierarchical meta- analysis. *Journal of Applied Ecology*, *51*, 746–755.

Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. *Journal of Statistical Software*, *36*, 1–48.

Viechtbauer, W., & Cheung, M. W. L. (2010). Outlier and influence diagnostics for meta- analysis. *Research Synthesis Methods*, *1*, 112–125.

Wang, M. C., & Bushman, B. J. (1998). Using the normal quantile plot to explore meta-analytic data sets. *Psychological Methods*, *3*, 46–54.

Wittwer, R. A., Bender, S. F., Hartman, K., Hydbom, S., Lima, R. A. A., Loaiza, V., et al. (2021). Organic and conservation agriculture promote ecosystem multifunctionality. *Science Advances*, *7*, eabg6995.

Wyckhuys, K. A. G., Heong, K. L., Sanchez-Bayo, F., Bianchi, F. J. J. A., Lundgren, J., Bentley, J. G., et al. (2019). Ecological illiteracy can deepen farmers' pesticide dependency. *Environmental Research Letters*, *14*, 093004.

Zalucki, M. P., Adamson, D., & Furlong, M. J. (2009). The future of IPM: Whither or wither? *Australian Journal of Entomology*, *48*, 85–96.