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Evaluation of interactions between honeybees and alternative managed pollinators: A meta-analysis of their effect on crop productivity

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ABSTRACT

The productivity of approximately 75% of crops worldwide depends to some extent on insect pollination. However, while global agriculture is becoming more dependent on pollinators, wild populations of pollinators are declining. For this reason, hives of *Apis mellifera* (honeybees), the most widely used pollinator, are commonly placed in the fields; in recent years, alternative managed pollinators (AMPs) such as *Bombus* spp. or *Osmia* spp. have also been used. Thus, for evidence-based pollination management, we need to know whether the pollination service provided by AMPs can replace, complement or synergistically interact with that provided by honeybees. We asked: Does crop productivity differ between fields with honeybees and those with AMPs? Does productivity increase by incorporating AMPs in addition to managed honeybees? Do the effects of managed honeybees and AMPs interact? We performed a meta-analysis based on 28 studies on 20 crops. We estimated effect sizes (ln(R)) for crop productivity (fruit/seed set, fruit/seed quality and yield) from 73 comparisons between honeybees and an AMP, and 21 comparisons between honeybees alone and honeybees plus an AMP. Overall, we found no evidence of difference in crop productivity between honeybees and AMPs when managed separately. However, the productivity of crops pollinated by honeybees together with AMPs was 22% ± 6 (SE) higher than that of crops pollinated only by honeybees. Moreover, we found a weak evidence of a positive effect of beehive density on crop productivity when an AMP was added, suggesting a synergistic interaction between honeybees and AMPs. We conclude that, on average, honeybee performance is similar to that of AMPs, and that increasing the number of managed pollinator species can improve crop productivity in the short-term, particularly in systems with impoverished pollinator faunas. More generally, this review confirms the positive effect of pollinator diversity on pollination service, suggesting this can be partly recreated using a suite of managed pollinators.

1. Introduction

Worldwide, ~75% of crop species depend to some extent on animal -mostly insect -pollination for crop productivity, making this a key function of agroecosystems (Klein et al., 2007). Global agriculture is becoming steadily more dependent on pollinators, given that the increase in area devoted to agriculture experienced in the last four decades has been majorly driven by pollinator-dependent crops (Aizen et al., 2008, 2019a). At the same time, the wild populations of pollinators that contribute to crop productivity (Garibaldi et al., 2013) are in decline due to habitat and forage loss and management practices that use vast amounts of agrochemicals (Kennedy et al., 2013; Biesmeijer et al., 2006; Goulson et al., 2010; Kremen et al., 2002, Potts et al., 2016). For this reason, to fulfill the pollination demand of pollinator-dependent crops and increase crop productivity, managed pollinators such as *Apis mellifera*, *Bombus* spp. and *Osmia* spp. are commonly placed in the fields,

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honeybees being by far the most widely used pollinator (Osterman et al., 2021; Paudel et al., 2015).

However, relying on *Apis mellifera* as a universal managed pollinator has some drawbacks. First, a recent global meta-analysis has demonstrated that deploying honeybee hives can reduce pollen limitation in self-compatible crops, but not in self-incompatible crops (Sáez et al., 2022), and despite the generalist characteristics of *Apis*, several crops are not efficiently pollinated by this species (e.g., Grass et al., 2018, MacInnis and Forrest, 2019). Second, in recent decades concern has risen over the regional increase of overwintering colony losses, especially in the United States of America and Europe (vanEngelsdorp et al., 2008, Potts et al., 2010), but also and more recently in Latin America (Requier et al., 2018). This situation has focused attention on alternative managed pollinators (hereafter, AMPs), such as some species of bumblebees (*Bombus* spp.) and solitary bees like *Osmia* spp. or *Megachile* spp.. A recent study has reviewed 66 insect species that have been managed or have the potential to be managed for crop pollination (Osterman et al., 2021). In spite of this increasing interest in AMPs, to date there is no quantitative synthesis that compares their performance, in crop productive variables, with that of the most important managed pollinator worldwide, the western honeybee *Apis mellifera* (but see Junqueira et al., 2021).

The productivity of pollinator-dependent crops improves with greater abundance and/or diversity of pollinators through several potential mechanisms (Winfree and Kremen, 2009, Garibaldi et al., 2013). The first is niche complementarity, when different species forage under different environmental conditions (Blüthgen and Klein 2011, Hoehn et al., 2008, Ellis et al., 2017). The second, sampling effect, occurs when greater richness increases the probability of including a species that can provide effective pollination (Klein et al., 2009; e.g., solitary bees pollinate alfalfa crops more efficiently than honeybees do). These two mechanisms imply that the observed effect of richness or diversity on productivity is due to complementarity or an additive effect (that is, productivity increases linearly with the inclusion of more species). Finally, a third mechanism is the synergistic interaction between species, when the efficiency of a species is increased in the presence of another species through behavior modification (Winfree and Kremen, 2009). In this case, in an environment with more pollinators the productivity of a crop will be greater than the sum of the productivity of that crop when pollinated by each pollinator species separately. Indeed, there is a paucity of studies that have spotted synergistic interaction between *Apis mellifera* and wild species of bees. For instance, DeGrandi-Hoffman and Watkins (2000) found that the amount of pollen in the body of managed honeybees increased with the abundance of non-*Apis* bees. In addition, Eeraerts et al. (2020a) found that honeybees changed between sweet cherry tree rows more frequently as wild bumblebees increased in abundance. This behavioral change was also observed to be produced with the presence of other non-*Apis* bees (Brittain et al., 2013; Greenleaf and Kremen, 2006). Exploring how these different mechanisms play out with *Apis mellifera* and AMPs could make more efficient pollination management possible. Moreover, the effect on productivity of increasing the number of managed pollinators and the interaction between managed pollinators have been investigated much less, and may give new insights into the role of AMPs in pollination services.

Evaluation of the pollination carried out by pollinators normally focuses on the study of single visit effectiveness in terms of pollen deposition or seed or fruit formation (reviewed in Page et al., 2021). This approach is especially valuable in community and network studies, since it enables us to distinguish between mere flower visitors and effective/efficient pollinators; i.e., those flower visitors that deposit conspecific pollen on a flower's stigmatic surface (Ne'eman et al., 2010, King et al., 2013). However, crop pollination in agro-ecosystems is the result of several visits received during the time of crop flower receptivity (see Table 1 in Garibaldi et al., 2020). Since recommendations for agricultural practices should be based on farmer-relevant scales, measurements, and units tested in real-world settings, we aimed to evaluate, on a farm scale, the final effect of honeybees and AMPs on crop productivity; i.e., fruit set (e.g., fruit per flower), seed set (e.g., seeds per fruit), their quality (e.g., weight), and/or crop yield (e.g., tn/ha).

Table 1
Overall effect sizes for comparative (i.e., alternative managed pollinator vs *Apis mellifera*) and additive experimental designs (*Apis mellifera* plus alternative managed pollinator vs *Apis mellifera*). Overall effect size shows the 95% confidence interval in brackets. N = number of comparisons analyzed. The number of studies included in the analysis are given in parenthesis.

	Number of comparisons for each response variable		
	Fruit/seed set	Quality	Yield
Comparative	-0.08 [− 0.22, 0.06] N = 37 (13)	-0.06 [− 0.13, 0.01] N = 16 (9)	-0.35 [− 1.00, 0.30] N = 20 (12)
Additive	0.22 [0.10, 0.35] N = 21 (11)	–	–

In this work we synthesized and quantified current scientific knowledge on the effect of honeybees and alternative managed pollinators on crop productivity. With a meta-analysis approach, we sought to answer the following questions: 1) Does crop productivity differ between honeybee and AMP pollinated fields? 2) Does the incorporation of AMPs in addition to managed honeybees increase crop productivity? 3) Does the effect of managed honeybees interact with the effect of AMPs?

2. Materials and methods

2.1. Literature search and data collection

We performed a literature search in Scopus, covering publications from 1962 to 2022 (last search November 23, 2021) using the following search strings: "Pollination" AND ("Fruit set" OR "Seed set" OR "Yield" OR "Production" OR "Productivity") AND ("Apis" OR "Honeybee" OR "Honey bee" OR "Honeybees" OR "Honey bees") AND ("Bombus" OR "Bumblebees" OR "Bumble bees" OR "Bumblebee" OR "Bumble bee" OR "Osmia" OR "Megachile" OR "Solitary bees" OR "Melipona" OR "Xylocopa"). A total of 349 articles were found. Given that Scopus is only capable of searching in titles, abstracts and keywords, we performed a complementary search using Google Scholar, which provides a full-text search.

Studies were comprehensively screened to assess whether they met the following criteria. First, the pollination must be performed by managed honeybees and at least one AMP. Second, the studies must evaluate the effect of crop pollination on any measure of crop productivity (i.e., fruit/seed set, fruit/seed quality, and/or crop yield (e.g., kg/ha)). Hence, we did not consider studies evaluating the effectiveness and/or efficiency of a single visit on pollen deposition or crop production, or other behavioral aspects of pollinators (e.g., frequency of switching between trees, Eeraerts et al., 2020b). In addition, studies in which management conditions varied between pollinator treatments (e.g., *Apis mellifera* in open field vs. *Bombus* spp. in a greenhouse) were also discarded. When the title and abstract screening leave doubts whether the study met with our criteria, we proceed to the full text screening.

We categorized the studies according to three experimental designs: comparative, additive and interactive. Studies with a comparative design applied the following two treatments: *Apis mellifera* vs AMPs. Studies with additive design applied the following two treatments: *Apis mellifera* vs *Apis mellifera* plus AMPs. Interactive design applied the following three treatments: *Apis mellifera* vs AMPs vs *Apis mellifera* plus AMPs. Therefore, the interactive design could be considered a combination of the previous two designs. Indeed, the data from this design were incorporated in the meta-analyses of the first two designs.

For each study we extracted the mean, standard deviation and number of observations of fruit/seed set, fruit/seed quality, and/or yield (e.g., kg/ha). When some of these values were missing, we tried to contact the authors. If the data were presented graphically, we extracted the values using the software *PlotDigitizer* (http://plotdigitizer.

sourceforge.net). We also classified the degree of pollinator dependence of each crop using the categories of Klein et al. (2007) (see Supp. Mat. 2 ibidem). When a crop was not classified, we were able to categorize it based on the result of that study, following the methods of Klein et al. (2007). This was done using the data of open and exclusion treatments performed in those studies. Tables A.1 and A.2 (Appendix) list all articles found.

2.2. Data analysis

For the calculation of effect sizes and statistical analysis, we only used studies with complete data (i.e., mean, SD and N, Tables A.1 and A.2). The effect sizes calculated represent the relative difference between the effects of the pollination treatments (i.e., *Apis* vs AMP, or *Apis* vs *Apis* plus AMP) on the crop productivity variable. When a study reported results for more than one year the effect sizes were calculated separately for each year, and all were included in the model. In studies that reported results of individual farms, we calculated the mean of all the farms together. To compare the responses to treatments in terms of crop productivity, we used the natural logarithm of the response ratio (i.e., Ln(R)) between treatment "AMP" (for comparative designs) or "*Apis* plus AMP" (for additive designs) and "*Apis*" as effect size. This metric linearizes and normalizes the relative difference between two treatments, as a measure of effect size across the studies. Ln(R) was estimated as X_{AMP}/X_{Apis} for the comparative design, and as $X_{AMP+Apis}/X_{Apis}$ for the additive design, where X_{AMP}, $X_{AMP+Apis}$ and X_{Apis} are the mean crop productivity values observed in experimental settings deploying AMP, AMP plus *Apis* or *Apis*, respectively. A positive value in the comparative design analysis (first question) indicates that crop productivity was higher with AMP than with *Apis* alone, whereas in the additive design analysis (second question), it indicates higher productivity with *Apis* plus alternative pollinator than with *Apis* alone. A negative value indicates the opposite, while the null value represents no difference between treatments. Calculations were made with R software (R Core Team, 2021), effect sizes were calculated with *escalc* function and overall effect sizes were calculated with *rma.mv* function, both from the 'metafor' package (Viechtbauer, 2010). Because responses in the same study are not completely independent, we included the study identity (study ID) as a random factor. It would have been desirable to also include crop species as a random factor, since there could be trends resulting from comparing crops with different characteristics. However, since most crop species were only represented in one study (Tables A.1 and A.2 in Appendix), adding this variable as a random factor did not add new information to our models. So the random factor "study ID" works as a composite variable that considers both the effect of the crop species together with the experimental setting of a given study. Publication bias was graphically tested using funnel plots (Fig. A.1 in Appendix).

We decided to run three separate meta-analyses, one for fruit/seed set, one for fruit/seed quality, and one for crop yield, since these variables might not necessarily be governed by the same physiological and ecological processes and therefore can even show contrasting responses (Dennis, 2000; Davis et al., 2004, Greene and Costa 2012). However, this was only possible for the comparative design, because we lacked sufficient data from additive design to test fruit/seed quality and yield (7 and 4 effect sizes respectively); we therefore drew up a model only for fruit/seed set response.

Finally, due to the low quantity of studies with the interactive design, we could not perform an individual meta-analysis for this design. To answer the question of whether honeybees interact with AMP, we therefore took the following approach: For the studies with an additive design, we registered honeybee hive density (it was informed in all studies as hives per ha.) and then regressed fruit/seed set effect size as a function of hive density. If the honeybees interact with AMPs, the effect sizes in additive design will be greater with greater density of beehives. Then, a positive interaction (synergy) between AMPs and *Apis mellifera* was indicated by a positive slope. A slope close to zero points to additive effects (or a complementary effect), while a negative slope indicates negative interaction. We performed this analysis with the *lme* function of the 'nlme' package (Pinheiro et al., 2017). Honeybee hive density was set as a fixed effect and study ID was set as a random effect. The assumptions of normality, independence and homoscedasticity of the model were checked visually (QQ-plot, predicted vs. residuals and histogram of residuals).

3. Results

3.1. General overview

We found 43 suitable studies (31 comparative design, 9 additive design and 3 interactive design) from which we obtained the complete data needed for its inclusion in a meta-analysis, i.e., mean, standard deviation and sample size, of 28 studies (17 comparative design, 9 additive design and 2 interactive design) (Fig. 1 and Tables A.1 and A.2, Appendix). Thirty crops belonging to 12 families were studied, Rosaceae (e.g., apple, almond) being the family most represented with 15 studies; followed by Ericaceae (e.g., blueberries) and Fabaceae (e.g., alfalfa) with 5 studies each; Solanaceae (e.g., tomato) and Cucurbitaceae (e.g., pumpkin) with 4 studies each; Brassicaceae (e.g., oilseed rape) with 3 studies; Asteraceae (e.g., sunflower) with 2 studies; and Actinidiaceae (kiwifruit), Apiaceae (carrot for seed production), Lamiaceae (wood betony), Paeoniaceae (oil peony tree) and Sapindaceae (lychee) with 1 study each. Twenty-three crops were perennial while twenty were annual, and most of them were from temperate climates, with a few exceptions like sweet pepper, chili pepper and melon.

3.2. Comparisons between Apis and alternative managed pollinators

The 19 studies with complete data (17 from comparative design and 2 from interactive design) evaluated in 12 crops the effect of *Apis mellifera* and AMPs on crop productivity (Table A.1). Crop pollinator dependence ranged from little (production reduction of <10% in the absence of pollinators) to essential (a reduction of >90%). Alternative pollinator species belonged to the genera *Bombus*, *Osmia*, *Megachile, Xylocopa*, *Melipona* and *Eristalis*. Most of the studies (15) were performed under greenhouse conditions; only three were open field and one study presented both conditions.

The overall effect sizes of our three analyses (i.e., response variables fruit/seed set, quality, and yield) are given in Table 1. Visualization of funnel plots indicates no publication bias (Fig. A.1 a,b,c). The 95% confidence intervals associated with all three effect sizes overlapped zero, indicating no statistically significant evidence of difference in crop productivity between pollination carried out by managed honeybees and AMPs. However, the fruit/seed set model showed considerable heterogeneity in the response, depending on the AMP species (Fig. 2-A). While the lack of evidence of effect was consistent among *Bombus* and other genera of managed pollinators, the *Osmia* effect sizes were consistently below zero.

3.3. Effect of incorporating an alternative managed pollinator together with Apis

Eleven studies (including the two with the interactive experimental design) with complete data evaluated in eight crops the effect of *Apis mellifera* plus AMP on crop productivity (Table A.2). The pollinator dependence level of most of the crops studied was categorized as great (production reduction between 40% and 90%), with the exception of two crops, one whose pollinator dependence was little and the other whose dependence was modest. Alternative pollinator species belonged to the genera *Bombus*, *Osmia*, *Megachile* and *Melipona*. Unlike the comparative studies, all additive studies were conducted in the open field and did not control total pollinator abundance. Analysis of the

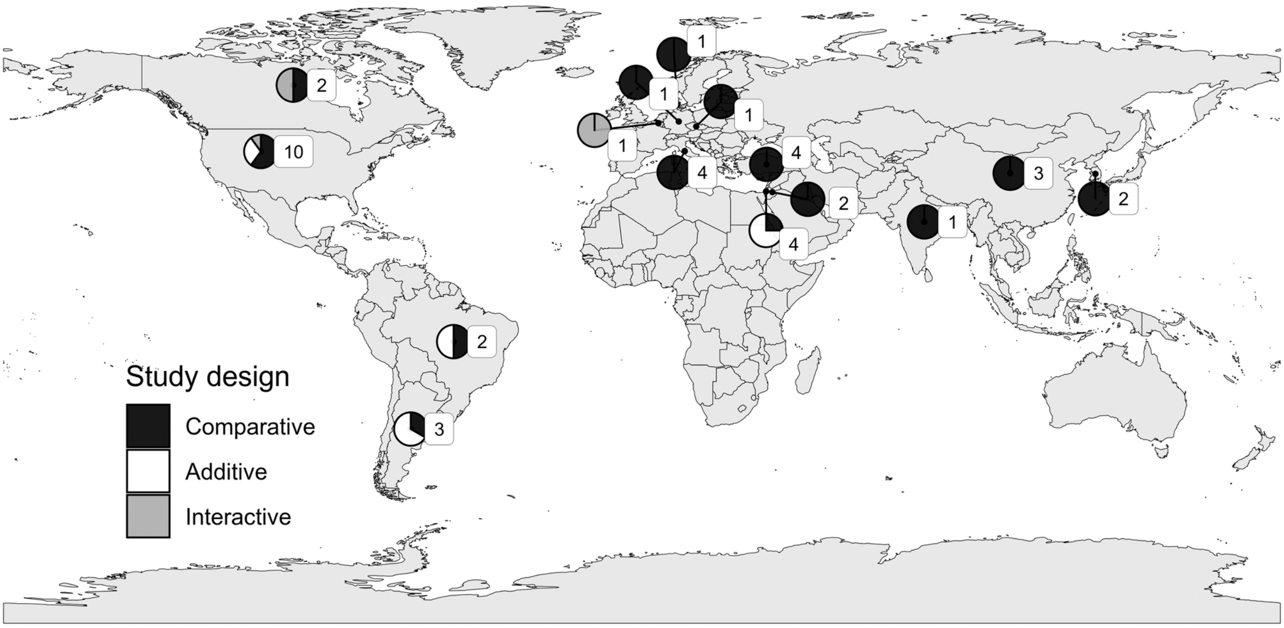

Fig. 1. Geographic distribution of the studies found. The number indicates the number of studies, while the pie charts show the proportion of each type of experimental design (black: comparative; white: additive; and gray: interactive).

fruit/seed set response showed an overall effect size (95% CI) of 0.22 (0.10, 0.35), indicating a strong ($p < 0.01$) evidence of a positive effect of the inclusion of another pollinator together with honeybees, which implies an increase of 22% ± 6 (SE) in crop productivity (Fig. 2-B, Table 1). Visualization of funnel plots indicates no publication bias (Fig. A.1 d).

3.4. Evidence of interactions between Apis and alternative pollinators

Only 3 studies (2 of which provided full data) used the interactive experimental design (Brittain et al., 2013; Fulton et al., 2015, Smessaert et al., 2018). Brittain et al. (2013) found evidence of a synergistic effect on almond fruit set when deploying *Apis* and *Osmia*, while Smessaert et al. (2018) found that using *Apis* alone produced higher levels of fruit set and yield in pear crop than when using *Bombus* alone or *Apis* together with *Bombus* (i.e., negative interaction). In turn, Fulton et al. (2015) presented a plethora of analyses in several dimensions of pollination and production of apples (e.g., economic assessment, behavioral changes of managed pollinators, stigmatic pollen load); however, despite using the interactive experimental design, the data were not analyzed in this direction. We calculated the effect of the three treatments (*Apis*, AMPs and *Apis*+AMPs), and found no evidence of difference between them (i.e., no interaction, data not shown). However, our alternative approach to this question, based on the effect of beehive density, provided further insights. The effect size of adding an AMP to crops with honeybees had a marginally significant response to increasing honeybee hive density, suggesting a synergistic interaction between honeybees and AMPs ($t\text{-value}_{8DF} = 2.132$, p-value = 0.067, Fig. 3).

4. Discussion

Our review assessed three topics: the relative performance of alternative managed pollinators with respect to honeybee, the possibility of improving honeybee pollination with the addition of alternative managed pollinators and the interaction between honeybee and alternative managed pollinators. Here we discuss the implications of our findings, their limitations, and possible future steps for investigation.

We found no evidence of a difference between the productivity of crops pollinated by managed honeybees and those pollinated by AMPs, particularly *Bombus*. A similar result was reported by Junqueira et al. (2021), who compared through a meta-analysis the contribution of *Apis* and non-*Apis* bees in the context of flower exclusion treatments. On the other hand, Page et al. (2021) conducted a meta-analysis of single visit efficiency and found that on a per visit basis, honeybees performed worse even than the average bee pollinator in pollinating crops (see Fig. 3 in Page et al., 2021). This result, which seemingly contradicts ours, may be explained by the high abundance and visit frequency of honeybees, which in turn may compensate for their lower per capita efficiency. The number of individuals in a honeybee hive (in the order of tens of thousands) may be several orders of magnitude higher than in a bumblebee colony box (e.g., ca. one hundred workers, Cavigliasso et al., 2020) or in the management units of solitary bees (e.g., 120 nests of *Osmia*, Pinzauti et al., 1996). For example, King et al. (2013) found that for *Agrimonia eupatorium,* the pollinator species with most pollen deposition on an hour and day basis was the least effective on a single visit basis. Similarly, Olsen (1996) defined “pollinator importance” as being the product of effectiveness and relative abundance, thus the most important pollinators of *Heterotheca subaxillaris* are those with intermediate levels of efficiency and relative abundance. Finally, Vázquez et al. (2005) showed through meta-analysis that the frequency of interaction between pollinators and flowers has a strong positive association with final pollination, rather than the per-interaction effect. While single visit efficiency studies are important for community and network studies (King et al., 2013), the results presented here highlight the value of analyzing the final effect of pollinators on crop productivity.

Comparative designs were usually implemented in greenhouses or flight cages (83% of the studies included in the meta-analysis). Although in this confined environment it could be expected that *Apis mellifera* performance would be compromised, we found no evidence of this. These findings are particularly relevant, since the global trade in bumblebees is based on the belief that *Bombus* are better pollinators than *Apis* in confined systems (Abrol, 2012, Dag, 2008). The result of this trade is immense propagule pressure, which facilitates the invasion of these species, causing a wide variety of negative impacts to native ecosystems and agriculture (Aizen et al., 2019b).

We found only eleven studies with complete data (including those with the interactive design) that analyzed the effect of deploying alternative pollinator species together with *Apis mellifera*. In 76% of fruit set

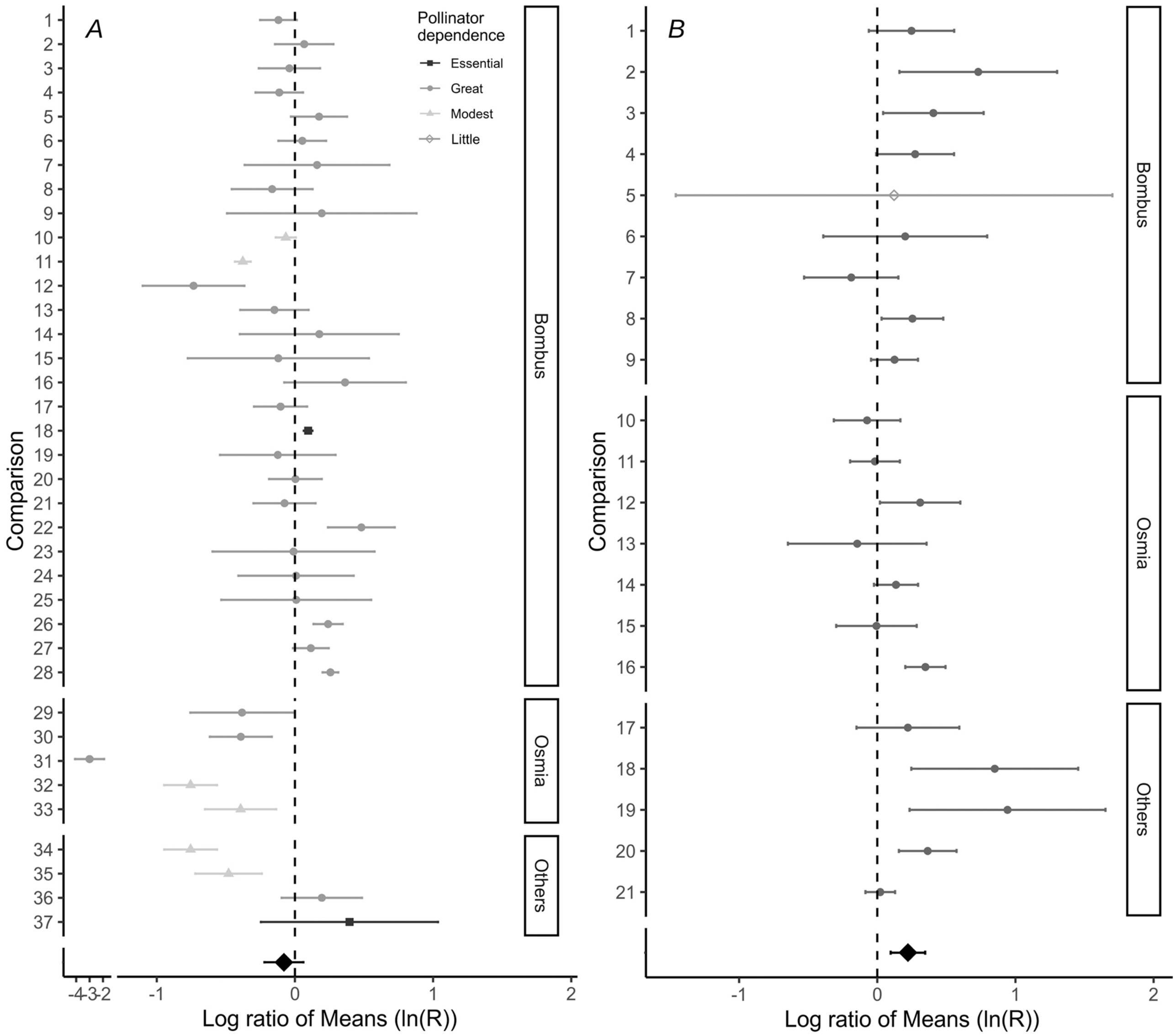

Fig. 2. Forest plot representing the effect size of fruit/seed set for each comparison for comparative and additive design analysis. The effect size represents the difference in fruit set or seed set between pollination treatments, A: alternative managed pollinator vs *Apis* and B: alternative pollinator plus *Apis* vs *Apis*. Circles, squares, triangles and rhombuses indicate the effect size comparison (and whiskers show the 95% confidence interval. The alternative pollinators studied are named on the right. Overall effect size is shown by a black diamond at the bottom of the plot. For clearer visualization comparisons were numbered, and references are given in Table A.3 (Appendix 1). A positive value in panel A (comparative design) indicates that crop productivity was higher with AMP than with Apis alone, whereas in panel B (additive design), it indicates higher productivity with Apis plus alternative pollinator than with Apis alone. A negative value indicates the opposite, while the null value represents no difference between treatments.

and seed set comparisons the effect was consistent and positive, leading to an overall increase in productivity of 22% (Fig. 2-B). While both complementary and synergistic interaction can produce this effect, the analysis of beehive densities suggests that the mechanism underling this pattern is a synergistic effect (Winfree and Kremen, 2009). Furthermore, the performance of *Osmia* when comparing the comparative and the additive designs also supports this explanation. When comparing the productivity of the crops pollinated by *Apis* or *Osmia*, it can be seen that the former produced better results, so it could be expected that the combination of these two pollinators would not generate an appreciable effect. However, analysis of Fig. 2-B, reveals that additive or synergistic effects were produced by the inclusion of *Osmia*, demonstrating that pollinator richness is essential for good agricultural yields.

4.1. Caveats, limitations and future research

One important limitation of the studies included in these meta analyses was the experimental conditions. Most comparative design studies were performed in flight cages or greenhouses, which is an uncommon condition for the majority of the crops studied. This makes any conclusion as to the effect of managed pollinators difficult to extrapolate to most real-world crop systems. In fact, Smessaert et al. (2018) explain that the negative effect they found of bumblebees and bumblebees plus honeybees was probably due to over-pollination of the pear trees in the cages assigned to those treatments (in concordance with Sáez et al., 2014). In open field studies, on the other hand, it can be difficult to distinguish between the effect of managed pollinators and other factors that may influence productivity, including wild pollinators. However, if carried out in an appropriate system, more accurate conclusions can be reached from these studies regarding the performance of these pollinators in terms of improving crop productivity.

Concerning additive and interactive studies, only one (Fulton et al., 2015) of the 12 studies controlled in some way the total number of individual pollinators in each treatment. For this reason, it is possible that

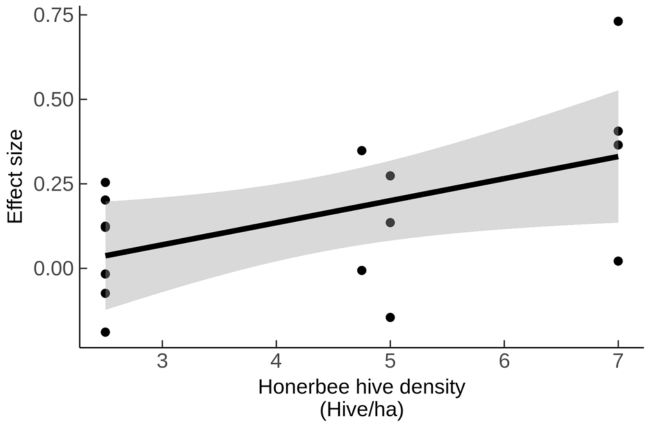

Fig. 3. Effect sizes from additive design studies versus honeybee hive density. The effect size represents the difference in fruit set or seed set between pollination treatments (*Apis* plus alternative pollinator vs *Apis*). A positive value indicates an improvement in response with the addition of an alternative pollinator. The gray band represents the 95% confidence interval of the prediction line.

the positive effect we found with the addition of AMPs to crops with honeybees is due to an increase in the absolute number of individuals visiting the crop flowers, regardless of their species. In any case, this mechanism does not explain the positive slope found in our beehive density analysis (Fig. 3), which suggest a synergistic effect between honeybees and AMPs. However, future research using these designs should incorporate an "abundance control" to prevent the misinterpretation of results and enable the effect of increasing diversity to be disentangled from the effect of increasing pollinator abundance.

Our analyses to address whether there might be synergistic interaction of honeybees and AMPs using honeybee hive density should be taken with caution. First, the number of points for analysis was very low and therefore the evidence is weak (i.e., p value = 0.067). Second, honeybee hives density might not be the best indicator of honeybee pollination performance, as honeybee hive quality is an important factor driving agricultural productivity (Geslin et al., 2017). Third, as we stated in the previous paragraph, all these studies were carried out in open field, which can introduce “noise” produced by the abundance of other insects or landscape effect. Finally, given the low quantity of studies, we do not have different densities of honeybee hive for the same crop. However, the density of honeybee hives used in each study correspond to the stocking density recommended for the crop studied (Rollin and Garibaldi, 2019). All in all, future investigations could replicate this analysis, with controls for honeybee hive quality, pollinators abundance, and a gradient of honeybee hive density.

In this work, we analyzed a multiplicity of crops with a different degree of pollinator dependence. Despite this, we were able to find strong patterns regarding the effect of honeybees and AMPs on crop productivity. Future research should investigate how these relationships change according to crop type (e.g., fruit crops or arable crops). Moreover, the pollinator dependence of the crop could modulate the effect of managed pollinators. In this study we were not able to test this issue analytically, as the data were few and unbalanced. Visual analysis does not suggest a clear pattern (Fig. 2). This can be due to several reasons. For example, crop pollinator dependence could change according to cultural practices and intra-specific variation (i.e., varieties within a crop). To address these questions, a greater number of studies and more information at intra-specific level are necessary.

It should be noted that the use of managed pollinators, whether honeybees or AMPs, is associated with several risks. First, the movement of species outside their native range can result in new species invasions (Agüero et al., 2020; Morales et al., 2013). Second, managed pollinators can spill over from crop fields to natural habitats, altering interaction networks between native plants and pollinators (Agüero et al., 2020; González-Varo and Vila, 2017). Third, the reared pollinator species (both honeybees and AMPs) can facilitate the spread of pollinator diseases through both inter and intra specific transmission (Arbetman et al., 2013; Colla et al., 2006; Fürst et al., 2014; Meeus et al., 2018). In fact, one possible cause of honeybee colony loss is the increasing incidence of several diseases, which is probably a product of the movement of beehives for crop pollination across great distances (Potts et al., 2010). Furthermore, if in addition to the environmental cost of using managed pollinators we consider the economic implications of hiring pollination services, we find another reason to search for alternatives to managed pollination (Velthuis and van Doorn 2006; Rucker et al., 2012). Taking all this into consideration, it would seem advisable to encourage the application of agricultural practices to boost natural populations of wild pollinators wherever they can provide crops with reliable pollination (Garibaldi et al., 2013; Kennedy et al., 2013).

5. Conclusion

We conclude that managing crop pollination through deployment of honeybee hives combined with other AMPs may constitute a short-term strategy for increasing crop productivity, but this decision must be taken with awareness of its possible impact on biodiversity. For example, our analysis of the comparative studies shows no evidence that the effect of the honeybee on productivity does not differ, on average, from that of alternative managed pollinators, so the use of the former may have less impact in regions where beekeeping is common practice, whereas the use of AMPs may be a better choice in regions where they are native. Nonetheless, our results show that using AMPs together with *Apis*, thus increasing the number of managed pollinators, may be a good short-term option to improve crop productivity, particularly in systems with impoverished pollinator faunas.

Authors’ contributions

PLH and LAG conceived the idea. PLH performed the bibliographic search and analyzed the data. PLH and CLM led the writing of the manuscript with inputs from AEV and LAG. All authors gave final approval for publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2022.108156.

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