Management factors strongly affect flower-visiting insects in intensive apple orchards

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ABSTRACT

Context: Pollination is an essential ecosystem service, and primary pollinators such as insects are largely declining. Agricultural intensification is one of the main drivers of such decline. The globally relevant apple production depends on this service. Apple orchards are often cultivated intensively over large monocultural landscapes, which are unsuitable for many pollinating species. Identifying and implementing appropriate management measures for pollinators is key to maintaining crop productivity and promote biodiversity.
Objective: We investigated the abundance of flower-visiting insects in intensive apple orchards in northern Italy. We assessed whether the abundance of flower-visiting insects, underpinning pollination, is affected by seasonal and weather patterns, and by fine-scale management variables.
Methods: We sampled 70 sites scattered all over the study area and counted five times flower-visiting insects (assigning them to broad taxonomical groups) at three randomly selected plots per site between April and September. We distinguished between insects visiting wildflowers and apple blossoms and assessed their response to ground and orchard management, and to variables describing the weather and season progression.
Results and conclusion: Honey bees were the dominant group (followed by wasps and ants, flies and syrphids), and their abundance negatively affected that of wild bees. Hour, date, and temperature (and the interaction between the latter two) were important for many groups and overall insect abundance. The presence of spontaneous flowers on the ground (both abundance and richness) positively affected the total number of insects on both wild and apple flowers, and of many single groups of flower-visiting insects. A taller grass sward positively affected many groups and all flower-visiting insects. Frequent mowing tended to promote the number of apple flowers' visitors, probably due to the lack of other flowers, but it also resulted in a negative effect on honey bees foraging on wildflowers. The presence of anti-hail nets negatively influenced the abundance of all insects and of many groups visiting flowers.
Significance: Management and conservation efforts should focus on ground vegetation and specific management practices (tillage, netting) to support more diverse pollinator communities, increasing biodiversity and lowering the dependence of apple yields on a single pollinating species. The presence of wildflowers and plant species richness in the ground cover is crucial, as it was a major driver of the pollinators' community. Enhancing the ground vegetation in orchards through sustainable management appears to be an effective management practice to sustain wild pollinators and, potentially, the pollination of apple trees.

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1. Introduction

Agricultural intensification has been reported as one of the main drivers of global change and pollinator decline, altering composition of pollinator communities, leading to a decrease in the richness and abundance of insect pollinator species (Brown and Paxton, 2009; Potts et al., 2010), jeopardising this essential ecosystem service on which c. 75 % of global food crops rely to some extent (Klein et al., 2007). Nonetheless, in recent decades, global cultivation of pollinator-dependent crops has considerably expanded, increasing, de facto, our reliance on insect pollination (Aizen et al., 2019; Olhnuud et al., 2022). Apples, with an annual production reaching 85 million tons worldwide and contributing to profits exceeding US $ 45 billion (FAO, 2019), are one of the most important fruit crops globally, and are also among the major fruit crops that rely on pollination (Pardo and Borges, 2020). In this scenario, pollinating insects play a key role (Delaplane and Mayer, 2000; Klein et al., 2007), with an annual economic value estimated at US $ 208.5 million for the apple industries (Allsopp et al., 2008). Insect pollinators have been reported to contribute also to apple quality (Garratt et al., 2017) and pest management (Cross et al., 2015), hence benefiting apple market value also in an indirect and less evident, but still relevant, way. However, apple orchards are often cultivated intensively over large extents, and require pollen transfer from another 'pollinizer' cultivar to achieve a profitable fruit yield (Delaplane and Mayer, 2000). In large commercial orchards, domestic European honey bees (*Apis mellifera*) are frequently used to enhance overall productivity (Garibaldi et al., 2009), and pollinator management in such contexts often includes the renting of honey bees hives (Park et al., 2020).

Nevertheless, the introduction of honey bees can result in a cascading effect on ecological communities and potentially affect native pollinators through competition, transmission of pathogens, and changes in plant communities (Mallinger et al., 2017). For instance, Badano and Vergara (2011) found a decrease in native pollinator diversity after the introduction of honey bees in highland coffee plantations, as well as a decrease in fruit production, and similar results were reported by Page and Williams (2023) in mountain meadows.

In addition, dependence on a single species for worldwide crop pollination services is risky (Breeze et al., 2014), and a growing body of evidence suggests that wild pollinators (e.g. non-*Apis* bees, syrphids) may supply an equal or even higher contribution than honey bees (Reilly et al., 2024; Eeraerts et al., 2023; Page et al., 2021). However, the monocultural landscapes usually created by intensive orchards are often unsuitable habitats for many wild pollinator species, which are impacted by extensive application of agrochemicals, limited foraging resources, intensive management, and lack of nesting sites (Alston et al., 2007; Roquer-Beni et al., 2021; Sheffield et al., 2008). For instance, Zanini et al., (2024) found that landscape heterogeneity in apple orchards is key for supporting pollination-related services, and should therefore be integrated into conservation and management practices.

In this study, we investigated the abundance of flower-visiting insects in intensively managed apple orchards in one of the major apple-growing areas of Europe. In the face of increasing agricultural demand and pollinator decline, identifying and implementing appropriate management measures suitable for pollinators is key to maintaining both biodiversity and crop productivity. Knowledge of the factors that affect species and communities underpinning crucial and biodiversity-mediated ecosystem functions is irreplaceable to effectively manage such services in agricultural ecosystems. Here, we aimed to determine which factors affect the abundance of flower-visiting insects - i.e. the suppliers of pollination. We considered seasonal and weather patterns, which are known to affect pollinators' activity and/or abundance, as well as fine-scale variables related to orchard management (and to ground management in particular), considering factors relevant to pollinators in perennial crops in the Alpine region (Granata et al., 2023, Biella et al., 2025). Moreover, we assessed the possible effect of the abundance of honey bees on wild bees, considering the potential impact

of the former on the latter (Geldmann and González-Varo, 2018; Mouillard-Lample et al., 2023). Sustaining diverse and effective pollinator communities requires appropriate orchard management practices (Gabriel et al., 2010), and enough foraging and nesting resources throughout the year (Holzschuh et al., 2012; Kremen et al., 2002). By identifying factors driving pollinators' abundance in apple orchards, effective management practices can be developed to shape policies and adapt management to preserve and enhance the crucially important pollinator communities.

2. Materials and methods

2.1. Study area

The study was carried out in 2023 in Val di Non, in Trento Province (northern Italy), beneath the Brenta Dolomites. The mean annual temperature is ~13.5°C at 150 m asl and ~8.5°C at 1000 m, and the average annual precipitation varies between 950 and 1050 mm throughout the area (Marini et al., 2012).

The study region is a wide North-South oriented glacial valley and one of the major apple cultivation areas in Europe (Fig. 1). It mainly lies between 400 and 1000 m, and flat and gentle-sloping areas are largely dominated by intensive orchards, >95 % of which are apples. The spatial arrangement is characterised by a mosaic of relatively small orchard parcels (mean ± SD: 2453.7 ± 1996.8 m^2). The approach to orchard management is homogenous, with the very great majority following integrated-pest management (IPM; organic apple orchards are less than 3 %). Over the past few decades, there has been a significant trend towards management intensification (resulting in landscape homogenisation), due to the adoption of dwarf and semi-dwarf rootstocks planted in rows (Fig. S1), a general increase in tree density within the orchards, and the spread of anti-hail nets (nowadays covering ~25 % of the apple orchards and being opened from mid-May to late September).

2.2. Sampling design and data collection

We located 70 sampling sites within the study area (Fig. 1) to (i) consistently and uniformly sample the entire orchard area, and (ii) represent the main environmental gradients found within it. These sites were made up of 200 m-long transects, and the site characteristics reported below are expressed as those found within a 100 m-buffer around the linear transect. Sites were located at an average distance of 810 m from each other (the minimum distance from one buffer to the nearest site's buffer was 492 m) and covered approximately 6 % of all apple orchards in the Val di Non. Site elevation ranged from 330 to 950 m, their average slope from 1.5° to 18°, and their distribution was also meant to represent all the main environmental conditions within the study area, encompassing a varying proximity to the most relevant land cover/habitat types surrounding farms (urbanised areas, forest patches, unmanaged grassland remnants, ponds, or cliffs). The average orchard cover within the buffer was 85.6 %.

2.2.1. Sampling of insects' visits

Pollinators' abundance and their interactions with apple blossoms and wild flowers are crucial components of the pollination ecosystem service. To estimate the potential intensity of pollination, we counted all insects visiting wildflowers and apple blossoms, categorising them into broad taxonomical groups, namely honey bees (*Apis mellifera*), bumblebees (*Bombus* spp.), wild bees, other Hymenoptera (i.e., wasps and ants), butterflies (Lepidoptera), syrphids (Syrphidae), other flies (Diptera), bugs (Rhynchota), and beetles (Coleoptera) (see below for a more detailed explanation). Among these groups, the first six include key pollinators, while the species belonging to the other three groups are expected to supply only a minor contribution to pollination within the study area. Given the potential variation in pollinator abundance and communities at very small spatial scales, our focus on flower-visiting
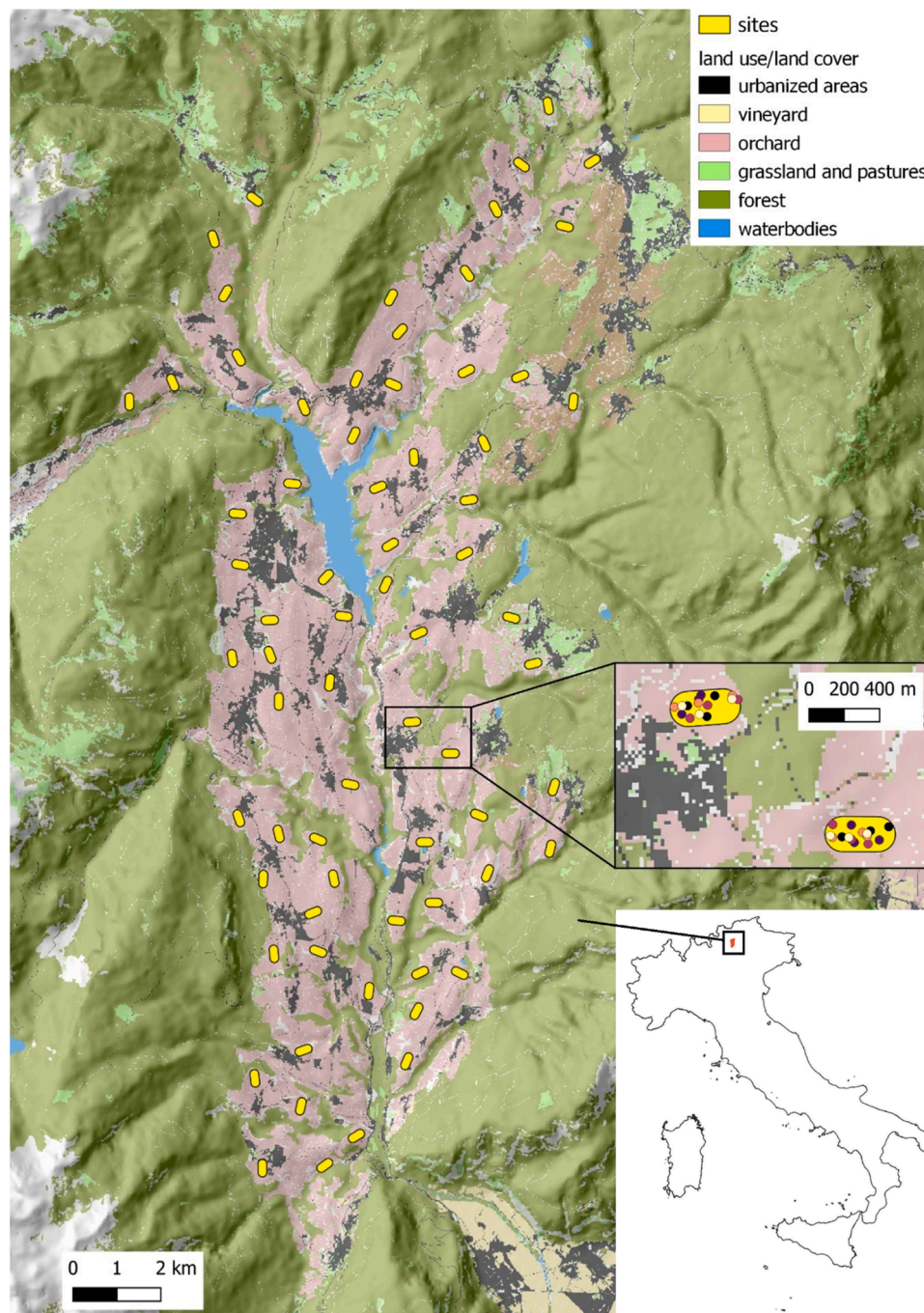
Fig. 1. Distribution of the study sites in Val di Non; the upper inset shows the sampling design for pollinator survey within a site: each individual plot is represented with different colours based on the sampling session in which data was collected ('magma' palette). The lower inset shows the location of the study area (red patch) within Italy.

insects was at a fine spatial scale. To cover most of the phenological season, we performed five subsequent surveys from late April to mid-September 2023. For each site and during each of these surveys (hereafter, 'sampling session' or 'visit'), we randomly selected three plots of 2.5 m-radius, located within the 100 m-buffer around each site (totalling 210 plots per session) and separated by at least 50 m from each other (Fig. 1), to reduce the risk of double counting the same individuals. Within each plot, we conducted a 5-minute observation period, during which we counted all insects present on flowers, distinguishing whether they were visiting apple flowers or flowers on the ground. Surveys were carried out from late morning to late afternoon, on days characterised by minimal or no wind (< 5 of Beaufort scale) and absence of rain, to ensure

the highest insect detectability.

2.3. Environmental drivers of flower-visiting insects

Environmental data were obtained through the direct measurement of variables in the field, focusing on apple orchard management (hereafter, 'management variables') and on seasonal and daily weather factors (hereafter, 'seasonal-weather variables'). For management variables, we recorded the inter-row distance and the distance between trees in a row (for the entire season). In addition, during each survey, we measured the height of the grass sward, any signs of (previous) soil tillage (tillage in the study area is usually performed before the period of

our surveys), the mowing regime, the presence of active anti-hail nets (Fig. 2), the presence of beehives and the presence and number of wild flowers' species. Beehives are routinely rent by farmers during apple bloom to ensure apple pollination; when present, they are generally placed in blocks of 6–12 beehives, within the orchards, spaced a few hundreds of meters apart from other blocks. To consider the possible interference of seasonal patterns and weather conditions on pollinator abundance, we recorded date and temperature (°C collected from local meteorological stations every hour), cloud coverage (expressed as a percentage of sky cover), and wind intensity (using the Beaufort scale: 0: calm; 1–2: weak; 3–4: moderate) for each plot sampling event. All the recorded variables are presented and described in Table 1.

2.4. Analyses

We used Generalised Linear Mixed Models (GLMMs) to test the effect of seasonal-weather and management variables on the abundance of flower-visiting insects. The site identity was included as a random factor to account for the possible non-independence of the data collected at the same site, and to take into account the environmental variation associated to different sites. Seasonal-weather and management variables were initially analysed separately, in order to (i) identify the most relevant type of predictors, and (ii) reduce possible multicollinearity issues in overly complicated models. As response variables, we modelled the abundance of (i) all the insects counted on ground flowers (regardless of flower type and insect group, hereafter "all flower-visiting insects"), (ii) all the insects on apple flowers ("all apple flower-visiting insects"), and (iii) of single taxonomical groups of insects (again for ground flowers, and for apple flowers only). To ensure adequate sample sizes, we modelled only those response variables with at least 30 records (i.e., at least 30 non-zero cases). For those related to apple flowers, only surveys during apple blooming season (i.e. April-May) were used and

Fig. 2. Examples of different apple orchards management: (A) unmown inter-row with a high grass sward; (B) completely mown inter-row; use of anti-hail netting system: (C) closed (i.e. inactive) nets, (D) open (i.e. active) nets (for analytical purposes, nets were considered as occurring at a plot only when open).

Table 1
List of variables used in the analyses, comprising descriptor of seasonal variations and weather conditions, and variables describing the orchard management. For each variable, we report (under the column "Value") the mean value ± standard deviation in all sites sampled during the study (for continuous predictors), or the number of cases per each level (for categorical variables).

Acronym	Description	Value
Seasonal-weather variables		
Date	Day of the year (from April to September)	
Months	From April to September, with April and May representing the apple blooming period and being the only months considered for apple flowers analyses	
Hour	Expressed as continuous value, where 0 and 1 is midnight, 0.5 is noon	0.54 ± 0.019
Temperature	Temperature (°C)	21.43 ± 4.12
Wind	0 = calm; 1 = weak; 2 = moderate	0: 383; 1: 533; 2: 79
Cloud coverage	% of cloud cover	41.17 ± 35.00
Management variables		
Inter-row distance	Distance between rows (cm)	317.45 ± 38.74
Distance between trees	Distance between trees in a row (cm)	77.74 ± 20.38
Nets	Presence/absence of open nets covering orchards (yes/no)	yes: 138; no: 857
Soil tillage	0 = no tillage; 1 = partial tillage; 2 = tillage	0: 866; 1: 120; 2: 9
Mowing regime	0 = unmown; 1 = partially mown (e.g., mown except inter-row); 2 = mown	0: 577; 1: 286; 2: 132
Flowers	Presence/absence of flowers (yes/no)	yes: 613; no: 382
Hive	Presence/absence of beehives in the site (yes/no)	yes: 66; no: 929
Sward height	<20 cm; 20–40 cm; >40 cm	<20: 272; 20–40: 508; >40: 215
Number of flower species		1.83 ± 1.87

the occurrence of anti-hail nets was not tested, since they start to be opened in the second half of May.

As covariates, beside the linear terms of all the variables, we entered the interaction between date and temperature, recognising their joint effect on insect abundance. The variable "hour" was entered in the models also as a quadratic term, to test for a non-linear relationship with flower-visiting insects. As we found a strong positive correlation between apple blooming months and the presence of ground flowers (p<0.001; "chisq.test" in R; (Pearson, 1900)), we created two separate models including only one of the two variables at a time. Finally, we created a subset of data with at least one bee (either honey bees or wild bees) and included honey bees visitation in the wild bees model (while keeping the other environmental variables) to investigate the potential effects of the interactions between wild and managed bees.

Prior to modelling, predictors' multicollinearity was assessed by computing the Variance Inflation Factor (VIF) of each predictor ("vif" function from the R package "car"; Fox and Weisberg, 2019; see also Figure S2 for pairwise correlations among predictors); we discarded variables with a GVIF (1 / (2 × Df)) greater than 3 (Fox and Monette, 1992). We built GLMs initially setting a Poisson error distribution with a log-link function, using the package "glmmTMB" (Brooks et al., 2017). We checked for overdispersion, uniformity of residuals, the occurrence of outliers, and potential zero-inflation issues by using the dedicated functions in the package "DHARMa" (Hartig, 2020). In case of overdispersion (p < 0.05), we switched to a negative binomial distribution (Hilbe et al., 2013) by means of the "glmer.nb" function (R-package "lme4"; Bates et al., 2014).

Within an information-theoretic approach, model selection was performed based on the AICc (Akaike's Information Criterion corrected for small sample size; (Burnham and Anderson, 2002)). To compare the AICc values for all conceivable models within each predictor group (seasonal-weather and management variables, hereafter "single

predictor group models"), we employed the "dredge" command from the R package "MuMIn" (Bartoń, 2024). We treated as equally supported all models which had an AICc less than 2 units higher than the lowest one (ΔAICc < 2), discarding those with uninformative variables (Arnold, 2010). In the case of more supported (ΔAICc < 2) models, we performed model averaging by means of the "model.avg" function (R-package "MuMIn"), considering full average estimates. Model averaging addresses model uncertainty and mitigates overestimation and underestimation (Steel, 2020). Then, we built a synthetic model by including all the terms selected by the above procedure for single predictor group models. We thus ended up with one synthetic model per response variable (cf. Brambilla et al., 2021), which was subject to the same AICc-based procedure.

At each step, we used the most supported model to calculate the lognormal conditional and marginal R^2 ("MuMIn::r.squaredGLMM" function; Bartoń, 2024) and to visualise predictors' effects by plotting them against the response variables ("visreg" command in the "visreg" package, Breheny and Burchett, 2017). All statistical analyses were performed with R software v. 4.3.1 (R Development Core Team, 2023).

3. Results

Overall, across the 70 sites scattered over apple orchards and through the five field sessions, we recorded 4814 insects on flowers, 3237 of which visited flowers on ground vegetation, and 1577 visited apple blossoms (Fig. 3). The most abundant groups in the whole sampling period were honey bees (2701 total individuals), wasps and ants (811), flies (514) and syrphids (389). The dominant visitors of apple flowers were by far honey bees, with a count of 1444 individuals, comprising 91.6 % of all apple flower-visiting insects. Among other apple flower visitors, we documented 45 wasps and ants, 35 bumblebees, 27 flies, 14 syrphids, 8 wild bees, 1 bug, and 3 other insects. Beetles and butterflies were never found on apple flowers.

After checking overdispersion and residuals' patterns, we selected a negative binomial distribution for all models, because overdispersion or odd residuals' patterns were found when adopting a Poisson error distribution. For all apple flower-visiting insects and the single group of honey bees foraging on apple flowers, a collinearity issue was found for the effects of date and the number of flower species (the two being correlated with r = 0.6), resulting in unexpected variations in the effect of each individual variable when the other variable was added to/removed from the model. Consequently, we decided to discard the date from the analysis, and include all informative variables along with the number of flower species in the final models. In the synthetic model for bumblebees on ground flowers, high standard errors were found for the effects of the variables "flowers" and "mowing regime". The AICc of the models with single-group predictors are reported in Table S1; a detailed summary of the synthetic models is presented in Table 2 and Table S2. A very relevant pattern emerging from our results was that the relative importance of management compared with that of the seasonal-weather conditions, was lower for insects on apple flowers, but higher for ground flowers (see AICc values in Table S1).

3.1. The effect of seasonal and weather conditions

For most flower-visiting insects, date, hour and temperature play a crucial role. Overall, the insect abundance exhibited a declining trend over the months, decreasing from the end of April to September (Fig. S3), and from April to May on apple flowers (Fig. S4a and S4b). However, the abundance of bumblebees foraging on flowers was predicted to rise throughout the sampling period (Fig. S3d), whilst wild bees and syrphids on flowers showed a slight decline (Fig. S3c, S3f). On apple flowers, the number of pollinators (substantially honey bees) strongly decreased from April to May (Table 2). Overall, the number of insects visiting flowers tended to decrease over hours (Fig. S5,S6), but some groups exhibited a non-linear relationship: honey bees on apple

Fig. 3. Pollinators and other flower-visiting insects found in apple orchards in Val di Non: (A) honey bees (*Apis mellifera*), (B) ant, (C) fly, (D) hoverfly (*Chrysotoxum* sp.), (E) buff-tailed bumblebee (*Bombus terrestris*), (F) ashy mining bee (*Andrena cineraria*).

flowers and all apple flower-visiting insects (with both models) were predicted to increase and then decline as the hour progresses (Fig. S5b, S5c,S6a,S6b), contrary to wasps and ants on flowers, whose abundance was predicted to decrease in the central hours and increase during the day (Fig. S5e). The number of flower visitors experienced a marginal rise with temperature (Fig. S7). The interaction between date and temperature was found to affect the abundance of honey bees, bumblebees and wild bees, which increased with relatively high temperatures, and decreased with low temperatures, as the date progressed (Fig. S8a, S8b, S8c), while wasps and ants, syrphids, and other insects exhibited an opposite pattern (Fig. S8d, S8e, S8f).

The abundance of pollinators diminished as the percentage of cloud cover increased (Fig. S9). Similarly, wind intensity had a negative effect on the number of apple flower foraging insects (according to both models) and wasps and ants on flowers (Fig.S10a, S10b, S10d), but not on bumblebees and syrphids, which were more abundant under weak and moderate wind conditions (Fig. S10c, S10e).

3.2. Management factors driving the abundance of flower-visiting insects

In total, we recorded 46 flowering plant species during the sampling period. The most visited flower species were *Taraxacum officinale* (151 records), *Trifolium repens* and *Trifolium pratense* (totalling 88 records)*, Ranunculus acris* (58 records), *Veronica polita* (55 records), *Ornithogalum umbellatum* (39 records), and *Lamium album* (38 records).

Flower presence predicted the abundance of the combined categories of all insects visiting ground flower and apple flower (Figs. 4a, 4b), as well as of single groups of visiting insects, i.e. honey bees (Figs. 4c, 4d),

wasps and ants (Fig. 4e), flies (Fig. 4f), and bumblebees (Fig. 4g). The number of flower species was positively related to the abundance of all groups of insects visiting ground flowers (Fig. 5), except flies, wasps and ants.

The height of the grass sward was also an important predictor for single groups such as bumblebees, flies, syrphids, and for all flower-visiting insects, which abundance was positively associated with a sward height ranging from 20 to 40 cm, and especially with a sward height exceeding 40 cm (Fig. 6).

The implementation of partial or complete mowing had a negative impact on the number of honey bees foraging on flowers (Fig. 7b), but resulted in a greater abundance of honey bees foraging on apple flowers (Fig. 7c), and consequently on all apple flower-visiting insects (which are represented by honey bees for 91.6 %), in the models where month was considered (Fig. 7a). Ultimately, soil tillage and the distances between trees and rows were not found informative for any synthetic models.

The presence of beehives had a positive effect on the abundance of honey bees (Fig. 8c), and on all apple flower-visiting insects in both models developed (Figs. 8a, 8b), including those for honeybees (Figs. 8d, 8e). However, the presence of honey bees negatively affected the number of wild bees (Fig. 8f). Finally, the presence of anti-hail nets exerted a negative influence on the abundance of insects visiting flowers, as well as on flower-visiting honey bees and bumblebees (Table 2 and Fig. S11).

Table 2
A summary of the estimated synthetic models for insects visiting apple flowers (when specified in the column name) or ground flowers (column named only according to the insect groups). Beta estimates and their standard errors are reported per each predictor included in each synthetic model, along with its marginal and conditional R^2. See the text about the very large SE values in the bumblebees' model. In bold, the effects for which estimates ± confidence intervals do not encompass zero.

	All flower-visiting insects	All apple flower-visiting insects (with months)	All apple flower-visiting insects (with flowers)	Honey bees on flowers	Honey bees on apple flowers (with months)	Honey bees on apple flowers (with flowers)	Bumblebees	Wild bees	Wild bees*	Wasps and ants	Flies	Syrphids	Other insects
Date	**−0.06** **±0.10**			**−0.21** **±0.15**			**1.21** **±0.28**	**−0.04** **±0.18**		**−1.39** **±0.31**		**0.004** **±0.14**	**−0.68** **±0.22**
Months during apple blooming (May)		**−4.11** **±0.28**			**−4.09** **±0.29**								
Hour	−0.10 ±0.08	**0.58** **±0.10**	**0.81±** **0.13**		**0.62** **±0.11**	**0.81** **±0.13**		**−0.51** **±0.17**	**−0.43** **±0.15**	−0.15 ±0.17		**−0.26** **±0.11**	**−0.33** **±0.16**
Hour^2		**−0.33** **±0.10**	**−0.38** **±0.13**		**−0.44** **±0.11**	**−0.53** **±0.13**				0.20 ±0.20			
Cloud	**−0.17** **±0.06**							**−0.35** **±0.16**	**−0.35** **±0.13**		**−0.49** **±0.10**	**−0.51** **±0.11**	
Wind (1)		**−0.23** **±0.16**	−0.22 ±0.24				**1.48** **±0.47**			−0.26 ±0.32		**0.58** **±0.21**	
Wind (2)		**−1.16** **±0.39**	**−1.87** **±0.50**				0.57±0.93			−0.48 ±0.58		**0.78** **±0.40**	
Temperature	**0.22** **±0.08**			**0.61** **±0.13**			**0.37±** **0.24**	**0.75** **±0.22**	**0.55** **±0.13**	**−0.46** **±0.28**		**0.32** **±0.13**	0.11 ±0.19
Months during apple blooming (May) × Temperature													
Date × Temperature				**0.44** **±0.15**			**1.11** **±0.27**	0.27 ±0.30		**−1.68** **±0.29**		**−0.57** **±0.18**	**−1.01** **±0.28**
Honey bees									**−0.34** **±0.17**				
Hail nets (yes)	**−0.47** **±0.18**			**−0.82** **±0.26**			**−1.33** **±1.16**						
Soil tillage (1)													
Soil tillage (2)													
Mowing regime (1)		−0.11 ±0.15		−0.17 ±0.17	−0.11 ±0.15		−0.11 ±0.41						
Mowing regime (2)		0.69 ±0.31		−0.93 ±0.33	0.73 ±0.31		−14.3 ±673.8						
Flowers (yes)	**5.08** **±0.43**		**1.80±** **0.37**	**4.08** **±0.62**		**1.81** **±0.38**	18.6 ±1710.5			**5.74** **±0.96**	**5.57** **±1.01**		
Hives (yes)		**0.51** **±0.22**	**1.57** **±0.35**	**0.85** **±0.25**	**0.62** **±0.23**	**2.07** **±0.39**							
Sward height (20−40)	**0.38** **±0.14**						1.12 ±1.10				0.18 ±0.26	**1.04** **±0.28**	
Sward height (>40)	**0.46** **±0.17**						1.98 ±1.08				**0.61** **±0.28**	**1.39** **±0.31**	
Number of flower species	**0.36** **±0.07**			**0.60** **±0.09**			**1.24** **±0.22**	**0.97** **±0.15**				**0.96** **±0.11**	**0.77** **±0.14**
Marginal/ Conditional R^2	0.89/ 0.89	0.82/ 0.89	0.48/0.61	0.83/ 0.85	0.81 /0.89	0.47/0.68	0.98/0.99	0.39/ 0.39	0.36/ 0.36	0.83/ 0.83	0.80/ 0.80	0.52/ 0.53	0.34/ 0.37

* here referring to the model where the abundance of honey bees is included as a covariate for predicting the abundance of wild bees, run on a subset of data with at least one bee found during the survey.

4. Discussion

In this study, we quantified the abundance of flower-visiting insects across apple orchards to assess the impact of agricultural management on pollinator communities. Overall, as expected, we found the dominant pollinators to be honey bees (mainly rented by farmers during the apple blooming period in the study region), while there was a limited presence of wild pollinators visiting apple orchards. This aligns with findings by Pardo and Borges (2020) and Dymond et al. (2021), who also observed a dominance of managed pollinators in agricultural systems. The most supported models integrated both seasonal-weather and management variables, indicating that pollinators exhibit responses influenced by a combination of factors. Interestingly, management factors always 'out-competed' seasonal-weather ones when wildflowers and wild insects were considered; only honey bees (which are sustained by beehives renting) were primarily driven by seasonal-weather factors when

visiting apple flowers (see Table S1). Nevertheless, seasonal-weather variables had a strong effect on the abundance of flower-visiting insects, which was significantly influenced by date and temperature. In most cases, their interaction was also statistically supported. This aligns with the widely recognised distinct seasonal patterns of insect activity (Gordo and Sanz, 2006; Huntley et al., 2008) and is likely related also to temporally different availability of flower resources. The abundance of most pollinators declined as the season progressed, with a peak in May when the highest number of individuals was recorded. However, in apple flowers the pollinators' abundance (mostly honey bees) was highest in April, coinciding with the peak of apple blooming. This phenomenon might be attributed to the phenological aspects of the life cycle of many insects, as they tend to avoid the summer heat. Many species may also experience severe disturbance in September, coinciding with the lowest count of pollinators during apple harvesting. However, results showed that the abundance of bumblebees increased throughout
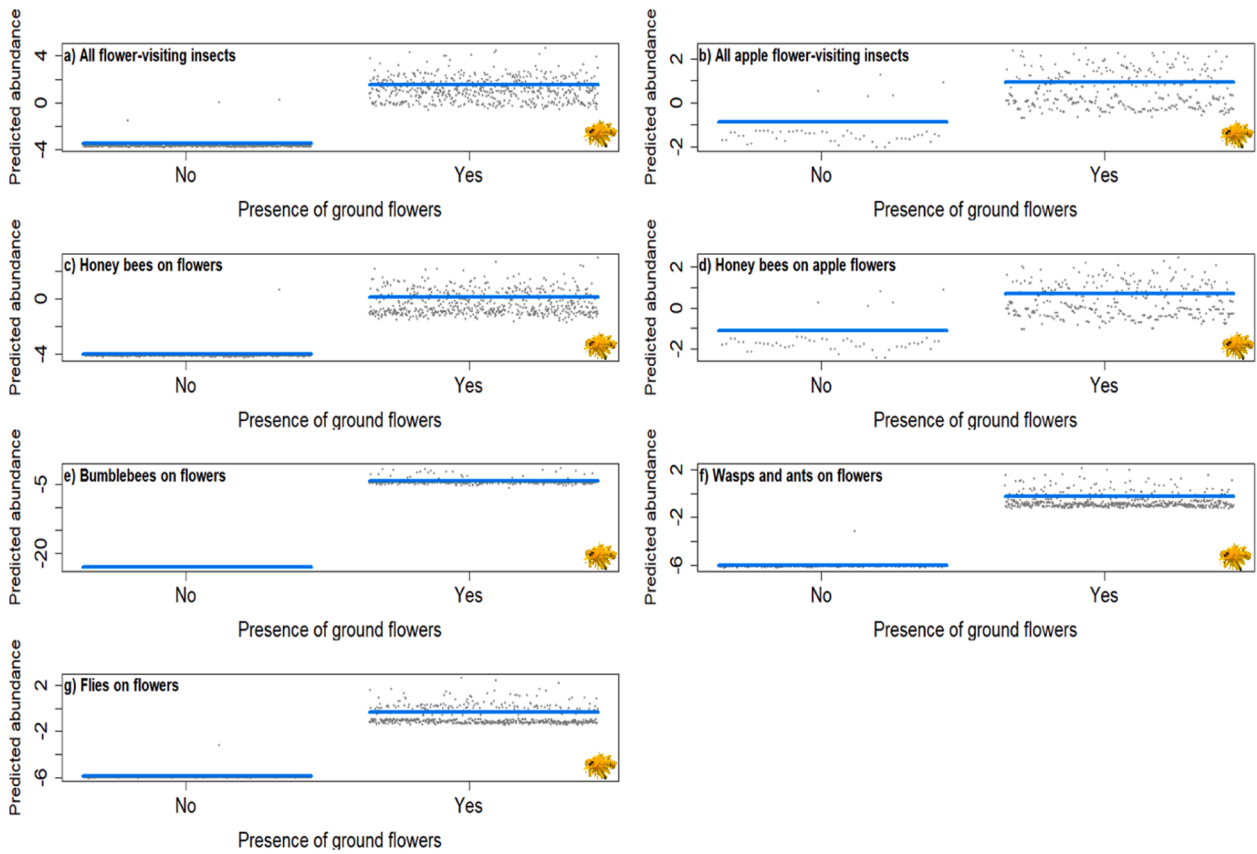
Fig. 4. Predicted abundance of a) all flower-visiting insects, b) all apple-flower visiting insects, c) honey bees on flowers, d) honey bees on apple flowers, e) bumblebees on flowers, f) wasps and ants on flowers, and g) flies on flowers in relation to the presence of ground flowers. Values on the y-axes are untransformed model predictions (also in the subsequent figures).
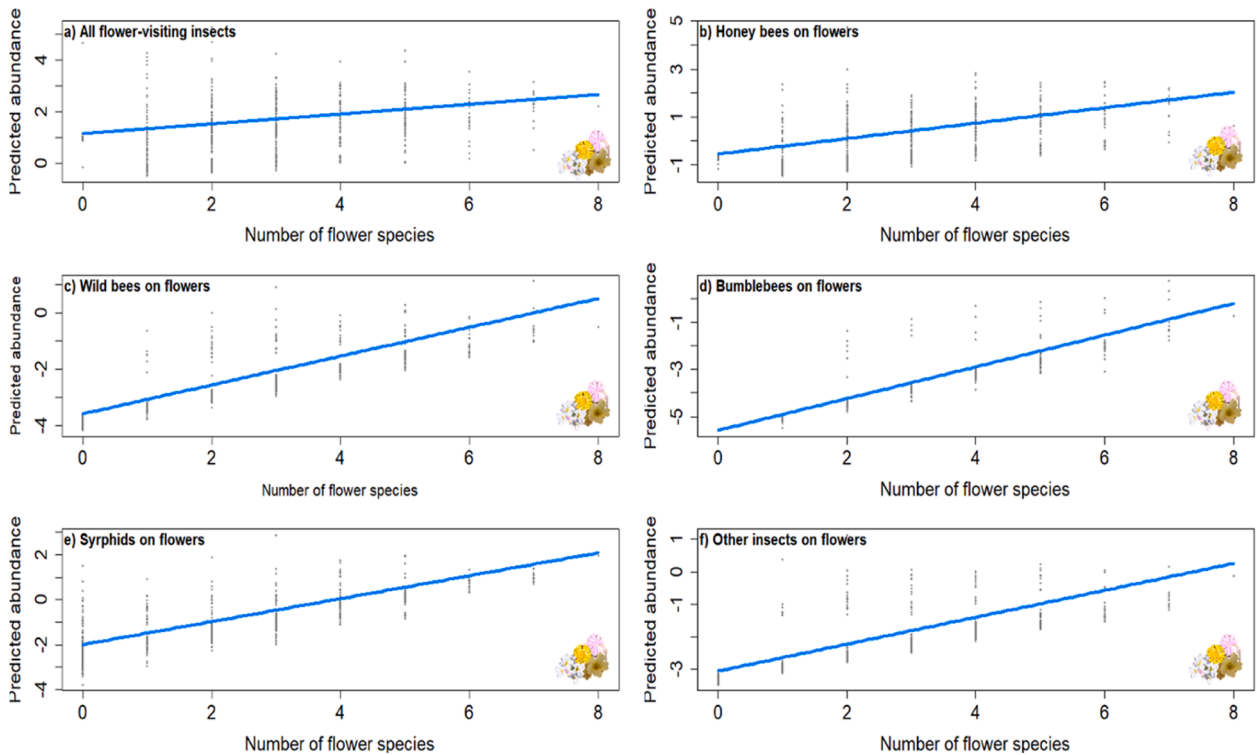

Fig. 5. Predicted abundance of a) all flower-visiting insects, b) honeybees on flowers, c) wild bees on flowers, d) bumblebees on flowers, e) syrphids on flowers, and f) other insects on flowers in relation to the number of flower species.
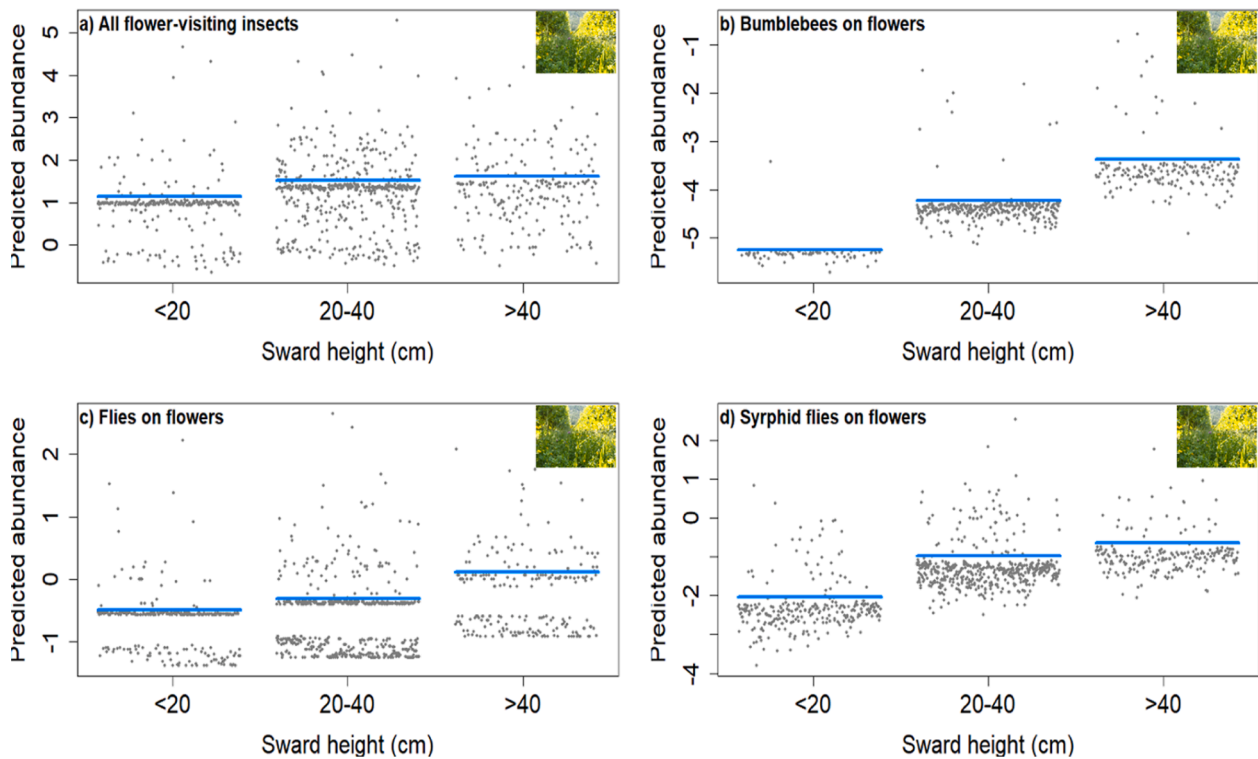
Fig. 6. Predicted abundance of a) all flower-visiting insects, b) bumblebees on flowers, c) flies on flowers, and d) syrphids on flowers in relation to the sward height.
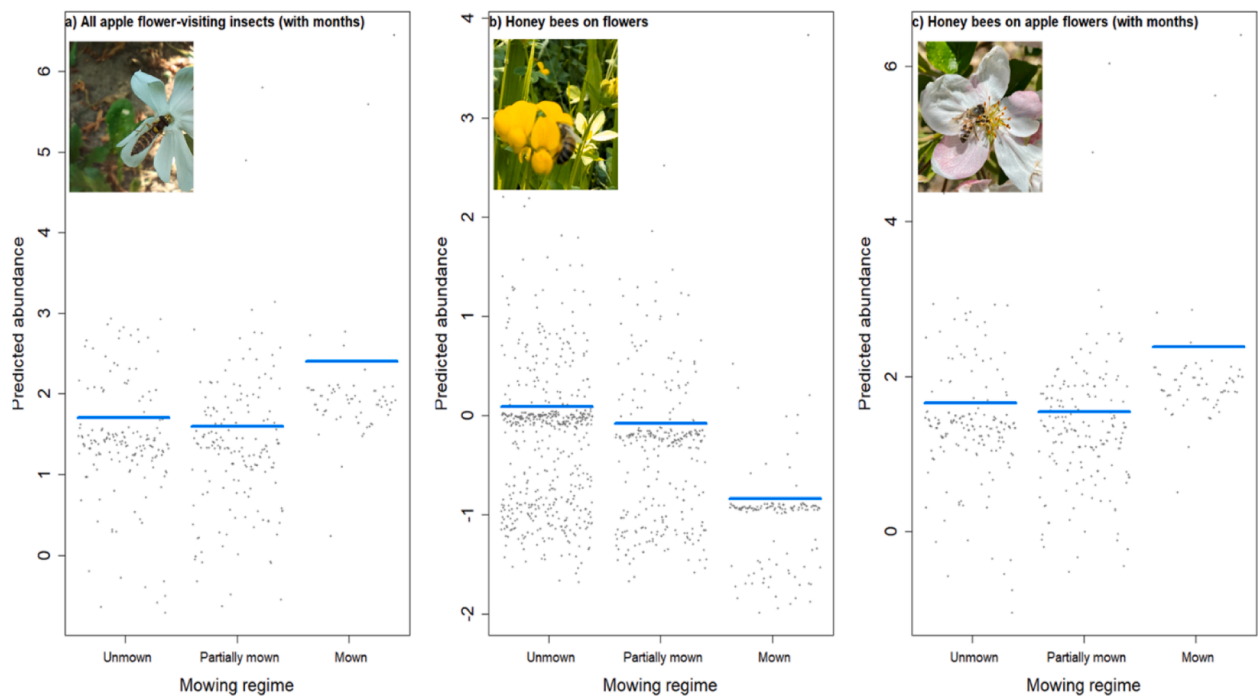
Fig. 7. Predicted abundance of a) all apple flower-visiting insects (with months), b) honey bees on flowers and c) honey bees on apple flowers (with months) in relation to the mowing regime.

the sampling period and under moderate wind conditions. This can be explained by their greater resilience to unfavourable weather conditions, allowing bumblebees to stay active for longer periods, both on a daily and seasonal basis (Martins et al., 2015). Wild bees, syrphids, and other insects were early visitors, whereas honey bees showed a higher frequency during the afternoon and tended to visit flowers in the central

hours of the day and apple flowers in the late afternoon. Furthermore, wasps and ants were found more abundant during the first and last hours of the day and tended to avoid visiting flowers during the central hours.

Among potential mechanisms underlying the variations observed, there could be distinctions in life histories (e.g. some flies rest on petals overnight, leveraging early morning radiation reflection; Vicens and
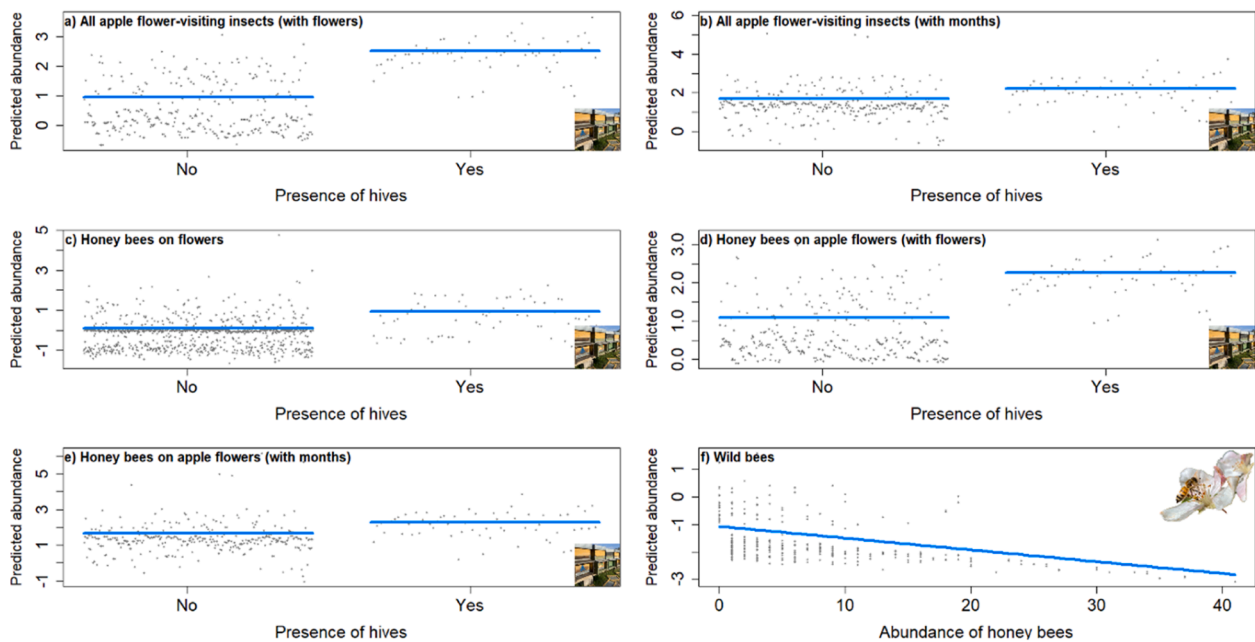
Fig. 8. Predicted abundance of a) all apple flower-visiting insects (with flowers), b) all apple flower-visiting insects (with months), c) honey bees on flowers, d) honey bees on apple flowers (with flowers), and honey bees on apple flowers (with months) in relation to the presence of hives, and f) predicted abundance of wild bees in relation to the abundance of honey bees.

Bosch, 2000), thermoregulation capabilities (where smaller wild bees might rely more on daytime central temperatures; Bishop and Armbruster, 1999), and potential interspecific competition (Brittain et al., 2013). Our data also suggest that a higher frequency of honey bees is associated with a lower abundance of other pollinators, a pattern already reported from other study systems (Graystock et al., 2020; Lindström et al., 2016). Specifically, we found a marked decline of wild bees' abundance in relation to increasing occurrence of honey bees, suggesting a possible negative effect of competition exerted by honey bees on their wild relatives, which should be further investigated.

Agricultural practices can drive pollinators' abundance (Shackelford et al., 2013), and our findings confirmed that. In the absence of mass flowering in apple trees (which is temporally limited to early spring), pollinators rely on floral resources found in the herbaceous layer. Besides, phenological overlap is considered a crucial factor in structuring plant-pollinator networks because insects cannot gain fitness advantages from plants that bloom outside their activity periods (Junker et al., 2013). We identified a positive relationship between the ground flora community and the visitation of pollinating insects to flowers, suggesting that enhancing the ground flora in orchards could be an effective management practice. The positive effect of the presence of wildflowers on pollinators visiting apple blossoms suggests that the ground flora has the potential to enhance insect visitation rate to apple flowers by promoting the availability of key resources, which has been related to pollinators' health and resilience (Parreño et al., 2022). However, Steele et al. (2022) found a different pattern, where honey bees primarily visited the forest during spring and focused on wildflowers between orchard rows after the apple bloom, suggesting that the post-bloom apple orchards provided valuable foraging opportunities. This discrepancy may be due to context-specific factors such as local vegetation, seasonal flowering patterns, or competition for floral resources.

The occurrence and abundance of wildflowers are primarily affected by management practices, including mowing and soil tillage (Winter et al., 2018). Leaving an unmown row, or decreasing the frequency of mowing in the grass layer, is a recommended strategy to boost the abundance of flowers in orchards and ensure a better availability of foraging habitats for beneficial natural enemies and pollinators (Tommasi et al., 2021). Revising mowing practices can improve

biological communities in orchards (Horton et al., 2003; Saunders et al., 2013) and vineyards (Brambilla and Gatti, 2022; Biella et al., 2025). Moreover, tall grass sward promoted the abundance of flower visitors, likely by improving the visual attraction of flowers to pollinators. Similarly, semi-natural habitats nearby fruit orchards can provide complementary food and nesting resources for pollinating insects (Eeraerts et al., 2021), as well as supporting a higher pollinator species richness and wild pollinator abundance in similar crop systems (Eeraerts et al., 2019). Therefore, their influence on pollinating insects' abundance and activity in our study system should be further investigated. Contrary to expectations, we found that mowing regime was associated with an increasing abundance of honey bees on apple flowers in models where month was considered, but had a strongly negative impact on bumblebees. Honey bees do not rely on ground nesting resources; the lack of floral ground resources due to mowing during the apple blooming period may promote the visitation of apple blossoms by them.

The few studies investigating the impact of tillage on bees in agricultural fields reported a negative impact on ground-nesting bees, reducing offspring emergence (Tschanz et al., 2024; Ullmann et al., 2016). However, in our study, soil tillage had no relevant effect on pollinating insects and was not supported in any synthetic model. This could be due to the fact that tillage takes place before the flowering season, hence before the peak of activity of most pollinating insects. More research should be carried out to explore the potential effects of tillage regimes on different bee species, considering factors such as social and solitary behaviour, size, phenology, nesting depth, soil types, and the use of different tillage methods and timing.

The reduced abundance of wild pollinators within apple orchards is likely attributable to the relatively high level of agrochemicals (Sheffield et al., 2008). Unfortunately, we lack specific information regarding pesticide use, but pesticides are applied quite uniformly across farms, because all farmers follow the same management protocols at the valley level. Therefore, we can be confident that there were no relevant differences across the different study sites.

In agricultural systems, protective nets are frequently used to mitigate the effects of severe weather conditions and manage pest species. The results of our study showed a negative impact on the abundance of pollinating insects foraging on flowers associated with the presence of

open anti-hail nets, consistently with Santos (et al. (2023), likely due to limited insect movement through the physical barrier presented by small-aperture mesh. Other studies reported the decreased abundance of arthropods in general, and large bees in particular, in the presence of hail nets (Meissle et al., 2023), the reduced number and duration of honey bees foraging trips (Evans et al., 2019), as well as negative effects on some bird species in our own study area (Brambilla et al., 2015, 2013), but further research is needed to better understand the impact of protective nets on pollination service and on biodiversity in general.

Apple orchardists often rent honey bees hives and bring them to orchards to improve pollination services (Park et al., 2020), as it happens in our study area. Our findings indicate that the number of honey bees is predicted by the presence of hives, which were therefore effective in increasing honey bees abundance and their visitation rates to apple flowers. Nevertheless, there was a negative association between flower visitation by honey bees and visitation rates by wild bees. The prevalence of honey bees on apple blossoms, potentially leading to high competition, may disproportionately impact short-tongued, generalist, and smaller-bodied solitary bees, which often forage on shallow flowers due to their shorter mouthparts, as such flowers are better suited for their body size (Ropars et al., 2020). Wild bees avoid mass blooms or floral patches when honey bees are abundant (Ropars et al., 2022), or alter their diet (Valido et al., 2019). Therefore, it has been suggested that limiting the introduction of beehives will decrease the dominance of *Apis mellifera*, promoting increased diversity through a more balanced distribution of species abundances, while simultaneously having virtually no negative impact on yield (Weekers et al., 2022). For instance, Osterman et al. (2021) found less honey bees on apple flowers when oilseed rape was present, but no influence on apple yields due to the presence of wild bees that ensured the pollination of apple. Furthermore, wild insects were found to increase fruit set twice as much as honey bees in different crops systems from all continents and further provided a better-quality pollination (Garibaldi et al., 2013). In addition, wild pollinators may promote a more efficient cross-pollination due to differences in foraging behaviour. For example, bumblebee's visitation rates were higher compared to honey bees, whose behaviour was positively driven by bumblebee abundance and richness in sweet cherry (Eeraerts et al., 2020).

Relying on a single pollinator species poses a notable risk, as it exposes crop pollination to the potential impacts of diseases and parasites affecting that specific species. In addition, a very high abundance of honey bees may be detrimental in multiple ways to wild pollinators, not only by interspecific competition for the same resources, but also by direct negative interferences (e.g. through aggressive behaviour, disease spreading, etc.; Hyjazie and Sargent, 2022; Martínez-López et al., 2022a, 2022b; Piot et al., 2022). Similarly to other studies e.g., Eeraerts et al. (2023), our results suggest that both honey bees and wild insects contributed to pollination, but negative interactions between domesticated bees and wild bees were likely occurring. Management strategies that consider an adequate use of hives and simultaneously provide suitable environments for wild pollinators should be therefore encouraged.

4.1. Study limitations

In our study system, there is a very low share of organic farms, and the existing ones are interspersed in a matrix dominated by non-organic fields. This results in the impossibility to test the potential differences between organic and IPM management regimes, and their relative effect on pollinator communities. Organic farms in the study area are highly intensive and mechanised, so similar patterns might apply to them. To evaluate the effects of intensification, old-style orchards with larger and sparser trees, scattered over a grassland-like surface, would provide the ideal control (e.g., Horak et al., 2013), but they are now very rare in the study area and occur unevenly across the valley.

A second limitation concerns the lack of data on apple effective

pollination and apple yield. Although we lack specific yield information for different apple varieties, in the Non Valley apple yield is extremely high everywhere, and farmers commonly reduce the number of growing fruits by thinning. Further data, especially on apple quality, could provide more nuanced insights into how pollinators may benefit apple yield and enhance market value (Burns and Stanley, 2022; Garratt et al., 2014; Olhnuud et al., 2022; Pardo and Borges, 2020). In turn, this could promote the adoption of more biodiversity-friendly practices by farmers, and shed light on the importance of supporting both wild and domesticated pollinators.

A further study limitation can be represented by the lack of quantification of flower availability (number of apple/ground flowers per area per survey) and their relative proportions (apple vs ground flowers). This makes it difficult to directly compare the number of insects visiting the two types of flowers, and lower abundances of insect visitors might be related to lower abundances of flowers. However, dealing with the absolute abundance or the relative proportion (apple vs. ground) of flowers can be challenging as (i) ground flowers are on a two-dimension surface (ground surface), whereas apple flowers are on a three-dimension surface (trees), and (ii) apple flowers occur only in April and May, when they are much more abundant than ground flowers, then disappear for the rest of the year. Furthermore, in our study system the lack of ground flowers and their low abundance was primarily related to the management regime applied to apple orchards and can be therefore used as a proxy for the influence of management factors on pollinators. Although it was not the aim of this study, information on competition and overlap between the different groups of flower-visiting insects would give an even better understanding of the pollination services provided in apple orchards and should be therefore explored. In addition, we did not account for landscape factors, which have clear effects on pollinating insects and can be therefore highly relevant in explaining their abundance and activity in apple orchards, as other studies pointed out (Dainese et al., 2019; Eeraerts, 2023; Kennedy et al., 2013). The global effect of landscape factors is somehow taken into account by using the transect ID as a random factor in models, but further research is required to shed light on their specific influence on pollinating insects. Finally, the negative effect of honey bees on wild bees should be interpreted with caution. Although we considered the effect of domesticated bees along with the environmental and management data, the apparent competition we found might be modulated by further factors and being landscape-dependent. Thus, it should be further explored by taking into account also the landscape effects.

5. Conclusions

In summary, our study provides insights into the factors influencing pollinator communities within the economically relevant apple orchards in Val di Non. Understanding the drivers of the abundance of flower-visiting insects and diversity is crucial for ensuring resilient pollinator communities. Our results highlight a prevailing trend of honey bees emerging as the dominant pollinators, especially for apple trees, whereas the presence of wild pollinators is limited within intensively managed apple orchards. Given the distinct foraging patterns of honey bees and wild pollinators, further conservation and management efforts should focus on supporting diverse and functional pollinator communities to improve pollination efficiency and resilience, increasing biodiversity and ensuring also the stability of apple crop yields (Penvern et al., 2019; Ropars et al., 2020).

To promote the occurrence of pollinating insects in apple orchards, farmers need to ensure the availability of appropriate environments for foraging and nesting. In this study, the presence of wildflowers and plant species richness in the ground cover is highlighted as a major driver of the pollinator community. Therefore, we would recommend farmers to maintain well-developed and diverse ground covers and flower margins to provide food and shelter resources for pollinators, especially outside of the apple blooming season (Martínez-Sastre et al., 2020), while at the

same time promoting indirect benefits, such as the supply of habitat suitable for natural enemies of apple pests, e.g. syrphids and ladybugs (Howard et al., 2024; Rosa García and Miñarro, 2014). Other pollinator-friendly practices should involve a reduction in the frequency of ground vegetation management (Horton et al., 2003; Maurer et al., 2020), enhancing the sward height with positive effects on pollinators.

Our study also emphasises the need for further research to guide effective management and conservation strategies, especially by focusing on the consequences of the negative effects exerted by honey bees on wild bees, and on the impacts associated with anti-hail nets. By advancing our understanding in this area, we can develop targeted approaches to protect pollinator populations and promote sustainable agricultural practices. Future research efforts should concentrate on determining the effective combination of management strategies (e.g. implementing flower strips, minimising agrochemical usage, adopting less stringent mowing practices, reducing the presence of hail nets) to maximise benefits for both pollinators and crop yield. In particular, investigating the potential interactive effects of agrochemicals and ground management on pollinators would be important to identify the most suitable practices, while at the same time addressing landscape effects on visitation rates and interactions among different groups potentially competing for the same resources.

CRediT authorship contribution statement

Emanuela Granata: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ekaterina Mogilnaia:** Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **Corrado Alessandrini:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Karan Sethi:** Writing – review & editing, Investigation. **Valeria Vitangeli:** Writing – review & editing, Investigation. **Paolo Biella:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Chiara Fedrigotti:** Writing – review & editing, Project administration, Investigation. **Francesca Roseo:** Writing – review & editing, Investigation. **Paolo Pedrini:** Writing – review & editing, Project administration, Funding acquisition. **Mattia Brambilla:** Writing – review & editing, Validation, Supervision, Software, Methodology, Funding acquisition, 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.2024.109382.

Data Availability

Data are available in Milan University Dataverse at https://doi.org/10.13130/RD_UNIMI/ABBKU1.

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