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Widespread pollination deficits in pear (*Pyrus communis* L.) orchards: The role of pollinators, landscape context and pesticide risk

Lucia Lenzi [a,*], Xavier Arnan [b], Jordi Bosch [c], Adele Bordoni [a,1], Laura Zavatta [a], Serena Magagnoli [a], Agata Morelli [a], Fabio Sgolastra [a]

[a] Dipartimento di Scienze e Tecnologie Agro-alimentari, Alma Mater Studiorum Università di Bologna, Bologna 40127, Italy
[b] Universidade de Pernambuco, Garanhuns 55294-902, Brazil
[c] CREAF, Centre de Recerca Ecològica i Aplicacions Forestals, Bellaterra 08193, Spain

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ABSTRACT

European pear (*Pyrus communis* L.) is an important entomophilous crop, and most varieties are self-incompatible, therefore strongly dependent on insect pollinators for fruit set. However, harsh conditions during bloom and low sugar content of nectar compared to other co-flowering fruit trees often lead to low pollinator visitation rates, causing shortfalls in production. Pollination deficits and the contribution of pollinator communities to pollination services have been well studied in apples, but we know much less about pollination services in pears. The aim of this study was to assess pollination services and detect pollination deficits in pear orchards, and to analyze the effects of local factors (pesticide load and other orchard management) and landscape factors ("pollinator-friendly" cover) on pollinators and pollination services. Despite the effect of orchard management on fruit retention, our results confirm the dependence of fruit set on pollination (mean: 37 %; range: 0 %-80 %). Our results also report significant pollination deficits across pear orchards (mean: 31 %, range: 0 %-74 %), and low pollination service (mean: 17 %, range: 0 %-60 %). The most abundant flower visitors were honeybees and Diptera Muscidae, while wild bees were the least abundant group. However, "pollinator-friendly" cover at 1.5 km had significant positive effect on wild bees' visitation rate. Managed (honeybees and bumblebees) and wild pollinators (all other pollinators) had no effect on pollination deficit, but higher bumblebee visits negatively affected seed set. Chemical analysis of pear flowers revealed high levels of pesticides residue, as all flowers were contaminated with at least four different pesticides, and pesticide risk had a negative effect on fruit set. Our results indicate insufficient pollination services in pear orchards and raise concerns about the management of pollination provision, highlighting the importance of semi-natural areas to boost wild bee visits and reduce pesticide pressure on pollinators.

1. Introduction

Almost 90 % of wild angiosperms and 75 % of the main agricultural crops rely on animals, mostly insects, for pollination (Klein et al., 2007; IPBES, 2016; Ollerton, 2017). Importantly, an important fraction of crop pollination services is provided by wild pollinators (Garibaldi et al., 2013), which are experiencing dramatic declines, largely driven by intensive agriculture, resulting in habitat loss and pesticide contamination (Bartomeus et al., 2013; Ollerton, 2017; Ramos-Jiliberto et al., 2020).

Agricultural intensification, exemplified by mass-flowering monoculture farms, is one of the major drivers of pollinator declines, mediated by the reduction of seminatural ecosystem cover, habitat degradation and decreased floral resources (Scheper et al., 2014). Natural habitats are essential to preserve nesting sites and diversified floral resources, thereby shaping diverse pollinator communities. Numerous studies have documented the positive effect of natural and seminatural landscape cover surrounding crops on arthropods, thus enhancing the provision of ecosystem services, including pollination (Ganser et al., 2018; Hass et al., 2018; Samnegård et al., 2018; Tamburini et al., 2020; Belien et al.,

* Correspondence to: Dipartimento di Scienze e Tecnologie Agro-alimentari, Alma Mater Studiorum Università di Bologna, Viale Fanin 40-50, Bologna 40127, Italy.
E-mail addresses: lucia.lenzi4@unibo.it (L. Lenzi), xavier.arnan@upe.br (X. Arnan), jordi.bosch@uab.cat (J. Bosch), adele.bordoni@unifi.it (A. Bordoni), laura.zavatta4@unibo.it (L. Zavatta), serena.magagnoli4@unibo.it (S. Magagnoli), agata.morelli2@unibo.it (A. Morelli), fabio.sgolastra2@unibo.it (F. Sgolastra).
[1] Dipartimento di Biologia, Università di Firenze, 50019 Sesto Fiorentino (FI), Italy

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2021; Roquer-Beni et al., 2021). For example, Holzschuh et al. (2012) showed that an increase in the proportion of habitat suitable for bees increased fruit set in cherry orchards. Moreover, landscape heterogeneity has been suggested to have a mitigation effect on overall pesticide contamination (Nicholson and Williams, 2021) and pollinator exposure to pesticides (Rundlöf et al., 2022; Shi et al., 2024), another factor associated with agricultural intensification. Insecticides may have direct negative impacts on pollinator populations by affecting immature development and reducing adult survival, and herbicides may have indirect impacts by reducing floral resources (Liere et al., 2017). Even fungicides, which are considered relatively non-toxic for bees, may lead to physiological and behavioural changes and reduce bee survival when they interact with other chemicals (Rondeau and Raine, 2022). In addition, various studies have reported impairments in plant-pollinator interactions as a consequence of pesticide exposure. Pesticides can induce alterations in plant metabolism or physiology, with repercussions on attractiveness to pollinators (Klatt et al., 2023; Tatarko et al., 2025). Other studies have reported alterations in bumblebee visitation rate following pesticide application (Stanley et al., 2015; Avila et al., 2023), as well as reduced pollen deposition on the stigmas (Tamburini et al., 2021), thereby affecting pollination services.

Within this context, reports of pollination deficits in highly pollinator-dependent crops are increasing (Polce et al., 2014; Gianni and Vania, 2018; Holland et al., 2020; Castro et al., 2021; Garratt et al., 2021; Siopa et al., 2024; Turo et al., 2024). Pollination deficits are defined as the inadequate quantity and/or quality of pollen deposited on the stigma (Vaissière et al., 2011), resulting in low crop yields (Webber et al., 2020). Suboptimal crop pollination can be triggered by several factors such as low pollinator diversity and abundance, asynchrony between the crop and its pollinators, asynchrony between inter-compatible cultivars (Polce et al., 2014), and inadequate availability or distribution of pollinizer cultivars (Quinet and Jacquemart, 2017; Reeves et al., 2022). Successful pollination may be estimated in terms of initial fruit set (Garratt et al., 2021), which is often related to final yield, or in terms of seed set (Webber et al., 2020), which is often related to fruit quality and shape (Olhnuud et al., 2022).

Pears are one of the most important crops globally. Most of the global production (82.2 %) occurs in Asia (mainly Asian pear species, *P. pyrifolia*, *P. sinkiangensis*) (Wu et al., 2018), followed by Europe (8.4 %), and the Americas (5.9 %) (*Pyrus communis*) (FAOSTAT, 2023). Like most Rosaceae species, pear presents a mechanism of genetic self-incompatibility that prevents inbreeding, even though some varieties exhibit parthenocarpy, and thus rely on cross-pollination among inter-compatible cultivars for reproduction (Fountain et al., 2019). For this reason, pear orchards should present at least two compatible cultivars with overlapping flowering periods (Quinet and Jacquemart, 2017; Goldway et al., 2019). Pear flowers are visited by a diverse array of bees and flies, but flower visitation rates are usually rather low (Quinet et al., 2016; Fountain et al., 2019). Several factors contribute to explaining these low visitation levels. First, pear flowers have a low sugar content (<25 %) compared to other co-blooming crops (Quinet and Jacquemart, 2017). Second, pear blooms early in the year, when temperatures may be too low for insect activity (Vicens and Bosch, 2000). Freezing temperatures in spring may also lead to flower frost damage and cause necrosis of the seed embryos (Musacchi et al., 2021; Reeves et al., 2022). Finally, the widespread application of pesticides in intensively managed orchards (Belien et al., 2021) can negatively affect visitation rates (Bloom et al., 2021; Tamburini et al., 2021). To overcome low pollination services, growth regulators are often applied to boost early fruit retention (Musacchi et al., 2021) even though seedless fruits are likely to exhibit shape deficiencies (Goldway et al., 2019); moreover, pears produced by parthenocarpy are usually smaller respect to those resulting from cross-pollination (Claessen et al., 2019). For all these reasons, pollination is regarded as an essential factor limiting yields in *P. communis* (Hünicken et al., 2021; Siopa et al., 2024).

Pollination deficits and the contribution of pollinator communities to pollination services have been well studied in apples (e.g., Garratt et al., 2014a; 2014b; 2021; Webber et al., 2020; Roquer-Beni et al., 2021; Olhnuud et al., 2022; Eeraerts et al., 2025) and other pollinator-dependent crops such as blueberry and kiwifruit, for example (Castro et al., 2021; Bordoni et al., 2024; Turo et al., 2024). By comparison, we know much less about pollination services in pear. In this study, we conducted pollination experiments, surveyed pollinators, and assessed pesticide levels and landscape composition in 16 pear orchards in Italy. Our objectives were to: i) assess pollination services and detect potential pollination deficits; and ii) assess the role of local (farm) factors such as pesticide risk and orchard management, and landscape factors ("pollinator-friendly" cover) on pear pollinator guilds and pollination services.

2. Materials and methods

2.1. Study sites

The study was conducted in 2023, from flowering season between March and April to harvesting in late August, in 16 pear orchards located in three provinces in the Emilia-Romagna region of Northern Italy (44°29′37″N 11°20′35″E). Emilia-Romagna is the leading Italian region for fruit production, both in terms of cultivated area (23 % of the total national area) and production (30–40 %). The region is characterized by a temperate subcontinental climate, with hot and humid summers and harsh, cold winters. 2023 was the hottest year since 1961, both for medium and highest temperatures; however, in early April, the minimum temperature registered was −2.6 °C and the maximum was 23°C; the average temperature during pear bloom was 12.5°C. Moreover, precipitation in 2023 was above average from March to May, with May recording a 230 % increase compared to the mean of the period (ARPAE, 2023); such conditions may have an impact on overall production by causing physiological stress in plants (Beillouin et al., 2020; Belien et al., 2021). The study orchards were all managed according to Integrated Pest Management guidelines and were at least 1.5 km apart from each other. In all orchards, *Abate Fétel* was the main variety, with *Williams* serving as the pollinating variety. In all orchards except one, where *Williams* trees were along the rows, disposition of pear varieties was into separate blocks, adjacent or alternate (Table S1). According to the Phytosanitary Notebook (register of pesticides applied in each farm), insecticides were applied in March, before bloom, while plant growth regulators and fungicides were applied also during bloom, when flowers were collected for chemical analysis. The application of herbicides was not reported.

2.2. Pollinator survey

In early April 2023, pear pollinators were monitored around midday during peak bloom with adequate weather conditions (sunny days, $T \geq 10$°C, low wind speed). One observer walked along a transect (400–700 m, depending on the orchard) between tree central rows for 30 min on two different days, totalling 1 h, and noted all insects observed visiting pear flowers on both sides of the transect. Because we expected low pollinators abundance, we did not use the sweep net to avoid potential disturbance to flower visitors. Pollinators were classed into broad functional groups, following Garratt et al. (2022) and were honeybees, bumblebees, wild bees, syrphids, muscoid flies and other pollinators (i.e. wasps, Coleoptera and Lepidoptera). To estimate the number of flowers sampled in each transect, we counted the number of inflorescences in 3 trees and multiplied this number by the average number of open flowers (estimated from 10 inflorescences of 3 random trees) and by the number of trees per transect. The number of flowers surveyed was used to calculate pollinator visitation rates (number of individual pollinators observed per flower).

All bumblebees recorded were *Bombus terrestris*. While in most of the orchards were completely absent, their numbers were higher only in two

farms, especially in one of them, in which commercial colonies were present. Therefore, we assumed that bumblebees (and honeybees) were managed in these two farms, and for the other orchards we included the few bumblebees into the wild bees group. In the statistical analysis regarding the effect of pollinators on production and pollination deficit, three groups of pollinators were considered: honeybees, bumblebees, considered as two groups of managed pollinators due to their different behaviour as flower visitors (Lee et al., 2017), and "wild pollinators" (wild bees, syrphids, muscoid flies and other pollinators).

2.3. Pollination experiments

To assess pollination levels and fruit set, 10 trees per orchard were randomly selected along three central rows within each orchard. Before flowering, 3 branches on each tree were marked for one of three pollination treatments: Pollinator exclusion (E), Open pollination (O) and Supplementary cross-pollination (S). Branches of the E treatment were covered with a tulle mesh bag (diameter=1 mm) until petal fall. Pollinator exclusion treatment provides data on the plant's ability to set fruit without pollination, and is aided by irrigation, fertilization and hormones applications, which together represent fruit retention management. Branches of the O treatment were left to be freely visited by pollinators; branches of the S treatment were hand-pollinated with pollen from the pollinizer variety (*Williams*) and left open. To obtain *Williams* pollen, flower buds were collected at the balloon stage. Anthers were cut in the laboratory and placed at 37°C for 24 h to enhance pollen release. Hand-pollinations were performed on two different days during full bloom.

On each branch, we assessed initial and final fruit set. Initial fruit set (percentage of flowers developing into fruitlets) is a good indicator of successful pollination and was assessed in May. Final fruit set was assessed in August, after the natural thinning occurred at the end of May. Seed set (the number of seeds per fruit) was established on 2 fruits per branch/treatment. However, because fruit set was low (see results), only 182 pears from the experimental branches (E = 9, O=51, S=122) could be collected. For this reason, to increase the sample size for seed set under open pollination, 20 additional fruits per orchard were randomly collected from other trees (N = 224).

2.3.1. Pollinator dependence, pollination service and pollination deficit

To assess the role of pollinating insects in pear production, we calculated two indices - pollination service (*PSer*) and pollinator dependence (*PDep*). Each index was calculated twice: once for the initial fruit set and the other for the final fruit set.

Pollination service (*PSer*) is an index that provides the effective contribution of pollinators to fruit set (Garratt et al., 2021), and it was calculated as:

$$PSer = \frac{fO - fE}{fO}$$

Where *f*O is the fruit set from the open pollination treatment and *f*E is the fruit set from the exclusion treatment.

Pollinator dependence (*PDep*) index denotes the dependence of the variety on pollinator visitation for fruit set (Garratt et al., 2021) and was calculated as:

$$PDep = \frac{fS - fE}{fS}$$

Where *f*S is the fruit set from the supplementary pollination treatment and *f*E is the fruit set from the exclusion treatment.

When *fO* or *fS* were 0, the *PSer* and the *PDep* indexes, respectively, were considered equal to 0.

Pollination deficit (*PDef*) measures the shortage in fruit production compared to the maximum potential fruit set when pollination is not limiting; pollination deficit was calculated as:

$$PDef = \frac{fS - fO}{fS}$$

When the fruit set achieved under open pollination was greater than under supplementary pollination, the deficit was considered equal to 0 (Garratt et al., 2014a; Castro et al., 2021).

Pollination service, pollinator dependence and pollination deficit indexes can also be calculated based on seed set. However, given the very low number of fruits obtained from the exclusion treatment (N = 9), and that we included fruits from other plants for open seed set, they were not calculated in our study.

2.4. Pesticide load and risk

At the peak of bloom, around 40 newly opened pear flowers (ca. 10 gr) were collected in each orchard and kept at −20°C for multi-residue analysis. This analysis, based on the detection of 775 active ingredients, was carried out by Agriparadigma (Ravenna, Italy) using the UNI EN 15662:2018 method (with gas chromatography tandem mass spectrometry,GC/MS/MS, and liquid chromatography tandem mass spectrometry, LC/MS/MS,) and the method CVUA EU RL-SRM QuPPe (Quick Method for the Analysis of Highly Polar Pesticides) Version 12 method 1.3 2021 (with LC/MS/MS) for glyphosate. With the residue data, a *risk index* (RI) was calculated as the sum of the "toxic units" of the active ingredients found in the flowers from each orchard. The index was calculated as the sum of each active ingredient (R) divided by its LD50 (for *Apis mellifera,* PPDB- Pesticide Properties Database https://sitem.herts.ac.uk/aeru/ppdb/). We examined both oral and contact LD50s and selected the lowest value, thus representing the worst-case scenario (Favaro et al., 2019; Sgolastra et al., 2024):

$$RI = \sum_{i=1}^{n} \frac{Ri}{LD50i}$$

Where *Ri* is the residue of compound *i,* expressed in mg/Kg found in the sample; LD50*i* is the acute oral/contact lethal dose of compound *i,* expressed in μg/bee.

2.5. Landscape characterization

Land use composition was assessed at 0.5, 1.0 and 1.5 km buffers from the center of the orchard with CORINE Land Cover (CLC, Coordination of Information on the Environment; Wyatt, 1988) reference year 2018. CLC land use types were grouped into 3 categories: "Agricultural", "Urban" and "Pollinator-friendly"; the latter includes all land use types providing suitable flower and nesting resources for pollinators (CLC categories 1.4, artificial non-agricultural vegetated areas; 2.3 and 2.4, pastures and heterogeneous agricultural areas; 3.1and 3.2, forests and shrubs and/or herbaceous vegetation associations; and 4, wetlands). Complete information on landscape characterization is available in Figure S1. The "pollinator-friendly" category was considered the main landscape factor that could positively influence pollinator abundance and pollination services. Landscape analyses were carried out with QGIS 3.22 version (https://qgis.osgeo.org).

2.6. Statistical analyses

One orchard (RA2) was already in bloom when the study started. For this reason, we were unable to perform the second pollinator survey and the pollinator exclusion treatment. This orchard was excluded from analyses of pollinator guilds and pollination services but was used in the pollination deficit and pesticide analyses.

2.6.1. Pollination services and pollination deficits

To test the effect of different pollination treatments on fruit set and seed set, Generalized Linear Mixed Models (GLMMs) were performed,

where either initial or final fruit set or seed set were the dependent variables, and experimental treatment (Exclusion, Open and Supplementary) was the independent variable; orchard identity was added as a random factor. When treatment was significant, a Tukey post-hoc test was performed to identify differences between levels (Exclusion, Open and Supplementary). GLMM was also used to test the relationship between initial fruit set, a metric for pollination, and final fruit set, a metric for production, adding orchard identity and experimental treatment as random factors (Garratt et al., 2021).

One sample *t*-test was performed to test if pollination deficit, both for initial and final fruit set, across orchards differed significantly from 0.

Seed set is dependent on pollination (Feuerbacher et al., 2024; Siopa et al., 2024) and may be an easier variable to assess than fruit set, even if seed set in pear is considerably variable across cultivars (Nyéki and Soltész, 1998). For this reason, we used GLMM models to test the relationship between seed set and fruit set under open pollination, and between seed set and pollination deficit (Webber et al., 2020), with orchard identity included as a random factor.

GLMMs were performed using the *lme* function from the nlme package (Pinheiro et al., 2025) and post-hoc tests using the *emmeans* function from the emmeans package (Lenth, 2024).

2.6.2. Effects of environmental variables on pollinator visitation

We tested for the effects of landscape composition and pesticide exposure on pollinators (Table S2). Linear models were performed with the visitation rate of each pollinator group as the response variable (one model per pollinator group), and the pesticide risk index and the proportion of pollinator-friendly landscape (arcsine-transformed), as explanatory variables. These analyses were repeated three times, with the percentages of pollinator-friendly landscapes at the three buffers (0.5, 1.0 and 1.5 km), given that the three radii were not highly correlated (Table S4).

2.6.3. Effect of pollinator visitation, pesticide risk and fruit retention management on pollination performance and fruit set

Fruit and seed set in pears are influenced by pollinator visitation (Hünicken et al., 2021), but also by fruit retention management practices (e.g. irrigation, hormone applications, fertilization) (Musacchi et al., 2021). In our study, the latter can be assessed through the ability of the cultivar to set fruit without pollinator visitation (fruit set in pollinator exclusion treatment). In addition, pesticide exposure may alter the foraging behaviour of pollinators, ultimately resulting in decreased pollination services (Klatt et al., 2023; Stanley et al., 2015). We performed a series of linear models in which the response variable was a measure of pollination performance (pollination service index, pollination deficit index) or a measure of fruit set (initial fruit set, final fruit set, seed set in open pollination branches). The explanatory variables were the visitation rates of the three pollinator groups, honeybees, bumblebees and wild pollinators, fruit set in the pollinator exclusion treatment (as a proxy of fruit retention management) and risk index (Table S2).

In all models, the response variables were log10 transformed when normality assumptions were not met.

To identify the environmental and pollinator visitation variables affecting pear pollination and production, we applied a model selection approach based on information theory in all analyses described in sections 2.6.2 and 2.6.3 that included more than one explanatory variable (Table S3). We began with a full model including all explanatory variables of interest and used the *dredge* function from the MuMIn package (Barton and Barton, 2015) to generate and compare all possible nested models. Model selection was based on Akaike's Information Criterion corrected for small sample sizes (AICc) (Anderson and Burnham, 2002; Mazerolle, 2023). Models with a $\Delta AICc < 2$ were considered to have substantial support. When the null model (i.e., the model without explanatory variables) was among the best models ($\Delta AICc < 2$), we interpreted that none of the predictors had a meaningful effect. In most cases where the null model was not among the best models, only one top-ranking model emerged. We then reran this selected model separately to test the statistical significance of its predictors, adopting a significance threshold of $\alpha = 0.05$. In one case, three models were sorted as best models ($\Delta AICc < 2$); therefore, we ran a model that included all variables selected across models (Table S3). To further assess model fit, we used AICc weights to evaluate the relative likelihood of the selected model in comparison to others. We also visually inspected quantile-quantile plots and residuals vs. fitted values plots to verify normality and homoscedasticity of residuals.

All analyses were conducted in R version 4.4.1 (RStudio Team, 2024).

3. Results

3.1. Pollinator diversity and abundance

A total of 1762 insects were observed visiting pear flowers. The majority were honeybees (*Apis mellifera*, 46 %), followed by muscoid flies (35 %), syrphids (10 %), bumblebees (*Bombus terrestris*, 4 %), wild bees (3 %) and other pollinators (wasps, Coleoptera and Lepidoptera, 2 %). The abundance of each pollinator functional group across the orchards is reported in Figure S2. Visitation rates were normalized for 10,000 flowers, and the mean (± standard error, SE) values were 2.84 (± 0.67), 2.27 (± 0.26), 0.62 (± 0.11), 0.15 (± 0.11), 0.24 (± 0.06) and 0.03 (±0.02) for honeybees, muscoid flies, syrphids, bumblebees, wild bees and other pollinators, respectively (Fig. 1).

3.2. Pollination experiments

Pollination treatment significantly affected initial ($\chi2 = 38.2$; df=2; $p < 0.001$) and final fruit set ($\chi2 = 50.2$; df=2; $p < 0.001$) (Fig. 2a, b). Open pollination significantly increased initial and final fruit set compared to pollinator exclusion, revealing a high dependence of both variables on pollinator visitation. Supplementary pollination significantly increased initial and final fruit set compared to open pollination, indicating a pollination deficit. Initial and final fruit set at the orchard level were highly related ($R^2m=0.73$, $R^2c= 0.77$, $t = 34.78$, $p < 0.0001$).

Seed set also differed significantly across the three pollination treatments (GLM: $\chi2 = 71.19$; df=2; $p < 0.001$) (Fig. 2c). It was significantly higher in fruits from supplementary pollination (mean ± SE=3.28 ± 0.19) than in fruits from the open pollination (1.96 ± 0.11) and than in fruits from the pollinator exclusion treatment (0.67 ± 0.55) *(Tukey test;* $p < 0.05$*)*.

Seed set was significantly correlated to final fruit set ($R^2m= 0.29$, $R^2c= 0.91$, $t = 2.50$, $p = 0.025$) and marginally significant to pollination deficit ($R^2m= = 0.20$, $R^2c= 0.90$, $t = -1.91$, $p = 0.077$). (Figure S3a, b).

3.2.1. Pollinator dependence, pollination service and pollination deficit

Mean (±SE) pollinator dependence (*PDep*) index was 0.40 ± 0.06 (range: 0–0.8) for initial fruit set and 0.33 ± 0.06 (range: 0–0.8) for final fruit set.

Mean (±SE) pollination service (*PSer*) index was 0.18 ± 0.04 (range: 0–0.6) for initial fruit set and 0.17 ± 0.04 (range: 0–0.5) for final fruit set.

Pollination deficit was significant both at initial (*t*-test: $t = 5.36$, df=14, $p < 0.001$) and final fruit set (*t*-test: $t = 5.8$, df=14, $p < 0.001$), with mean (±SE) values of 0.31 ± 0.06 (range: 0.00–0.74) and 0.33 ± 0.06 (range: 0.00–0.74), respectively. The 95 % confidence intervals were 0.19–0.44 and 0.21–0.45 for initial and final fruit set, respectively.

3.3. Pesticides and landscape composition

The multi-residue analysis on the pear flowers revealed the presence

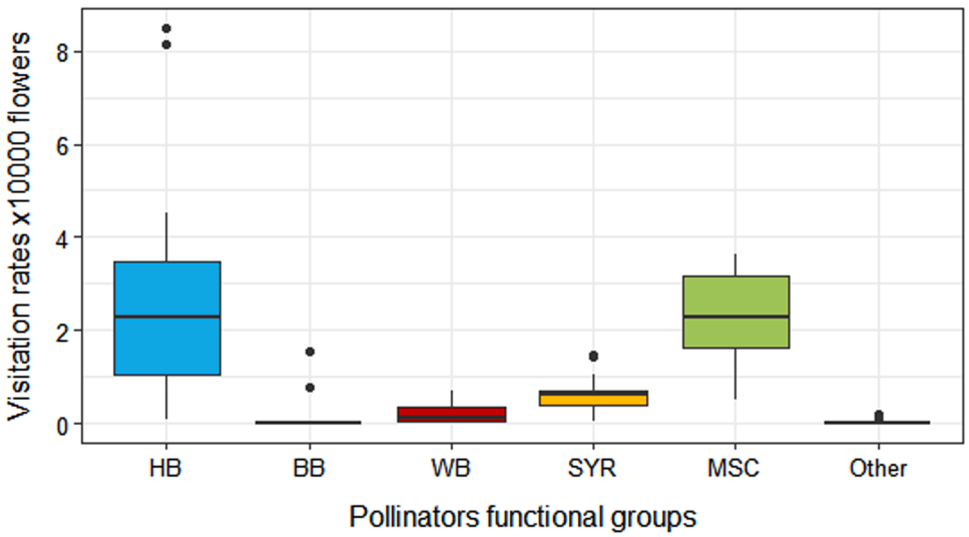

Fig. 1. Visitation rates (n° of individuals per n° of flowers in the transect, normalized for 10,000 flowers) of pollinators functional groups. HB= Honeybees, BB= Bumblebees, WB= Wildbees, SYR= Syrphids, MSC= Muscoid flies.

of 39 pesticides (Table S5) that were grouped into different categories: insecticides, fungicides, herbicides, plant growth regulators, and acaricides. The number of compounds per orchard ranged from 4 to 15 (mean ± SD= 9.93 ± 3.47), and total residue concentrations ranged from 0.011 mg/kg to 264 mg/kg (mean ± SE= 69.76 ± 36.0 mg/kg) (Fig. 3a, b). Fungicides were the most abundant pesticide group (52.3 %), with Dithianon and Pyrimethanil being the most frequent active ingredients, and Captan and its metabolites reaching unusually high levels (264 mg/kg) in one orchard. Insecticides accounted for 25.64 % of the residue levels, with Pyriproxyfen detected in all orchards except one. Also noteworthy is the finding of the herbicide Glyphosate in 75 % of the orchards. The list of all pesticides detected, and their residue level is reported in Table S5. The risk index ranged from 0.02 to 11.75 (mean ± SE=1.41 ± 0.71, median= 0.64); the highest risk index was detected in the orchard with high levels of Captan (MO2, Fig. 3c).

The landscape was rather homogeneous across sites, with a predominance of agricultural land (mean ± SD = 84.2 ± 7.5 %, 83.3 ± 2 % and 82.6 ± 6.6 %) and a low percentage of "pollinator-friendly" areas (mean ± SD= 4.09 ± 3.6 %, 4.86 ± 3.08 % and 5.2 ± 2.9 %) at 0.5, 1.0 and 1.5 km, respectively.

3.4. *Effects of pesticides and landscape composition on pollinators*

For honeybee, bumblebee, syrphid and muscoid fly visitation rates, the null model was consistently among the best-supported models; therefore, risk index or pollinator-friendly landscape at the 3 radii were not relevant. However, for wild bees' visitation rate model selection highlighted pollinator-friendly landscape at 1.5 km as an explanatory variable, and it resulted as significant (estimate = 8.30e-05, SE = 3.48e-06, t = 2.39, p = 0.033) (Fig. 4).

3.5. *Effects of pollinator visitation, fruit retention management, and pesticide risk on pollination services, pollination deficits and fruit production*

The model selection for initial fruit set identified fruit retention management and risk index as relevant explanatory variables (Table S3). Initial fruit set increased with the ability of the cultivar to initiate fruits without pollinators (a proxy of fruit retention management) (estimate = 2.08, SE = 0.23, t = 8.97, $p < 0.001$) and decreased with increasing risk index (estimate= −0.002, SE=0.00, t = -5.07, $p < 0.001$). Since orchard MO2 was identified as an outlier for the risk index, we re-run the model without it. Model selection retained fruit retention management but not risk index, and it was still significant (estimate = 2.08, SE = 0.24, t = 8.60, $p < 0.001$) (Figure S3). For the final fruit set open, the null model was among the best-supported models (Table S3), indicating no relevant effects of the three explanatory variables.

For seed set, three best supported models emerged and included bumblebee visitation rate, fruit retention management and honeybee visitation rate, so we ran a model with these explanatory variables (Table S3). Surprisingly, the model unveiled a negative effect of bumblebees' visits on seed set (estimate= −8069.57, SE=3251, t = -2.48, p = 0.028) (Figure S5). Orchard FE1, which had the highest number of bumblebees, was identified as an outlier. We reran the model without this orchard, and the model selection reported the null model among the best models (ΔAICc <2); then the effect of bumblebee visitation was no longer relevant.

Model selection showed that, for pollination service and deficit in initial and final fruit set, the null model was consistently among the best models, indicating that pollinators and orchard management were not relevant for these response variables (Table S3).

4. Discussion

The aim of this study was to assess pollination services and pollination deficits in pears, an important self-incompatible crop. Additionally, we wanted to explore how landscape context and pesticide exposure influenced pollinator visitation and pear fruit production. Our results confirmed the high dependence of *P. communis* on pollinators and revealed low levels of pollination services and widespread pollination deficits. At the same time, our study confirmed the positive effect of pollinator-friendly landscapes on wild bee visitation to pear flowers. Alongside, we found a negative effect of pesticide risk on initial fruit set and a negative effect of bumblebees' visits on seed set, even if driven by one orchard in both cases.

4.1. *Pollinator guilds*

In line with other pear studies (Quinet et al., 2016; Fountain et al., 2019), we found a low overall pollinator visitation rate. In addition to the low attractiveness of pear flowers (Quinet and Jacquemart, 2017), in our study, this was probably exacerbated by the harsh weather conditions experienced during bloom, with temperatures often below 13°C during the day and below 0°C at night, which is a common condition for crops blooming in early spring like *P. communis* (Belien et al., 2021;

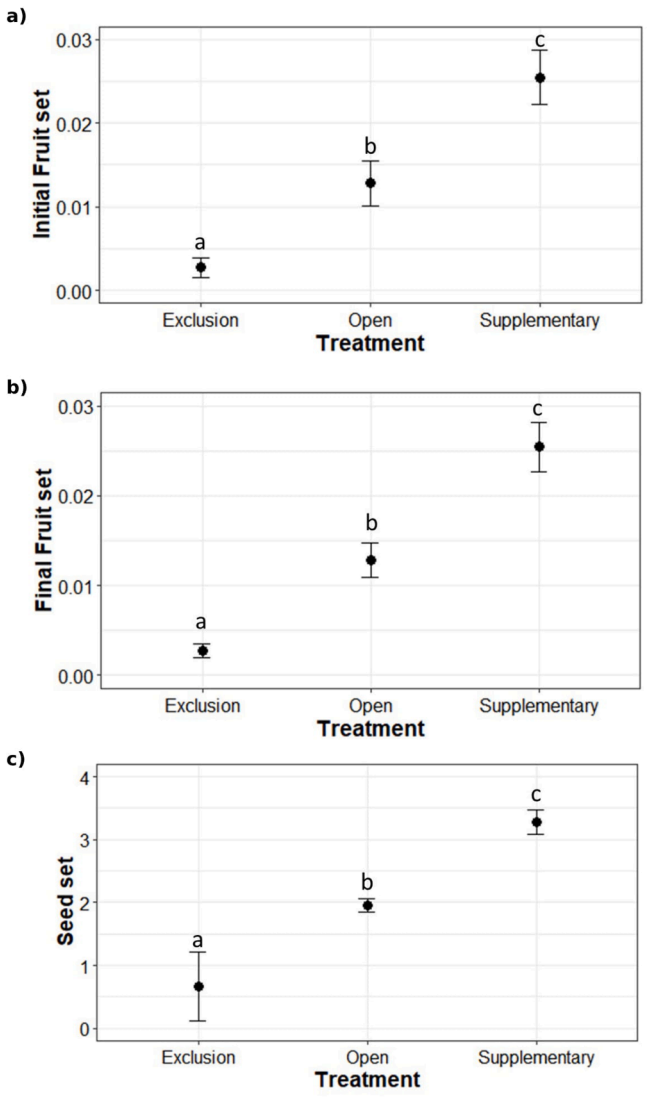

Fig. 2. Mean (±SE) initial (a) and final fruit set (b), expressed as the proportion of flowers that set fruit, and seed set (c) in branches of the pollination experiment (pollinator exclusion, open pollination, and supplementary pollination) in 15 pear orchards. Different letters denote significantly different means (Tukey test; $p < 0.05$).

Reeves et al., 2022).

The pollinator community was dominated by the honeybee *Apis mellifera*, in line with the results of Fountain et al. (2019). However, we did not observe any effect of honeybees' visitation on fruit set, as well as for other pollinators, as also reported by other studies (Eeraerts et al., 2025 and references therein). Although much less abundant than honeybees, we found a negative effect of bumblebee visitation on seed set. Even though bumblebees are considered efficient pollinators of *P. communis* (Jacquemart et al., 2006; Zisovich et al., 2012), some studies reported negative effect of *Bombus terrestris*' visits to flowers. For instance, the study of Smessaert et al. (2021) documented lower fruit set and seed set in *Conference* pear after bumblebee visits, that were attributed to flower damage caused during visitation. Also, Mayer and Lunden (1997) observed that bumblebees tended to work newly opened pear flowers with unripe anthers, therefore, not effectively transferring pollen. Moreover, Sáez et al. (2014) showed that increased bumblebees' visitation damage raspberry pistils, therefore compromising drupelet set. These mechanisms may provide possible explanation for our result, although further studies are needed to clarify the effectiveness of these managed pollinators in pear orchards. Many studies show that wild bees are more effective pear pollinators than honeybees (Monzón et al., 2004; Garibaldi et al., 2013; Fountain et al., 2019; Reilly et al., 2020; Belien et al., 2021; Hünicken et al., 2021; Roquer-Beni et al., 2022), but in our study, wild bees accounted for just 3 % of the visits recorded. The study of Monzón et al. (2004) shows the beneficial effects of solitary bee visitation on pear seed set even against a strong background of honeybees. Therefore, enhancing wild bee communities near pear orchards would likely improve fruit quality and provide stability in terms of pollination services.

4.2. Pollination dependence, service and deficit

Pear is known to be a strong pollinator-dependent crop because of genetic self-incompatibility (Delaplane and Mayer, 2020; Quinet and Jacquemart, 2017; Goldway et al., 2019; Belien et al., 2021), and our results confirm the dependence of *P. communis* on pollinators, reporting a dependence for the cultivar *Abate Fétel*. Indeed, the pollinator dependence index was around 40 % and 33 % for initial and final fruit set, respectively. According to Siopa et al. (2024), *P. communis* has an average pollinator dependence of 74 %, but with variations across cultivars, ranging from a minimum of 15 % to a maximum of 100 %.

As expected, based on the low visitation rates observed in our study and in others (Quinet et al., 2016; Fountain et al., 2019; Hünicken et al., 2021), pollination services in our pear orchards were rather low (around 17 %). Pollination deficits were pervasive across the study orchards, with mean values around 31 % and reaching 74 % in one orchard. Pollination deficits may be influenced by insufficient compatible pollen deposition; in fact, it is a common practice to place honeybee hives in pear orchards to boost cross-pollination (Goldway et al., 2019), but in our study, we did not observe a beneficial effect of honeybee visits on fruit set or pollination deficit reduction. This may be because honeybees tend to move along tree rows rather than between rows (Monzón et al., 2004; Quinet and Jacquemart, 2017), hindering cross-pollination between cultivars. This aspect may also be exacerbated by the layout of pear cultivars in the orchards (e.g., pollinisers planting design and density), which were primarily organized into blocks (Quinet and Jacquemart, 2017). We reported significant pollination deficits, although we observed a significant effect of the ability of the plant to set fruit without pollination, probably influenced by management practices based on hormone application, fertilization and other practices that promote fruit retention. Given that the cultivar resulted dependent on pollinators and experienced a pollination deficit, it would benefit from an increase in pollination service (Hünicken et al., 2021; Sáez et al., 2022).

However, our results indicate that the two most commonly managed species for pear pollination—honeybees and bumblebees—are not particularly effective, raising concerns about the current management of pollination services. Other managed pollinators, such as *Osmia spp*. have proven to be more efficient because they are attracted by pear flowers and are active under lower temperatures (Maccagnani et al., 2003; Monzón et al., 2004; Fountain et al., 2019; Goldway et al., 2019).

4.3. Pesticide risk and landscape characterization

We evaluated pesticide contamination and characterized the landscape surrounding the orchards to evaluate the effect of local and landscape factors on pollinator guilds and pollination services. We detected 39 different compounds in pear flowers, including 10 insecticides, reflecting their persistence from pre-bloom sprays. The risk index ranged from 0.02 to 11.75 to (mean=1.41). One orchard, MO2, had a very higher risk index, mostly due to high levels of the fungicide Captan, which was applied during bloom. We found no effect of the risk index on pollinator visitation rate. However, the risk index had a negative effect on initial fruit set, which is the metric for pollination, even if this effect was driven by the MO2 orchard. Pesticide exposure may affect the behaviour of pollinators as reported by different studies

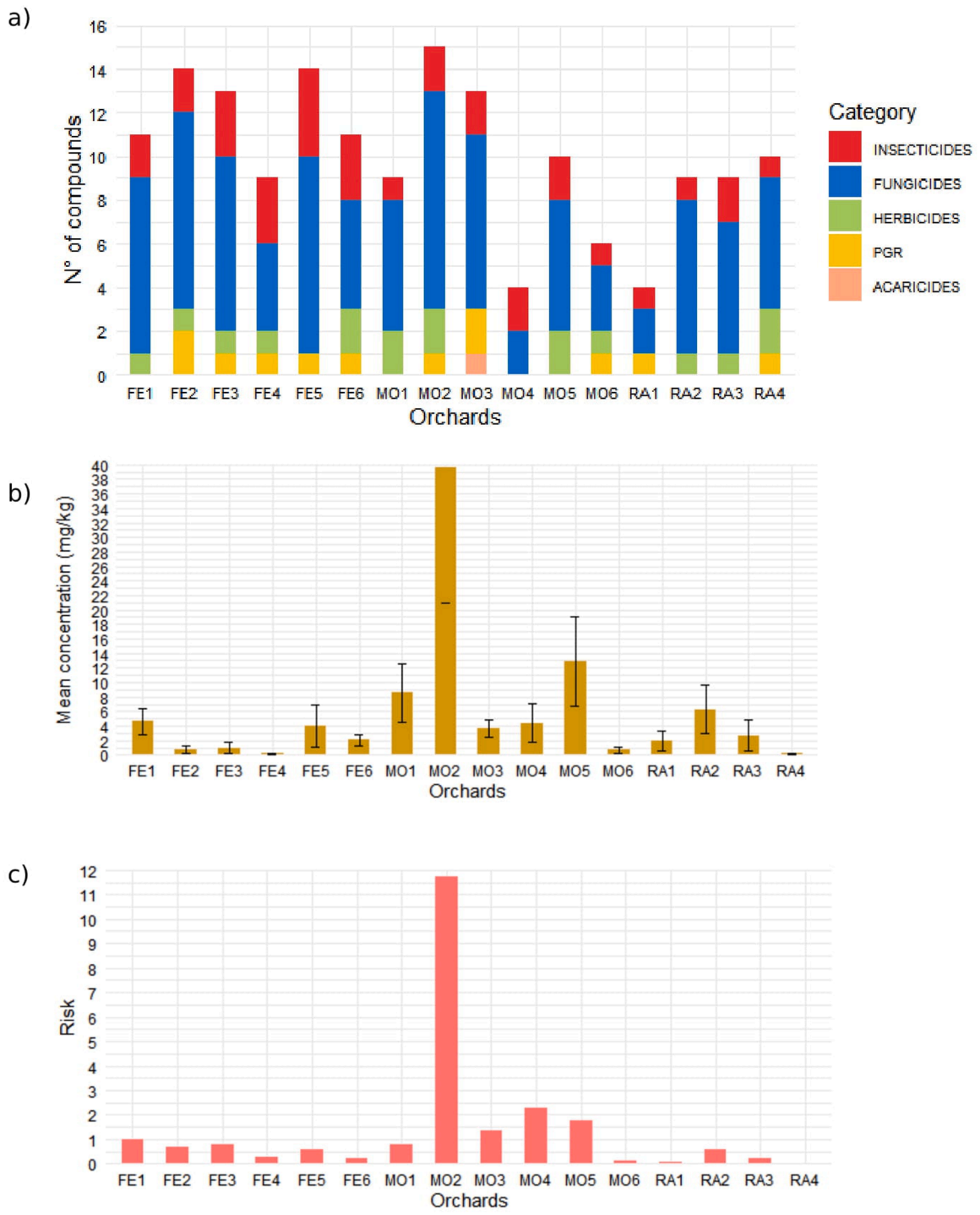

Fig. 3. Number of compounds grouped by pesticides categories across orchards (a); mean (± SE) concentration (mg/kg) of pesticides across orchards (b) and Risk index in each orchard (c). PGR = Plant Growth Regulators.

(Stanley et al., 2015; Tamburini et al., 2021; Avila et al., 2023; Klatt et al., 2023), therefore, even if the risk did not affect pollinators visitation rates it may have interfered indirectly with the pollination process. Indeed, Tamburini et al. (2021) reported a reduction in pollen deposition per flower visit by bumblebees after pesticide exposure, therefore, compromising the pollination process Moreover, Stanley et al. (2015) observed a reduced seed set in apple orchards with bumblebee colonies previously exposed to pesticides, even if individuals showed an increased foraging activity, thus suggesting a behaviour's alteration. Our results confirm the high level of pesticide contamination in agricultural areas (Sgolastra et al., 2024), with high numbers of compounds, some of which could interact synergistically (Sgolastra et al., 2017). The study was conducted in an intensively farmed area, with low cover of the landscape suitable for pollinators. Nevertheless, we observed a significant positive effect of pollinator-friendly cover at 1.5 km on wild bee visitation rate to pear flowers. The proportion of this pollinator-friendly cover was around 5 %, likely too low to maintain larger populations of wild bees that are able to provide an effective contribution in pollination service; the study of Eeraerts (2023) suggests that a proportion up to 15 % of semi-natural areas have a positive effect

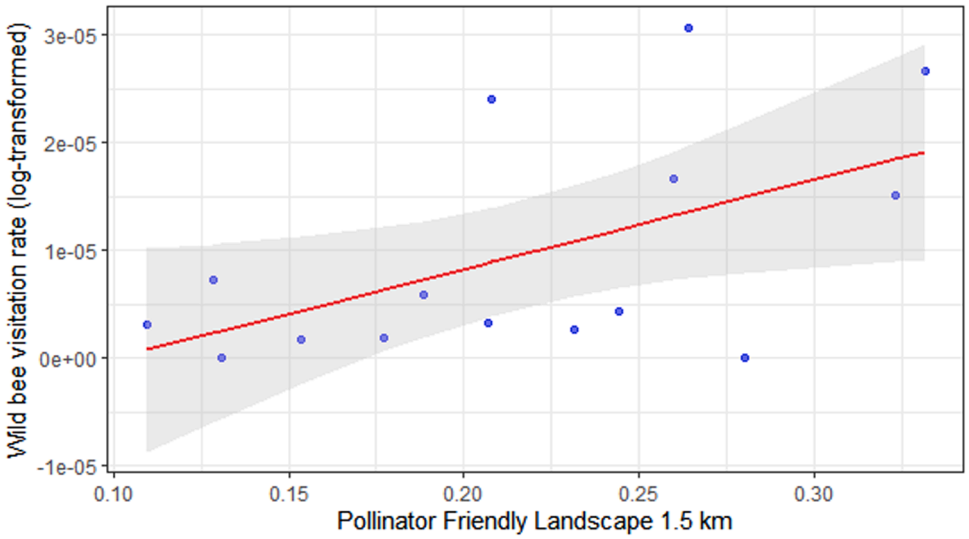

Fig. 4. Significant relationship between Pollinator-friendly landscape cover at 1.5 km (arcsin-transformed) and visitation rate of Wild bees (log-transformed).

on pollination services to cherry crop, while Holzschuh et al. (2012) found a significant effect in a context with more than 18 % of high-diversity habitats. Indeed, increasing the availability of pollinator-friendly habitat would enhance wild bees visitation to pear orchards and possibly promote the stability of their populations, thus improving pollination (Ganser et al., 2018; Magrach et al., 2023; Rundlöf et al., 2022) and other ecosystem services (Tamburini et al., 2020).

5. Concluding remarks

Our study reports on pollinator visitation rates and widespread pollination deficits in *Pyrus communis*, on which there are currently few studies, in a leading production area. Importantly, these deficits are not offset through the use of phytohormone applications to enhance fruit retention. Our results also suggest that the two most abundant (managed) pollinator species are not significantly contributing to pear pollination services in the study orchards and that enhancing semi-natural areas to boost wild bees' visits to pear flowers would be a more effective strategy. Our study also reveals that pear orchards are heavily contaminated with multiple pesticides, which may have contributed over the years to a significant decline in wild bee populations (as suggested by their low frequency in the study areas), ultimately resulting in negative impacts on pollination services. The main limitation of our study is that it was carried out under critical weather conditions, which may have exacerbated pollination deficit. Future research should be done under more favourable weather conditions and focus on a deeper investigation on pear pollinator community by identifying the contribution of different pollinator species to pollination service. Alongside, the restoration of semi-natural habitats surrounding pear orchards and the reduction of pesticide applications would enhance diverse wild pollinator communities and may reduce pollination deficits in this understudied crop.

CRediT authorship contribution statement

Lucia Lenzi: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Xavier Arnan:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Jordi Bosch:** Writing – review & editing, Validation, Supervision, Methodology. **Adele Bordoni:** Writing – original draft, Investigation, Data curation. **Laura Zavatta:** Writing – review & editing, Formal analysis, Data curation. **Serena Magagnoli:** Writing – review & editing, Investigation. **Agata Morelli:** Writing – review & editing, Investigation. **Fabio Sgolastra:** Writing – original draft, Supervision, Methodology, Funding acquisition, Data curation, Conceptualization.

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.

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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.2025.110113.

Data Availability

Data will be made available on request.

References

Anderson, D.R., Burnham, K.P., 2002. Avoiding pitfalls when using information-theoretic methods. J. Wildl. Manag. 912–918.

ARPAE 2023. Agenzia regionale per la prevenzione, l'ambiente e l'energia dell'Emilia-Romagna. ⟨https://www.arpae.it/it⟩.

Avila, L., McCullough, C., Schiffer, A., Moreno, J.M., Ganjur, N., Ofenloch, Z., DuPont, T., Nottingham, L., Gerardo, N.M., Brosi, B.J., 2023. Effects of a field-sprayed antibiotic on bee foraging behavior and pollination in pear orchards. ISSN 0167-8809 Agric. Ecosyst. Environ. 359 (2024), 108757. https://doi.org/10.1016/j.agee.2023.108757.

Bartomeus, I., Ascher, J.S., Gibbs, J., Danforth, B.N., Wagner, D.L., Hedtke, S.M., Winfree, R., 2013. Historical changes in northeastern US bee pollinators related to shared ecological traits. Proc. Natl. Acad. Sci. USA 110 (12), 4656–4660. https://doi.org/10.1073/pnas.1218503110.

Barton, K., Barton, M.K., 2015. Package 'mumin'. Version 1 (18), 439.

Beillouin, D., Schauberger, B., Bastos, A., Ciais, P., Makowski, D., 2020. Impact of extreme weather conditions on European crop production in 2018. Philos. Trans. R. Soc. B37520190510. https://doi.org/10.1098/rstb.2019.0510.

Belien, T., Raymaekers, S., Eeraerts, M., Mommaerts, V., Claus, G., Bogen, C., Piot, N., Smagghe, G., Spanoghe, P., Bylemans, D., 2021. Towards integrated pest and pollinator management in intensive pear cultivation: a case study from Belgium. Insects 2021 12, 901. https://doi.org/10.3390/insects12100901.

Bloom, E.H., Wood, T.J., Hung, K.-L.J., Ternest, J.J., Ingwell, L.L., Goodell, K., Kaplan, I., Szendrei, Z., 2021. Synergism between local- and landscape-level pesticides reduces wild bee floral visitation in pollinator-dependent crops, 2021 J. Appl. Ecol. 58, 1187–1198. https://doi.org/10.1111/1365-2664.13871.

Bordoni, A., Lami, F., Raffaele, G., Lenzi, L., Fiori, G., Zanetti, F., Morandi, B., Sgolastra, F., 2024. Field trials to enhance kiwifruit production using Osmia bicornis and supplementary flowering plants. Bull. Insect 77 (2), 307–318. ⟨https://cris.unibo.it/handle/11585/998572⟩, 2024, ISSN 1721-8861.

Castro, H., Siopa, C., Casais, V., Castro, M., Loureiro, J., Gaspar, H., Dias, M.C., Castro, S., 2021. Spatiotemporal variation in pollination deficits in an insect-pollinated dioecious crop, 2021 Plants 10, 1273. https://doi.org/10.3390/plants10071273.

Claessen, H., Keulemans, W., Van de Poel, B., De Storme, N., 2019. Finding a compatible partner: self-incompatibility in European Pear (*Pyrus communis*); molecular control, genetic determination, and impact on fertilization and fruit set. Front. Plant Sci. 10, 407. https://doi.org/10.3389/fpls.2019.00407.

Delaplane, K., Mayer, D., 2000. Crop Pollination by Bees. Entomol Exp. Applic 99. https://doi.org/10.1079/9780851994482.0000.

Eeraerts, M., 2023. A minimum of 15% semi-natural habitat facilitates adequate wild pollinator visitation to a pollinator-dependent crop. Biol. Conserv. 278 (2023), 109887. https://doi.org/10.1016/j.biocon.2022.109887.

Eeraerts, M., Osterman, J., Batáry, P., Klein, A.-M., Albrecht, M., Andersson, G.K.S., Báldi, A., Bernauer, O.M., Blechschmidt, L., Blitzer, E.J., Borges, P.A.V., Bosch, J., Burns, K.L.W., Campbell, A.J., Castro, S., Cook, J.M., Daelemans, R., Danforth, B.N., de Groot, A.G., Dorji, K., Földesi, R., Gaines Day, H.R., García, D., Garibaldi, L.A., Garratt, M.P.D., Gonzalez, A., Grab, H., Gratton, C., Halvorsen, M.K., Hambäck, P.A., Hatteland, B.A., Honnay, O., Hulsmans, E., Kaasen Vestheim, S., Kleijn, D., Kovács-Hostyánszki, A., Lechowicz, M.J., Leclercq, N., Liu, Y., Loureiro, J., Mallinger, R.E., Marshall, L., Meeus, I., Miñarro, M., Nabaes Jodar, D.N., Pardo, A., Park, M.G., Paxton, R.J., Pérez-Méndez, N., Pincante De Carvalho, R.A., Pirttilehto, P., Pisman, M., Potts, S.G., Raine, N.E., Reilly, J.R., Roquer-Beni, L., Samnegård, U., Stanley, D.A., Sutter, L., Teixeira-Martins, K., Tierney, S.M., Veldtman, R., Vereecken, N.J., Wäckers, F., Weekers, T., Wilson, J.K., Wu, P., Verheyen, K., 2025. Global synthesis of apple pollination research highlights general pollen limitation and positive contributions of wild bees compared to honeybees. J. Appl. Ecol. 00, 1–15. https://doi.org/10.1111/1365-2664.70155.

FAOSTAT, 2023. Food and Agriculture Organization of the United Nations. FAO. ⟨https://www.fao.org/faostat/en/#data/QCL⟩.

Favaro, R., Bauer, L.M., Rossi, M., D'Ambrosio, L., Bucher, E., Angeli, S., 2019. Botanical Origin of Pesticide Residues in Pollen Loads Collected by Honeybees During and After Apple Bloom. Front. Physiol. 10, 1069. https://doi.org/10.3389/fphys.2019.01069.

Feuerbacher, A., Herbold, T., Krumbe, F., 2024. The economic value of pollination services for seed production: a blind spot deserving attention, 2024 Environ. Resour. Econ. 87, 881–905. https://doi.org/10.1007/s10640-024-00840-7.

Fountain, M.T., Mateos-Fierro, Z., Shaw, B., Brain, P., Delgado, A., 2019. Insect pollinators of conference pear (*Pyrus communis* L.) and their contribution to fruit quality. J. Pollinat. Ecol. 25. https://doi.org/10.26786/1920-7603(2019)547.

Ganser, D., Mayr, B., Albrecht, M., Knop, E., 2018. Wildflower strips enhance pollination in adjacent strawberry crops at the small scale. Ecol. Evol. 2018 8, 11775–11784. https://doi.org/10.1002/ece3.4631.

Garibaldi, L.A., Steffan-Dewenter, I., Winfree, R., Aizen, M.A., Bommarco, R., Cunningham, S.A., Kremen, C., Carvalheiro, L.G., Harder, L.D., Afik, O., Bartomeus, I., Benjamin, F., Boreux, V., Cariveau, D., Chacoff, N.P., Dudenhöffer, J. H., Freitas, B.M., Ghazoul, J., Greenleaf, S., Hipólito, J., Holzschuh, A., Howlett, B., Isaacs, R., Javorek, S.K., Kennedy, C.M., Krewenka, K.M., Krishnan, S., Mandelik, Y., Mayfield, M.M., Motzke, I., Munyuli, T., Nault, B.A., Otieno, M., Petersen, J., Pisanty, G., Potts, S.G., Rader, R., Ricketts, T.H., Rundlöf, M., Seymour, C.L., Schüepp, C., Szentgyörgyi, H., Taki, H., Tscharntke, T., Vergara, C.H., Viana, B.F., Wanger, T.C., Westphal, C., Williams, N., Klein, A.M., 2013. Wild pollinators enhance fruit set of crops regardless of honey bee abundance. Science 339. ⟨https://www.science.org/doi/10.1126/science.1230200⟩.

Garratt, M.P.D., Breeze, T.D., Jenner, N., Polce, C., Biesmeijer, J.C., Potts, S.G., 2014b. Avoiding a bad apple: Insect pollination enhances fruit quality and economic value. Agric. Ecosyst. Environ. 184 (2014), 34–40. https://doi.org/10.1016/j.agee.2013.10.032.

Garratt, M.P.D., Truslove, L., Coston, D., Evans, R., Moss, E., Dodson, C., Jenner, N., Biesmeijer, J., Potts, S., 2014a. Pollination deficits in UK apple orchards. J. Pollinat. Ecol. 12, 9–14. https://doi.org/10.26786/1920-7603(2014)8.

Garratt, M.P.D., de Groot, G.A., Albrecht, M., Bosch, J., Breeze, T.D., Fountain, M.T., Klein, A.M., McKerchar, M., Park, M., Paxton, R.J., Potts, S.G., Pufal, G., Rader, R., Senapathi, D., Andersson, G.K.S., Bernauer, O.M., Blitzer, E.J., Boreux, V., Campbell, A.J., Carvell, C., Földesi, R., Garcıa, D., Garibaldi, L.A., Hambäck, P.A., Kirkitadze, G., Kovacs-Hostyanszki, A., Martins, K.T., Miñarro, M., O'Connor, R., Radzeviciute, R., Roquer-Beni, L., Samnegard, U., Scott, L., Vereecken, N.J., Wäckers, F., Webber, S.M., Japoshvili, G., Zhusupbaeva, A., 2021. Opportunities to reduce pollination deficits and address production shortfalls in an important insect-pollinated crop. Ecol. Appl. 31 (8), e02445. https://doi.org/10.1002/eap.2445.

Garratt, M.P.D., O'Connor, R.S., Carvell, C., Fountain, M.T., Breeze, T.D., Pywell, R., Redhead, J.W., Kinneen, L., Mitschunas, N., Truslove, L., Xavier e Silva, C., Jenner, N., Ashdown, C., Brittain, C., McKerchar, M., Butcher, C., Edwards, M., Nowakowski, M., Sutton, P., Potts, S.G., 2022. Addressing pollination deficits in orchard crops through habitat management for wild pollinators. Ecol. Appl. 33 (1), e2743. https://doi.org/10.1002/eap.2743.

Gianni, T., Vania, M., 2018. Artificial Pollination in Kiwifruit and Olive Trees. Pollination in Plants. Intech Open. https://doi.org/10.5772/intechopen.74831.

Goldway, M., Raz, A. & Stern, R. 2019. An updated view on fertilization and pollination in European pears (*Pyrus communis*). In: A.Ramos Luz (Ed.), Pear: Cultivars Production and Harvesting. (pp.49-82) Edition:, January 2019. ISBN: 978-1-53616-037-6Hass, A. L., Kormann, U.G., Tscharntke, T., Clough, Y., Baillod, A.B., Sirami, C., Fahrig, L., Martin, J-L., Baudry, J., Bertrand, C., Bosch, J., Brotons, L., Burel, F., Georges, R., Giralt, D., Marcos-García, M.Á., Ricarte, A., Siriwardena, G. and Batáry, P. 2018. Landscape configurational heterogeneity by small-scale agriculture, not crop diversity, maintains pollinators and plant reproduction in western Europe. Proceedings of the Royal Society B. 28520172242 ⟨http://doi.org/10.1098/rspb.2017.2242⟩.

Hass, A.L., Kormann, U.G., Tscharntke, T., Clough, Y., Baillod, A.B., Sirami, C., Fahrig, L., Martin, J.-L., Baudry, J., Bertrand, C., Bosch, J., Brotons, L., Burel, F., Georges, R., Giralt, D., Marcos-García, M.Á., Ricarte, A., Siriwardena, G., Batáry, P., 2018. Landscape configurational heterogeneity by small-scale agriculture, not crop diversity, maintains pollinators and plant reproduction in western Europe. Proc. R. Soc. B 285 (1875), 20172242. https://doi.org/10.1098/rspb.2017.2242.

Holland, J.M., Sutter, L., Albrecht, M., Jeanneret, P., Pfister, S.C., Schirmel, J., Entling, M.H., Kaasik, R., Kovacs, G., Veromann, E., Bartual, A.M., Marini, S., Moonen, A.-C., Szalai, M., Helsen, H., Winkler, K., Lof, M.E., van der Werf, W., McHugh, N.M., Smith, B.M., Wallis, D.W., Cresswell, J.E., 2020. Moderate pollination limitation in some entomophilous crops of Europe. ISSN 0167-8809 Agric. Ecosyst. Environ. 302 (2020), 107002. https://doi.org/10.1016/j.agee.2020.107002.

Holzschuh, A., Dudenhoeffer, J.-H., Tscharntke, T., 2012. Landscapes with wild bee habitats enhance pollination, fruit set and yield of sweet cherry. Biol. Conserv. 153, 101–107. https://doi.org/10.1016/j.biocon.2012.04.032.

Hünicken, P.L., Morales, C.L., Aizen, M.A., Anderson, G.K.S., García, N., Garibaldi, L.A., 2021. Insect pollination enhances yield stability in two pollinator-dependent crops. ISSN 0167-8809 Agric. Ecosyst. Environ. 320 (2021), 107573. https://doi.org/10.1016/j.agee.2021.107573.

IPBES 2016. The assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production. {C}{C}S.G. Potts, V.L. Imperatriz-Fonseca, and H.T. Ngo (eds{C}{C}). Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany. 552 pages.

Jacquemart, A.-L., Michotte-Van, A., Raspé, O., 2006. Compatibility and pollinator efficiency tests on *Pyrus communis* L. cv. 'Conference. J. Hortic. Sci. Biotechnol. 81, 827–830. https://doi.org/10.1080/14620316.2006.11512145.

Klatt, B.K., Wurz, A., Herbertsson, L., Rundlöf, M., Svensson, G.P., Kuhn, J., Vessling, S., de La Vega, B., Tscharntke, T., Clough, Y., Smith, H.G., 2023. Seed treatment with clothianidin induces changes in plant metabolism and alters pollinator foraging preferences, 2023 Dec Ecotoxicology 32 (10), 1247–1256. https://doi.org/10.1007/s10646-023-02720-0.

Klein, A.-M., Vaissière, B.E., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., Tscharntke, T., 2007. Importance of pollinators in changing landscapes for world crops. Proc. R. Soc. B 274303–274313. https://doi.org/10.1098/rspb.2006.3721.

Lee, K.Y., Yim, S.H., Seo, H.J., Shin, M., Yoon, H.J., 2017. Pollination efficiency of honeybees (*Apis mellifera* L.) and bumblebees (*Bombus terrestris* L.) in different cultivars of Asian pear (*Pyrus pyrifolia* Nakai). J. Apic. 32 (4), 303–314. https://doi.org/10.17519/apiculture.2017.11.32.4.303.

Lenth, R.V. (2024). emmeans: Estimated Marginal Means, aka Least-Squares Means (R package version 1.10.5). Recuperado de ⟨https://CRAN.R-project.org/package=emmeans⟩.

Liere, H., Jha, S., Philpott, S.M., 2017. Intersection between biodiversity conservation, agroecology, and ecosystem services. Agroecol. Sustain. Food Syst. 41 (7), 723–760. https://doi.org/10.1080/21683565.2017.1330796.

Maccagnani, B., Ladurner, E., Santi, F., Burgio, G., 2003. *Osmia cornuta* (Hymenoptera, Megachilidae) as a pollinator of pear (*Pyrus communis*): Fruit- and seed-set. Apidologie 34, 207–216. https://doi.org/10.1051/apido:2003009.

Magrach, A., Giménez-García, A., Allen-Perkins, A., Garibaldi, L.A., Bartomeus, I., 2023. Increasing crop richness and reducing field sizes provide higher yields to pollinator-dependent crops. J. Appl. Ecol. 60, 77–90. https://doi.org/10.1111/1365-2664.14305.

Mayer, D.F., Lunden, J.D., 1997. A comparison of commercially managed bumblebees and honey bees (hymenoptera: Apidae) for pollination of pears. Acta Hortic. (437), 283–288. https://doi.org/10.17660/ActaHortic.1997.437.33.

Mazerolle, M.J. 2023. _AICcmodavg: Model selection and multimodel inference based on (Q)AIC(c)_. R package version 2.3.3, <⟨https://cran.r-project.org/package=AICcmodavg⟩>

Monzón, V.H., Bosch, J., Retana, J., 2004. Foraging behavior and pollinating effectiveness of *Osmia cornuta* and *Apis mellifera* (Hymenoptera: Megachilidae, Apidae) on 'Comice' pear. Apidologie 35 (6), 575–585. ⟨https://hal.science/hal-00891855v1⟩, 2004.

Musacchi, S., Iglesias, I., Neri, D., 2021. Training Systems and Sustainable Orchard Management for European Pear (*Pyrus communis* L.) in the Mediterranean Area: A Review, 2021 Agronomy 11, 1765. https://doi.org/10.3390/agronomy11091765.

Nicholson, C.C., Williams, N.M., 2021. Cropland heterogeneity drives frequency and intensity of pesticide use. Environ. Res. Lett. 16, 074008. https://doi.org/10.1088/1748-9326/ac0a12.

Nyéki, J., Soltész, M., 1998. The variation of seed content of fruits in pear varieties, also as function of different conditions of fertilization, as open pollination, natural autogamy and allogamy. Acta Hortic. (475), 237–250. https://doi.org/10.17660/ActaHortic.1998.475.30.

Olhnuud, A., Liu, Y., Makowski, D., Tscharntke, T., Westphal, C., Wu, P., Wang, M., Van der Werf, W., 2022. Pollination deficits and contributions of pollinators in apple production: a global meta-analysis. J. Appl. Ecol. 00, 1–11. https://doi.org/10.1111/1365-2664.14279.

Ollerton, J., 2017. Pollinator diversity: distribution, ecological function, and conservation. Annu. Rev. Ecol. Evol. Syst. 48. https://doi.org/10.1146/annurev-ecolsys-110316-022919.

Pinheiro, J., Bates, D., Team, R.Core, 2025. nlme: linear and nonlinear mixed effects models. R. Package Version 3, 1–168. ⟨https://CRAN.R-project.org/package=nlme⟩.

Polce, C., Garratt, M.P., Termansen, M., Ramirez-Villegas, J., Challinor, A.J., Lappage, M. G., Boatman, N.D., Crowe, A., Endalew, A.M., Potts, S.G., Somerwill, K.E., Biesmeijer, J.C., 2014. Climate-driven spatial mismatches between British orchards and their pollinators: increased risks of pollination deficits. Glob. Change Biol. 20, 2815–2828. https://doi.org/10.1111/gcb.12577.

Quinet, M., Jacquemart, A.-L., 2017. Cultivar placement affects pollination efficiency and fruit production in European pear (Pyrus communis) orchards, 2017 Eur. J. Agron. 91, 84–92. https://doi.org/10.1016/j.eja.2017.09.015.

Quinet, M., Warzée, M., Vanderplanck, M., Michez, D., Lognay, G., Jacquemart, A.-L., 2016. Do floral resources influence pollination rates and subsequent fruit set in pear (*Pyrus communis* L.) and apple (*Malus* × *domestica* Borkh) cultivars? Eur. J. Agron. 77, 59–69. https://doi.org/10.1016/j.eja.2016.04.001.

Ramos-Jiliberto, R., Moisset de Espanés, P., Vazquez, D.P., 2020. Pollinator declines and the stability of plant–pollinator networks. Ecosphere 11 (4), e03069. https://doi.org/10.1002/ecs2.3069.

Reeves, L., Garratt, M., Fountain, M., Senapathi, D., 2022. Climate induced phenological shifts in pears – A crop of economic importance in the UK. Agric. Ecosyst. Environ. 338 (2022), 108109. https://doi.org/10.1016/j.agee.2022.108109.

Reilly, J.R., Artz, D.R., Biddinger, D., Bobiwash, K., Boyle, N.K., Brittain, C.J.Brokaw, Campbell, J.W., Daniels, J., Elle, E., Ellis, J.D., Fleischer, S.J., Gibbs, J., Gillespie, R. L., Gundersen, K.B., Gut, L., Hoffman, G., Joshi, N., Lundin, O., Mason, K., McGrady, C.M., Peterson, S.S., Pitts-Singer, T.L., Rao, S., Rothwell, N., Rowe, L., K. Ward, L., Williams, N.M., Wilson, J.K., Isaacs, R., Winfree, R., 2020. Crop production in the USA is frequently limited by a lack of pollinators. Proc. R. Soc. B Biol. Sci. 287 (1931). https://doi.org/10.1098/rspb.2020.0922.

Rondeau, S., Raine, N.E., 2022. Fungicides and bees: a review of exposure and risk. ISSN 0160-4120 Environ. Int. 165 (2022), 107311. https://doi.org/10.1016/j.envint.2022.107311.

Roquer-Beni, L., Alins, G., Arnan, X., Boreux, V., García, D., Hambäck, P.A., Happe, A.-K., Klein, A.-M., Miñarro, M., Mody, K., Porcel, M., Rodrigo, A., Samnegård, U., Tasin, M., Bosch, J., 2021. Management-dependent effects of pollinator functional diversity on apple pollination services: a response-effect trait approach. J. Appl. Ecol. https://doi.org/10.1111/1365-2664.14022.

Roquer-Beni, L., Arnan, X., Rodrigo, A., Bosch, J., 2022. What makes a good pollinator? Relationship between pollinator traits and pollination effectiveness in apple flowers. Èntomol. Gen. 42 (6), 875–882. https://doi.org/10.1127/entomologia/2022/1571.

RStudio Team, 2024. RStudio: Integrated Development Environment for R (versione 2024.12.0). PBC, Boston, MA. ⟨https://posit.co/⟩ (URL).

Rundlöf, M., Stuligross, C., Lindh, A., Malfi, R.L., Burns, K., Mola, J.M., Cibotti, S., Williams, N.M., 2022. Flower plantings support wild bee reproduction and may also mitigate pesticide exposure effects. J. Appl. Ecol. 59, 2117–2127. https://doi.org/10.1111/1365-2664.14223.

Sáez, A., Aguilar, R., Ashworth, L., Gleiser, G., Morales, C.L., Traveset, A., Aizen, M.A., 2022. Managed honeybees decrease pollination limitation in self-compatible but not in self-incompatible crops. Proc. R. Soc. B 289, 20220086. https://doi.org/10.1098/rspb.2022.0086.

Sáez, A., Morales, C.L., Ramos, L.Y., Aizen, M.A., 2014. Extremely frequent bee visits increase pollen deposition but reduce drupelet set in raspberry. J. Appl. Ecol. 51, 1603–1612. https://doi.org/10.1111/1365-2664.12325.

Samnegård, U., Alins, G., Boreux, V., Bosch, J., García, D., Happe, A.K., Klein, A.-M., Miñarro, M., Mody, K., Porcel, M., Rodrigo, A., Roquer-Beni, L., Tasin, M., Hambäck, P.A., 2018. Management trade-offs on ecosystem services in apple orchards across Europe: Direct and indirect effects of organic production. J. Appl. Ecol. 56, 802–811. https://doi.org/10.1111/1365-2664.13292.

Scheper, J., Reemer, M., van Kats, R., Ozinga, W.A., van der Linden, G.T.J., Schaminée, J. H.J., Siepel, H., Kleijn, D., 2014. Museum specimens reveal loss of pollen host plants as key factor driving wild bee decline in The Netherlands. Proc. Natl. Acad. Sci. 111 (49), 17552–17557. https://doi.org/10.1073/pnas.1412973111.

Sgolastra, F., Medrzycki, P., Bortolotti, L., Renzi, M.T., Tosi, S., Bogo, G., Teper, D., Porrini, C., Molowny-Horas, R., Bosch, J., 2017. Synergistic mortality between a neonicotinoid insecticide and an ergosterol-biosynthesis-inhibiting fungicide in three bee species. Pest Manag. Sci. 73, 1236–1243. https://doi.org/10.1002/ps.4449.

Sgolastra, F., Arnan, X., Azpiazu, C., Bordoni, A., Bosch, J., Lenzi, L., Martins, C., Parrilli, M., Porrini, C., 2024. Honey bees and mason bees as biological indicators of landscape pesticide loads: different results but similar conclusions. ISSN 1470-160X Ecol. Indic. 166 (2024), 112425. https://doi.org/10.1016/j.ecolind.2024.112425.

Shi, X., Ma, C., de Kraker, J., Gong, S., Hodgson, J.A., Luo, S., van der Steen, J.J.M., Xiao, H., Wang, F., Tie, X., Chen, Z., Zou, Y., 2024. Influence of agricultural intensification on pollinator pesticide exposure, food acquisition and diversity. J. Appl. Ecol. 61, 1905–1917. https://doi.org/10.1111/1365-2664.14701.

Siopa, C., Carvalheiro, L.G., Castro, H., Loureiro, J., Castro, S., 2024. Animal-pollinated crops and cultivars—A quantitative assessment of pollinator dependence values and evaluation of methodological approaches. J. Appl. Ecol. 61, 1279–1288. https://doi.org/10.1111/1365-2664.14634.

Smessaert, J., Torfs, J., Honnay, O., Keulemans, W., 2021. Pollination mix: honeybees and bumblebees as possible pollinators for *Pyrus communis* 'Conference. Acta Hortic. 405–414. https://doi.org/10.17660/ActaHortic.2021.1303.56.

Stanley, D., Garratt, M., Wickens, J., Potts, S.G., Raine, N.E., 2015. Neonicotinoid pesticide exposure impairs crop pollination services provided by bumblebees. Nature 528 (2015), 548–550. https://doi.org/10.1038/nature16167.

Tamburini, G., Bommarco, R., Wanger, T.C., Kremen, C., van der Heijden, M.G.A., Liebman, M., Hallin, S., 2020. Agricultural diversification promotes multiple ecosystem services without compromising yield. Sci. Adv. 6 (45), eaba1715. https://doi.org/10.1126/sciadv.aba1715.

Tamburini, G., Pereira-Peixoto, M.-H., Borth, J., Lotz, S., Wintermantel, D., Allan, M.J., Dean, R., Schwarz, J.M., Knauer, A., Albrecht, M., Klein, A.-M., 2021. Fungicide and insecticide exposure adversely impacts bumblebees and pollination services under semi-field conditions. ISSN 0160-4120 Environ. Int. 157 (2021), 106813. https://doi.org/10.1016/j.envint.2021.106813.

Tatarko, A.R., Richman, S.K., Leonard, A.S., 2025. Impacts of a fungicide and an insecticide on pollinator visitation and wildflower fitness. Funct. Ecol. 00, 1–11. https://doi.org/10.1111/1365-2435.70053.

Turo, K.J., Reilly, J.R., Fijen, T.P.M., Magrach, A., Winfree, R., 2024. 2024. Insufficient pollinator visitation often limits yield in crop systems worldwide. Nat. Ecol. Evol. 8, 1612–1622. https://doi.org/10.1038/s41559-024-02460-2.

Vaissière, B., Freitas, B., Gemmill-Herren, B., 2011. Protocol to Detect and Assess Pollination Deficits in Crops: A Handbook for its Use. Roma. In: Italia, 2011. FAO.

Vicens, N., Bosch, J., 2000a. Weather-dependent pollinator activity in an apple orchard, with special reference to *Osmia cornuta* and *Apis mellifera* (Hymenoptera: Megachilidae and Apidae). Environ. Entomol. 29 (3), 413–420. https://doi.org/10.1603/0046-225X-29.3.413.

Webber, S.M., Garratt, M.P.D., Lukac, M., Bailey, A.P., Huxley, T., Potts, S.G., 2020. Quantifying crop pollinator-dependence and pollination deficits: The effects of experimental scale on yield and quality assessments. ISSN 0167-8809 Agric. Ecosyst. Environ. 304 (2020), 107106. https://doi.org/10.1016/j.agee.2020.107106.

Wu, J., Wang, Y., Xu, J., Korban, S.S., Fei, Z., Tao, S., Ming, R., Tai, S., Khan, A.M., Postman, J.D., Gu, C., Yin, H., Zheng, D., Qi, K., Li, Y., Wang, R., Deng, C.H., Kumar, S., Chagné, D., Li, X., Wu, J., Huang, X., Zhang, H., Xie, Z., Li, X., Zhang, M., Li, Y., Yue, Z., Fang, X., Li, J., Li, L., Jin, C., Qin, M., Zhang, J., Wu, X., Ke, Y., Wang, J., Yang, H., Zhang, S., 2018. 2018. Diversification and independent domestication of Asian and European pears. Genome Biol. 19, 77. https://doi.org/10.1186/s13059-018-1452-y.

Wyatt, B., 1988. CORINE: an information system on the state of the environment in the European Community. Build. Databases Global Sci. (book) 378–396.

Zisovich, A.H., Goldway, M., Schneider, D., Steinberg, S., Stern, E., Stern, R.A., 2012. Adding bumblebees (*Bombus terrestris* L., Hymenoptera: Apidae) to pear orchards increases seed number per fruit, fruit set, fruit size and yield. J. Hortic. Sci. Biotechnol. 87 (4), 353–359. https://doi.org/10.1080/14620316.2012.11512876.