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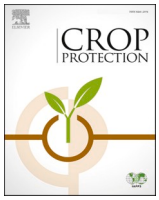

Pest note

The role of cultivar interactions with arthropods in integrated pest and pollinator management strategies for apple orchards

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ABSTRACT

The diversification of floral resources is a pillar of pollinator conservation in agroecosystems, potentially also supporting biological control agents in Integrated Pest and Pollinator Management (IPPM) frameworks. Given the necessity to reduce pesticide use for IPPM systems to work, ideally farmers should use crop cultivars that are not only highly attractive and dependent on pollinators, but also highly resistant to pests. Cultivar selection should thus be informed by a correct understanding of trade-offs and synergies between plant traits related to pollination and pest susceptibility.

In the present exploratory study, we set 3 pairs of experimental apple orchards (agroecological vs. conventional management) in Northern Italy with the aim of i) assessing the effects of pollinator-friendly agroecological measures (cultivar diversification, flowering cover crops) on beneficial arthropods, and ii) investigating the interaction of individual apple cultivars with pollinators and pests, highlighting trade-offs and synergies between functions.

The tested pollinator-friendly measures appeared to be useful multifunctional tools capable of increasing the abundance of pollinators and predatory arthropods. The 9 tested cultivars differed in terms of pollinator dependence and pest resistance, with some important trade-offs. Cultivars such as the commercially important 'Pink Lady®', which would especially benefit from increased pollination service, may be unfit for a fully agroecological management due to pest susceptibility.

The management of non-crop vegetation is an important tool to support beneficial arthropods in apple orchards, but cultivar selection is a critical element for a truly successful IPPM system; given the observed trade-offs with pollination traits, pest-resistant cultivars should be prioritized.

1. Introduction

Biodiversity conservation within agroecosystems is increasingly recognized as a pivotal effort, given that the ever-expanding agricultural areas now represent the largest terrestrial biome on Earth (Ellis and Ramankutty, 2008; Ramankutty et al., 2018) and that biodiversity provides many ecosystem services vital to agriculture itself, including crop pollination, biological pest control and soil quality regulation (Palm et al., 2014). Permanent cropping systems, such as orchards and vineyards, may play a key role in this endeavour because they are inherently less disturbed than annual crop systems and can provide favourable habitats for many taxa when properly managed (Fan et al., 2024; Kreitzman et al., 2022). From this point of view, there is particular interest in devising efficient agroecological strategies for biodiversity management in orchards (De Leijster et al., 2019; Kreitzman et al., 2022), with a special focus on beneficial arthropod diversity because orchards strongly depend not only on biological control, but also on entomophilous pollination (Demestihas et al., 2017), which influence both yield and fruit quality (Bordoni et al., 2024; Garratt et al., 2014). In that regard, Integrated Pest and Pollinator Management (IPPM) has been proposed as an expansion of Integrated Pest Management (IPM) that explicitly considers the need for pollinator conservation (Biddinger and Rajotte, 2015; Leach et al., 2022). The success of this kind of framework depends on a hierarchical decision support system encompassing

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landscape management, local habitat management and external inputs while considering the ecology of pollinators, natural enemies and pests simultaneously (Egan et al., 2020; Lundin et al., 2021).

A central tenet of IPPM, and agroecological management in general, is the creation of diversified, structurally complex and resource-rich microhabitats able to host a variety of beneficial species, a goal often pursued by increasing plant diversity within the agroecosystem (Albrecht et al., 2020; Isbell et al., 2017; Lundin et al., 2021). Considering the crop, plant diversity can be increased by using multiple crop species, or multiple genetically distinct varieties of the same species (Rakotomalala et al., 2023; Wan et al., 2022). In the apple *Malus domestica* (Suckow) Borkh., for example, different cultivars may attract (and thus support, and in turn depend on) different guilds of pollinators (Burns and Stanley, 2022; Garratt et al., 2016). Additionally, cultivars flowering at different moments may reduce competition for pollinators between each other, and support pollinators for a longer time (Grab et al., 2017; Riedinger et al., 2014). More broadly, overall plant/habitat diversity in agroecosystems can be increased either by conserving and encouraging wild plant biocenoses (Nicholls and Altieri, 2013), or by creating new plant-rich habitats in the form of sown flower strips or cover crops (Triquet et al., 2024; Tschumi et al., 2016). Indeed, flowering cover crop species can support many different pollinator guilds (Mallinger et al., 2019), and enhance at the same time other aspects of biodiversity and ecosystem services (Candelaria-Morales et al., 2022; Lami et al., 2024). In perennial crops, for instance, cover crops that provide food for pollinators may also act as a favourable microhabitat for natural enemies (Karamaouna et al., 2019; Ploeg et al., 2025). Pollinator-friendly measures based on floral cover, however, are not always linked with an improvement in the delivery of other ecosystem services, and this multifunctionality might depend on the environmental context (Cappellari et al., 2023).

Another central pillar of agroecological management is the reduction of damaging external inputs such as pesticides (Garibaldi et al., 2019). Indeed, if the creation of favourable habitats (such as flower strips) is not paired with a reduction in dangerous inputs, the habitat itself might turn into an ecological trap, attracting beneficial arthropods and then killing them or reducing their fitness (Ganser et al., 2019; Tarano et al., 2025). In this regard, IPPM and similar frameworks are especially relevant for entomophilous crop species (Egan et al., 2020), as pesticide exposure may negatively impact pollination and yield (Lenzi et al., 2026), with insecticides in particular being especially damaging to pollinators when considered on their own (Iwasaki and Hogendoorn, 2021; Nkontcheu Kenko and Ngameni, 2022). Cultivar selection is a key element: crop varieties that are highly attractive for pollinators (and highly dependent on them) are the ones most likely to benefit from IPPM (Isaacs et al., 2017). At the same time, cultivars with a natural resistance to pests are the most likely to thrive without frequent insecticidal treatments (Egan et al., 2020); excessive pest pressure can diminish or even negate the benefits of increased pollination (Lundin et al., 2013; Sutter and Albrecht, 2016), and while biological control is often enhanced under agroecological management (Tooker et al., 2020), particularly sensitive crop varieties may still need chemical inputs. The “perfect” IPPM cultivar should thus be both highly attractive and dependent on pollinators, and highly resistant to pests. As plant traits, and ecosystem functions in general, can present both trade-offs and synergies across cultivars and environments (Lami et al., 2025; Tamburini et al., 2016; Yang et al., 2023), cultivar selection for IPPM would greatly benefit from the identification of positive and/or negative associations between desirable traits linked with both pest and pollinator interactions.

In the present exploratory study, we set out to test the effects of pollinator-friendly agroecological measures (cultivar diversification, flowering cover crops) on beneficial arthropods in apple orchards, and to investigate the interactions of individual apple cultivars with pollinators and pests, focusing on potential trade-offs and synergies relevant for the identification of cultivars fit for IPPM. The study took place in 3 orchard pairs (agroecological vs. conventional) in the area of Bologna, in Northern Italy. Apple was chosen as a model because it is one of the most important and widespread fruit crops in Europe and the world (Muder et al., 2022). Specifically, our aims were to 1) assess whether pollinator-friendly measures based on plant diversity could increase the abundance of both pollinators and predatory natural enemies in the studied system; 2) compare the tested apple cultivars in terms of attractiveness to pollinators, pollinator contribution to fruit production and quality (size, seed set, sugar content), and susceptibility to damage caused by major pest arthropods; and 3) identify trade-offs and synergies (i.e. problematic or advantageous trait associations) between pollinator- and pest-related traits across the studied cultivars, also highlighting the most promising cultivars for IPPM in terms of pollinator dependence and resistance to pests. Our results could inform future larger scale research, and improve the planning of agroecological measures for the conservation of beneficial arthropod assemblages in Mediterranean apple orchards, all while safeguarding fruit production and quality.

2. Materials & methods

2.1. Sampling sites

The study took place in three pairs of apple orchards established in 2023 in the experimental farm of the University of Bologna, with the coordinates of the pairs being respectively 44°32′41.6"N 11°22′53.3"E, 44°32′39.8"N 11°22′58.7"E and 44°32′36.8"N 11°23′09.8"E (Fig. S1a). Each pair included an agroecological multi-variety orchard and a conventional mono-variety control orchard at 10 m from each other. Conventional control orchards included only trees of the ‘Rosy Glow’ cultivar, commercially known as ‘Pink Lady®’ (henceforth simply ‘Pink Lady®’), which is one of the most widespread and commercially important apple varieties in the world (López et al., 2007). Agroecological orchards were cropped with 9 different apple cultivars, including the ‘Pink Lady®’, ancient varieties and varieties developed at the University of Bologna (Table S1). The rootstock for all trees was M9 T337. The size of the orchards was 50 × 21 m, each including 7 tree rows (with 3.5 m interrows) and 50 trees per row (350 trees per orchard in total, with a distance of 1 m between trees of the same row). In each agroecological orchard, each cultivar was present with at least 25 trees planted consecutively in a row, with spatial arrangement of cultivars changing randomly in each of the three agroecological orchards (Fig. S1b). In both conventional and agroecological orchards, the two most external rows were considered buffers and not included in the samplings described in the main text. Due to the young age of the trees, until 2024 fruits were removed before ripening to encourage tree growth; 2025 was the first year in which fruits were left on trees until harvest. No managed honeybee (*Apis mellifera* L.) colonies were installed within or nearby the orchards.

In conventional orchards, interrows only included wild vegetation such as grasses and entomophilous flowering weeds. In agroecological orchards, interrows were sown with a mix of 14 flowering cover crop species chosen for their ability to support pollinators (“Mix apistico Eco 5” - bee mix in compliance with Eco-scheme 5 - by Mas Seeds). The mix included *Achillea millefolium* L., *Anethum graveolens* L., *Fagopyrum esculentum* Moench, *Lotus corniculatus* L., *Medicago lupulina* L., *Medicago sativa* L., *Melilotus albus* Medik., *Melilotus officinalis* (L.) Lam., *Onobrychis viciifolia* Scop., *Sinapis alba* L., *Sulla coronaria* (L.) B. H. Choi & H. Ohashi, *Trifolium incarnatum* L., *Trifolium pratense* L. and *Trifolium resupinatum* L. Cover crops in agroecological orchards were mown only in July, while interrows in conventional orchards were mown monthly. The cover crops were sown in March each year except for 2025, in which a prolonged period of intense rains led to a late sowing in May, and to a stunted growth of most cover crop species that year.

Pest control treatments were performed starting in 2025, the first year during which apples were harvested. Treatments against the codling moth *Cydia pomonella* (L.) included the use of pheromone traps in all orchards (Checkmate® CM-XL, activated on April 23rd 2025), while

control orchards also received insecticide treatments, specifically one chlorantraniliprole treatment (Coragen®) on July 10th 2025 and one Spinosad treatment (Laser® 120 SC) on July 14th 2025; the second treatment just a few after the first was made necessary by a rain event. Control orchards also received one insecticidal treatment against the brown marmorated stink bug *Halyomorpha halys* Stål (henceforth BMSB), specifically an acetamiprid treatment (Kestrel®) on May 14th 2025 – a relatively early treatment targeting adults exiting the overwintering phase, as it is commonplace in Italy. All insecticides were applied long after the end of apple blooming, which happened roughly during the third week of April. It should be noted that agroecological orchards were not completely agrochemical-free: treatments such as fungicides were applied both to agroecological and conventional orchards (Table S2), as field technicians deemed them necessary also due to the frequent rains of spring 2025. To follow this directive and yet adhere as strictly as possible to the IPPM framework, we nonetheless opted to avoid completely the use of insecticides in agroecological orchards, as insecticides are the most dangerous agrochemicals for pollinators (Iwasaki and Hogendoorn, 2021; Nkontcheu Kenko and Ngameni, 2022), while most other products applied in our orchards have a low toxicity towards this insect guild (Osservatorio Nazionale Miele, 2026).

2.2. Pollinator sampling

Pollinator surveys on apple flowers were performed by visual transects in the flowering period (April) of 2024 and 2025, roughly once per week, for a total of 4 sampling rounds in 2024 and 3 in 2025, during sunny, windless days, and always between 10:00 a.m. and 15:00 p.m. We counted the number of insects visiting tree flowers during a 15-min period, walking with a constant speed along rows. In this observation, only the insects directly interacting with the target flower were considered. The total number of flowering trees and the number of flowers of 3 random trees were counted in each orchard, to give an estimate of the number of available flowers per orchard (i.e. average number of flowers on the 3 random trees multiplied by the number of flowering trees), so that we could calculate the average number of visitors per flower in each orchard and sampling period.

Pollinators visiting interrow vegetation were surveyed in 2024 using a 1×1 m quadrat positioned 3 times (at a distance of 10 m between each position) in 3 different interrows of the orchard. Quadrats were observed for 5 min each (for a total of 15 min per orchard), counting the individual insects interacting with flowers, with observations being repeated monthly from April to July, and always taking place between 10:00 a.m. and 15:00 a.m. during sunny, windless days. We also recorded which plant species were in bloom in the observed quadrats in each orchard type and date, considering both cover crops and flowering weeds (Table S3). This sampling was not repeated in 2025 due to the near-absence of cover crops that year. Observed pollinators were categorized into their main morphogroups/macrotaxa (see Results).

We only considered pollinators interacting with flowers due to the short distance between agroecological and conventional orchards in each pair. The latter had the advantage of ensuring that environmental conditions among orchards of the same pair where homogeneous; however, even the least mobile pollinator species could easily and frequently spillover to nearby plots (Greenleaf et al., 2007). Rather than focusing on abundance or diversity in general, we therefore considered the functional aspect – i.e., the number of pollinators that actually fed on and pollinated flowers in each orchard.

2.3. Predatory arthropod sampling

Ground-dwelling arthropods were sampled using pitfall traps (3 traps per plot, at a distance of 10 m from each other in 3 different interrows) activated once per month from April to June 2024, remaining active for 1 week per round. Pitfall traps consisted of 500 ml soft plastic cups, with a plastic cover protecting the trap from rain and large animals. Traps were activated with roughly 300 ml of 40% propylene glycol. At the conclusion of each sampling round, specimens collected with pitfall traps were stored in 70% ethanol, and later sorted for predatory arthropods.

Arthropods dwelling on interrow vegetation were sampled using a sweep net. Three 25-m transects were established in each plot in adjacent interrows, and sampled monthly from April to June 2024. Within each transect, 20 sweep net strokes per round were performed, with one stroke consisting of the left and right movements of the net over roughly the same area.

Insects dwelling on fruit tree canopies were sampled by mechanical knock-down: 30 random trees per plot were selected, 1 branch per tree was beaten with a stick, and the falling arthropods were collected in a plastic bag using a large funnel. We also performed a visual inspection of 30 other random trees per orchard, one branch per tree, recording all predatory arthropods. The sampling was performed monthly from April to July of 2024.

Samples from field were frozen in the lab and then sorted for predatory arthropods. We pooled the data from mechanical knock-down and visual sampling to obtain the total abundance of tree-dwelling predators. None of these predator samplings were repeated in 2025 due to the absence of cover crops that year, and also due to the fact that the field operator was unavailable for a part of the season because of an injury. In 2024, the sampling of interrow vegetation and ground-dwelling arthropods was not performed in July due to the mowing of the cover crops, and tree-dwelling predators were sampled immediately after the mowing. After that, due to the lack of differential interrow vegetation or insecticide treatment between orchards that year, we interrupted the sampling.

2.4. Pollinator contribution to yield and fruit quality

In 2025 (the first year in which fruits were left on trees until harvest) we performed a manipulative experiment to assess pollinator attractiveness and pollinator contribution to fruit production and quality in all apple cultivars, with 'Pink Lady®' in agroecological and conventional orchards being considered separately. We selected 3 random trees per cultivar in each orchard, for a total of 90 trees; during flowering, we performed an additional pollinator survey focused on these experimental trees, with the aim of assessing whether pollinators had a preference for specific apple cultivars. Each tree was observed for 5 min during the peak flowering period of its cultivar; all pollinator interactions with flowers were recorded, and we counted the total number of available flowers to calculate the average number of visits per flower of each tree.

On each of the 90 trees, we selected one branch for the control (open pollination), and one branch for pollinator exclusion by applying a tulle bag before flowering, with only self-pollination or wind-mediated pollination being possible (Bordoni et al., 2024; Garratt et al., 2014). The number of flowers on each experimental branch was counted. When plants produced fruitlets, we quantified the percentage fruitlet set (i. e. the percentage of flowers that reached the fruitlet stage) on each experimental branch. After that, manual fruit thinning (leaving roughly 20-25 fruits per tree due to their young age) was performed normally on all trees, including experimental trees, but not on the experimental branches.

Final fruit set (the percentage of flowers that reached the fruit stage) was recorded at harvest (Table S1). Data about fruit quality was collected on 2 random fruits per branch/treatment where available – otherwise, one or zero fruits were collected. Fruit quality measures included weight, seed set (number of seeds per fruit), average diameter, height and sugar content (measured in juice with a refractometer).

2.5. Pest susceptibility measures

We decided to focus on the codling moth and BMSB, as they are two

of the most damaging and widespread pests of apple worldwide (Leskey and Nielsen, 2018; Witzgall et al., 2008). As in many studies involving these species, we decided to consider pest-related damage rather than abundance (Ioriatti et al., 2025; Joseph et al., 2014; Sauphanor et al., 2012), as it is more directly relevant to fruit production. In 2025, we performed surveys of damage caused by both species on apple fruits of each studied cultivar, with 'Pink Lady®' in agroecological and conventional orchards being considered separately. Surveys were performed roughly one week before the harvesting of each cultivar (Table S1); in each orchard, 10 random trees were selected, and 10 random fruits per tree were observed, with all BMSB- or codling moth-related damages being recorded, both in terms of number of damaged fruits and in terms of number of individual damages per fruit. In 7 out of the total 300 surveyed trees, we observed a lower number of fruits because the trees produced fewer than 10 apples.

2.6. Statistical analysis: arthropod abundance and arthropod-cultivar interactions

We used Generalized Linear Mixed Effect Models (GLMMs) to test the effect of orchard management (agroecological vs. conventional), sampling date and their interaction on the abundance of the pollinators and predators surveyed in all the considered microhabitats – i.e. cover crops, apple trees and ground (Models 1-6 in Table 1). As it was count data, we used either Poisson or negative binomial GLMMs, depending on which better fitted model assumptions in each case. For pollinators visiting apple flowers, aside from total abundance, we also ran a gaussian GLMM testing the effects of management and sampling date on the average number of pollinator visitors per flower, square-root transformed to meet model assumptions (Model 2 in Table 1). In these models, orchard pair ID and orchard ID were used as nested random factors; for pollinators visiting apple flowers, we also included year as an additional random factor.

Regarding pollinator interactions with apple cultivars, a gaussian GLMM was used to test the effect of cultivar on the average number of pollinator visits per flower, with orchard pair ID as random effect (Model 7 in Table 2). GLMMs were also used to test the effect of cultivar, pollination treatment, and their interaction on fruit production and quality indicators (Models 8-14 in Table 2). Binomial GLMMs were used for production models (percentage of flowers that developed into fruitlets and fruits, respectively), a Poisson GLMM was used for seed production, and gaussian GLMMs were used for fruit diameter, height, weight and sugar content. Weight was log-transformed to meet model assumptions. In these models, orchard pair ID and tree ID were used as nested random effects, with experimental branch ID also included for quality measures taken at the individual fruit level (seed set, diameter, height, weight, sugar content). Conventional 'Pink Lady®', agroecological 'Pink Lady®' and 'Polpa Rossa' were not included as cultivars in the fruit quality models, as they only produced respectively 0, 1 and 2 fruits in total in the pollinator exclusion treatment, and thus we could not carry out a meaningful fruit quality comparison between pollinator exclusion and open pollination.

For both codling moth and BMSB, binomial and Poisson GLMMs were used to test the effect of cultivar on the percentage of damaged fruits per tree and the number of damages per fruit, respectively (Models 15-18 in Table 2). Orchard pair ID was included as a random factor, with tree ID also being added nested within it for the models on the number of damages per fruit.

In all cases, non-significant interactions ($P > 0.05$) were removed from the models to avoid overfitting and correctly interpret the main effects (Engqvist, 2005; Lami et al., 2021). In the case of significant effects, we carried out a post-hoc test by calculating pairwise comparisons with a Tukey adjustment.

2.7. Statistical analysis: trade-offs and synergies

To test for possible trade-offs and synergies between pollination indicators and pest incidence, we first calculated the contribution of pollinators to production and fruit quality parameters. The contribution was calculated for each experimental tree according to formula $C = (O - E)/O$, where O represents the values observed in the control shoots (open pollination) and E represents the values observed in the shoots excluding pollinators (Garratt et al., 2023). In cases where the value of E was greater than that of O, E was used as the denominator. For fruit-level quality parameters, we calculated an average value for O and E fruits, respectively, before calculating the contribution.

In order to calculate true synergies and trade-offs, all considered indicators should be positively related to a desirable function (Tamburini et al., 2016). We therefore transformed pest susceptibility indicators (i. e. the incidence of codling moth and BMSB damage) into pest resistance indicators, for which higher values corresponded to lower damage incidence. Specifically, we considered the percentage of

Table 1
Results of the generalized linear mixed-effects models testing the effects of orchard management and sampling date on the abundance of pollinator flower visitors and arthropod predators in the studied microhabitats. The number of pollinator visitors per apple flower was square-root transformed to meet model assumptions.

Model type	Dependent variable	Fixed effects	Df	Chi-square	p
Model 1					
Poisson GLMM	Abundance of apple flower visitors	Management	1	3.24	0.07
		Date	6	129.87	<0.001
		Management × Date	6	41.00	<0.001
Model 2					
Gaussian GLMM	Number of visitors per apple flower[a]	Management	1	0.01	0.92
		Date	6	18.26	<0.01
Model 3					
Negative binomial GLMM	Abundance of interrow flower visitors	Management	1	13.16	<0.001
		Date	3	16.42	<0.001
Model 4					
Poisson GLMM	Ground-dwelling predators abundance	Management	1	1.47	0.23
		Date	2	17.57	<0.001
		Management × Date	2	12.41	<0.01
Model 5					
Poisson GLMM	Interrow vegetation predators abundance	Management	1	4.81	0.03
		Date	2	21.19	<0.001
Model 6					
Negative binomial GLMM	Tree-dwelling predators abundance	Management	1	0.01	0.91
		Date	3	7.55	0.06
		Management × Date	3	9.39	0.02

[a] Square-root transformed.

Table 2
Results of the generalized linear mixed-effects models testing the effects of pollination treatment and apple cultivar on pollinator contribution indicators (Models 7-14), and of apple cultivar on pest incidence indicators (Models 15-18). Fruit weight was log-transformed to meet model assumptions.

	Model type	Dependent variable	Fixed effects	Df	Chi-square	p
Pollination	*Model 7*					
	Gaussian GLMM	Pollinator visits per flower	Cultivar	9	8.55	0.48
	Model 8					
	Binomial GLMM	Fruitlet set (Fruitlets/Flowers)	Pollination treatment	1	336.45	<0.001
			Cultivar	9	66.82	<0.001
			Pollination × Cultivar	9	47.82	<0.001
	Model 9					
	Binomial GLMM	Fruit set (Fruits/Flowers)	Pollination treatment	1	22.89	<0.001
			Cultivar	9	33.58	<0.001
	Model 10					
	Poisson GLMM	Seed set	Pollination treatment	1	75.87	<0.001
			Cultivar	6	4.08	0.67
			Pollination × Cultivar	6	24.37	<0.001
	Model 11					
	Gaussian GLMM	Average fruit diameter (mm)	Pollination treatment	1	6.15	0.01
			Cultivar	6	44.36	<0.001
	Model 12					
	Gaussian GLMM	Fruit height (mm)	Pollination treatment	1	0.01	0.91
			Cultivar	6	111.37	<0.001
	Model 13					
	Gaussian GLMM	Fruit weight (g)[a]	Pollination treatment	1	3.69	0.06
			Cultivar	6	255.92	<0.001
	Model 14					
	Gaussian GLMM	Fruit sugar content (Brix)	Pollination treatment	1	0.16	0.69
			Cultivar	6	93.70	<0.001
Pest incidence	*Model 15*					
	Binomial GLMM	Codling moth - Damaged fruits per tree (%)	Cultivar	9	416.07	<0.001
	Model 16					
	Poisson GLMM	Codling moth - Damages per fruit	Cultivar	9	345.26	<0.001
	Model 17					
	Binomial GLMM	BMSB - Damaged fruits per tree (%)	Cultivar	9	458.89	<0.001
	Model 18					
	Poisson GLMM	BMSB - Damages per fruit	Cultivar	9	231.45	<0.001

[a] Log-transformed.

undamaged fruits rather than damaged fruits; as for the number of damages per fruit, we transformed it in a resistance indicator with formula $R = (Xmax - X)/Xmax$, where X is the value of each measure of damage incidence per fruit, and $Xmax$ is the highest value of X in the dataset (Lami et al., 2025). This resulted in an index ranging from 0 (minimum damage resistance per fruit) to 1 (maximum damage resistance in the studied context).

Pairwise correlation coefficients are a simple, effective and widespread method for the study of trade-offs and synergies between ecosystem functions (Lami et al., 2025; Mouchet et al., 2014; Tamburini et al., 2016). For each orchard/cultivar combination, we therefore calculated the average values of each indicator of pollinator contribution and pest resistance, and we then performed Pearson correlations between all possible pairs of indicators.

Additionally, to paint a general picture of the pollination and pest resistance functions of each apple cultivar, we used radar charts. In this case, all indicators were represented using a 0-100% scale. For conventionally grown 'Pink Lady®', we had no values pertaining to pollinator contribution to fruit quality indicators, as no fruits were produced under pollinator exclusion; for agroecological 'Pink Lady®' and 'Polpa Rossa', we represented fruit quality parameters based on the very limited number of pollinator exclusion fruits (1 and 2, respectively).

All the previously described statistical analyses were performed with packages *lme4* v1.1-35.5 (Bates et al., 2015), *visreg* v2.7.0 (Breheny and Burchett, 2017), *DHARMa* v0.4.7 (Hartig, 2020), *corrplot* v0.95 (Wei and Simko, 2017) and *fmsb* v0.7.6 (Nakazawa, 2025) in R v4.4.1 (R Core Team, 2019).

3. Results

3.1. Effects of agroecological management on pollinator abundance

The average number of available flowers in each orchard across the whole season (mean ± standard deviation) was 3667 ± 2691 and 3473 ± 1603 in agroecological and conventional orchards respectively in 2024, and 14714 ± 11947 and 13517 ± 8793 respectively in 2025. We observed a total of 1320 apple flower visitors during the flowering periods of 2024 and 2025, and a total of 198 pollinators visiting interrow vegetation flowers across the growing season of 2024 (Table S4). The most abundant pollinator categories on apple flowers were the honeybee (59%) and beetles (26%), while the most abundant categories on interrow flowers were wild bees (54%) and honeybees (26%).

The interaction between orchard management and sampling date affected the total abundance of pollinators visiting apple flowers (Table 1, Fig. 1a). In 2024, there was no significant difference between conventional and agroecological orchards for the first part of April. In the middle of the month, however, conventional orchards attracted significantly more apple flower visitors compared to agroecological orchards, while in the second half of the month (nearing the end of flowering period) the number of apple flower visitors decreased, but it was significantly higher in agroecological than in conventional orchards. A different pattern was observed in 2025, with agroecological orchards hosting significantly more apple flower visitors than conventional orchards at the beginning of April, and no significant differences between management types later in the month. On the other hand, orchard management had no significant effect on the average number of pollinators per apple flower (Table 1), irrespective of the weekly

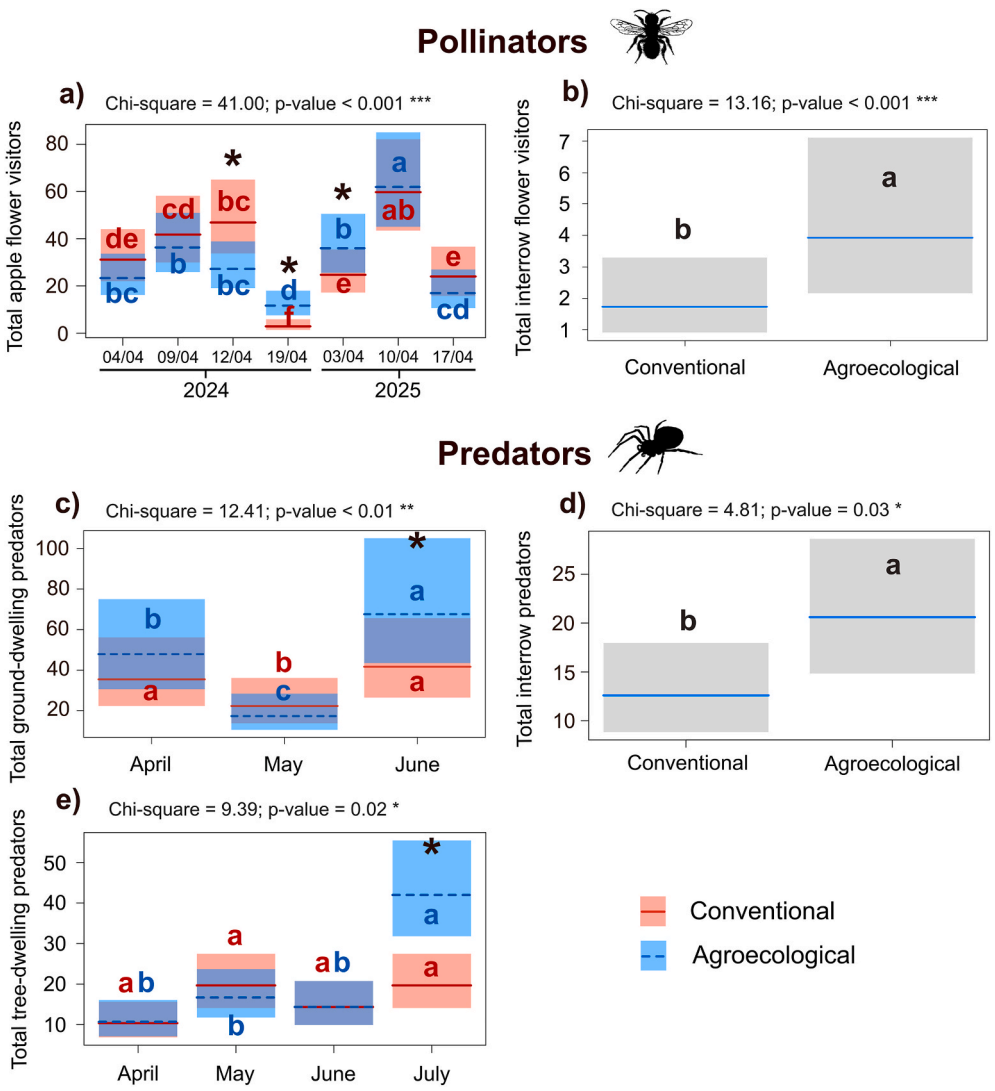

Fig. 1. Effect of orchard management on apple flower visitors (a), interrow flower visitors (b), soil-dwelling predators (c), interrow vegetation predators (d) and tree-dwelling predators (e). All plots except (a) are based on data from 2024 only. Where the interaction between orchard management and sampling date was significant, it was left in the model and thus shown in the plots (a, c, e). The fitted lines indicate model predictions, while the shaded areas are 95% confidence intervals. Different letters indicate statistically significant differences between dates for conventional (in red) and agroecological (in blue) orchards, and for the entire dataset (in black), while asterisks indicate statistically significant differences between orchard management regimes within the same date, all according to post-hoc pairwise comparisons with Tukey adjustment. Models are based on total abundances per orchard and per sampling round. See Table 1 for model results. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

fluctuations observed during 2025 (Fig. S2a). Finally, agroecological orchards attracted a significantly higher number of pollinators visiting interrow vegetation flowers compared to conventional orchards (Table 1, Fig. 1b) irrespective of monthly fluctuations (Fig. S2b).

3.2. *Effects of agroecological management on predatory arthropod abundance*

We collected a total of 755 ground-dwelling predators, 220 interrow-vegetation-dwelling predators and 443 tree-dwelling predators across the growing season of 2024 (Table S5). Spiders were the most abundant predator category in all 3 microhabitats (63%, 71% and 60% in ground, interrow vegetation and trees respectively); other abundant groups included the beetle families Carabidae as ground-dwelling predators (28%) and Coccinellidae as interrow- and tree-dwelling predators (16% and 19%, respectively).

In the case of ground-dwelling predators, there was a significant interaction between orchard management and sampling date (Table 1). Predator abundance had monthly fluctuation in both orchard types, but in June we recorded significantly higher numbers of ground-dwelling predators in agroecological orchards than in conventional orchards (Fig. 1c). The abundance of predators found on interrow vegetation was also significantly higher in agroecological orchards (Table 1, Fig. 1d) irrespective of monthly fluctuations (Fig. S2c). Finally, for most of the season there were no differences between orchard types in terms of tree-dwelling predator abundance, but in July we found significantly higher numbers of these predators in agroecological orchards (Table 1, Fig. 1e).

3.3. *Pollinator contribution to yield and fruit quality*

Around 90% of pollinator visits recorded during the tree-level monitoring (905 out of 1009) were performed by honeybees. There were no significant differences between cultivars in terms of average number of pollinator visits per flower (Table 2). Cultivar and pollination treatment, however, affected several yield and fruit quality parameters. There was a significant interaction between these two explanatory

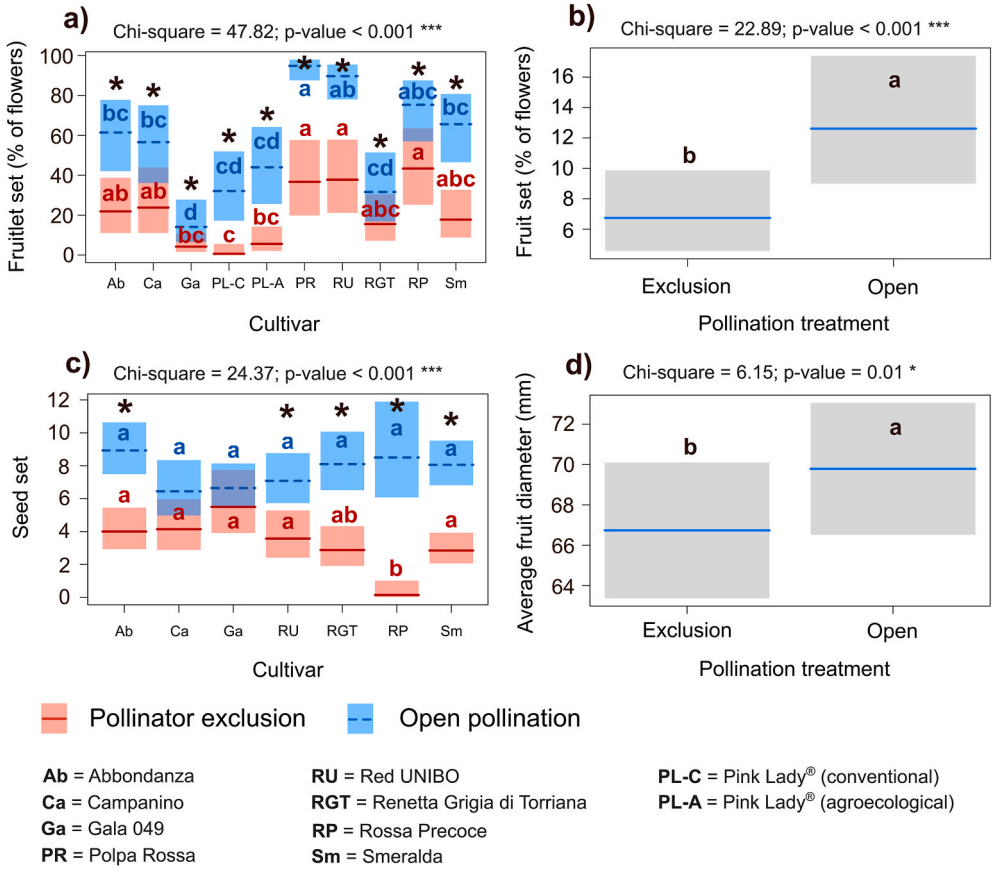

Fig. 2. Effect of pollination treatment on fruitlet set (a), fruit set (b), seed set (c) and average fruit diameter (d). Where the interaction between pollination treatment and apple cultivar was significant, it was left in the model and thus shown in the plots (a, c). The fitted lines indicate model predictions, while the shaded areas are 95% confidence intervals. Different letters indicate statistically significant differences between pollination treatments for the entire dataset (in black), and between apple cultivars for pollinator exclusion (in red) and open pollination (in blue) treatments, while asterisks indicate statistically significant differences between pollination treatments within the same cultivar, all according to post-hoc pairwise comparisons with Tukey adjustment. See Table 2 for model results. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

variables influencing fruitlet set (Table 2). In all considered cultivars, pollinator exclusion led to a significantly lower fruitlet set, but this effect was more marked in certain cultivars such as 'Pink Lady®', 'Polpa Rossa' and 'Red UNIBO'; 'Pink Lady®' fruitlet set, in particular, dropped near to zero with pollinator exclusion under both orchard management regimes (Fig. 2a). Fruit set, on the other hand, significantly decreased under pollinator exclusion (Table 2, Fig. 2b) irrespective of fruit production variability between cultivars (Fig. S3a).

As for fruit quality, pollinator exclusion affected seed set and average fruit diameter. Regarding seed set, there was a significant interaction with apple cultivar (Table 2): most tested cultivars had a significantly lower seed set under pollinator exclusion, with the effect being particularly strong in 'Rossa Precoce', while for two of the cultivars ('Campanino', 'Gala 049') there were no significant differences between pollinator exclusion and open pollination (Fig. 2c). Finally, average fruit diameter significantly decreased with pollinator exclusion (Table 2, Fig. 2d) regardless of variability within cultivars (Fig. S3b). Fruit height, weight and sugar content varied significantly between cultivars, but they were not affected by pollination treatment (Table 2, Fig. S3c–e).

3.4. Pest damage incidence

There were significant differences between cultivars in terms of fruit damage related to codling moth and BMSB. 'Red UNIBO' and agroecologically managed 'Pink Lady®' were especially susceptible to codling moth, considering both the percentage of damaged fruits and the number of damages per fruit (Table 2, Fig. 3a–b). Conventionally managed 'Pink Lady®' was significantly less damaged, but it was still shown to be more susceptible than other cultivars grown in the agroecological orchards, such as 'Campanino', 'Rossa Precoce' and (considering only the percentage of damaged fruits) 'Gala 049'.

BMSB damage was especially prevalent in 'Pink Lady®' (both conventional and agroecological), with the similar patterns observed for tree-level damage and fruit-level damage (Table 2, Fig. 3c–d). All other cultivars had a significantly lower BMSB damage incidence, with an especially low susceptibility for 'Gala 049', 'Polpa Rossa', 'Renetta Grigia di Torriana' and 'Rossa Precoce'.

3.5. Trade-offs and synergies

The results of the pairwise Pearson correlations between pollination and pest resistance indicators were reported in a correlogram (Fig. 4). We found many synergies (positive correlations) between different pollination indicators, such as pollinator contribution to fruitlet and fruit set (when considering yield), and to fruit weight, height, average diameter and seed set (when considering fruit quality). We found a lower number of trade-offs (negative correlations), such as between pollinator contribution to fruitlet set and to fruit weight/diameter, or between contribution to diameter and sugar content. We also found many synergies between indicators of resistance to codling moth and BMSB. However, there were also numerous trade-offs between pollination functions and pest resistance indicators: specifically, the average number of pollinator visits per flower and pollinator contribution to fruitlet/fruit set were negatively related to multiple indicators of

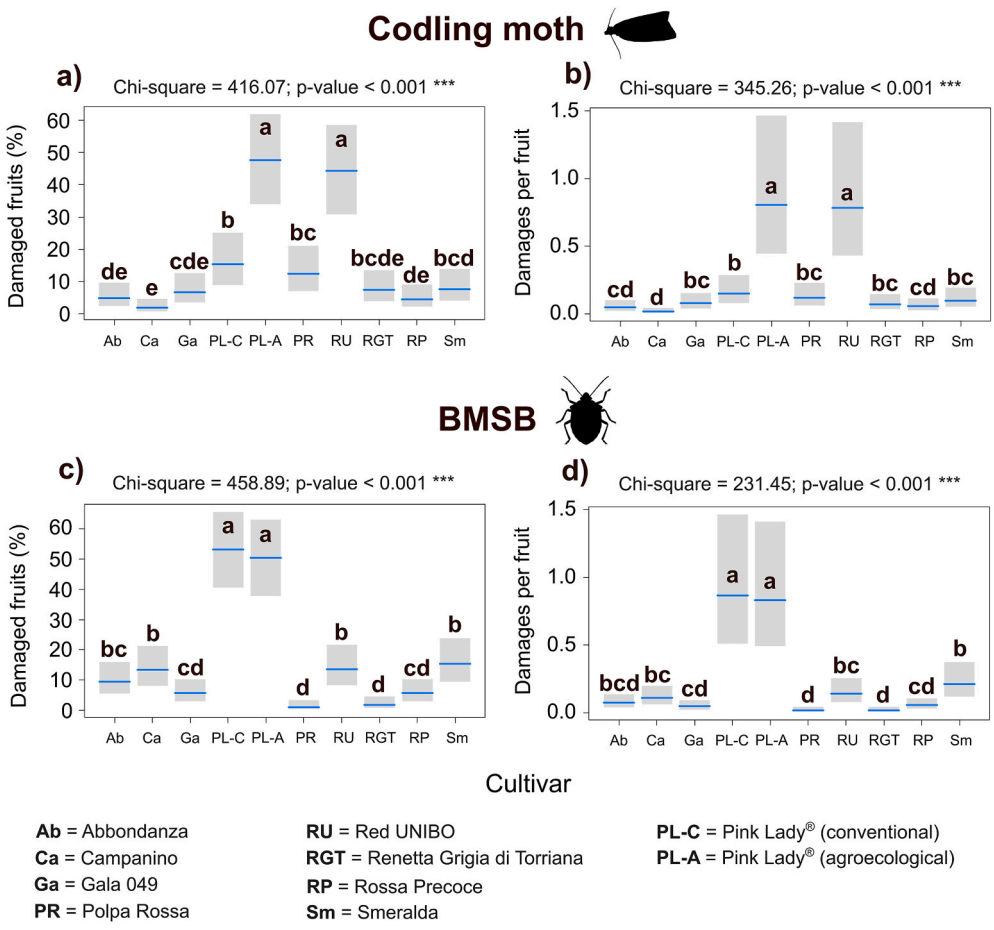

Fig. 3. Effect of apple cultivar on the percentage of damaged fruits per tree and on the number of damages per fruit related to codling moth (a-b) and BMSB (c-d). The fitted lines indicate model predictions, while the shaded areas are 95% confidence intervals. Different letters indicate statistically significant differences between apple cultivars according to post-hoc pairwise comparisons with Tukey adjustment. See Table 2 for model results.

resistance to codling moth, BMSB or both. Pollinator contribution to fruit height was also negatively related to tree-level BMSB resistance.

Recapitulatory pollination/pest radar charts for each cultivar are presented in Fig. S4, furtherly highlighting 'Pink Lady®' (both conventional and agroecological) as especially dependent on pollinators, but also especially susceptible to pests.

4. Discussion

4.1. Effects of pollinator-friendly measures on pollinator abundance

While it is known that specific varieties of apple (and other crops) can differ in terms of support to pollinators (Burns and Stanley, 2022; Chacoff et al., 2024; Garratt et al., 2016), this was not the case of the cultivars tested in this study, at least considering pollinator abundance. The average number of pollinators per flower was comparable among agroecological and conventional orchards, and the average number of visits was also comparable among different cultivars when measured at the level of individual trees in 2025. This suggests that the observed patterns may have been linked with the number of flowers available in each agroecological/conventional orchard in any given moment, rather than with the differential attractiveness of the flowers; indeed, the flowering period and the average number of flowers per tree vary across apple cultivars (Table S1) (Delgado et al., 2021). The changing pattern between 2024 and 2025, on the other hand, may be explained by the growth of the trees and the consequent differential change in the number of available flowers per cultivar, as highlighted by the increase in the estimated number of available flowers per orchard in the second year. In 2025, with more mature trees, data suggested an advantage of the multi-variety agroecological orchards over the control, at least in terms of number of apple flower visitors at the beginning of the flowering period; however, as this is an evolving scenario with trees that are still growing, continued annual monitoring will be necessary to draw robust conclusions. The majority of visits observed during tree-level monitoring were performed by honeybees, which are usually prevalent in intensified agricultural landscapes and may outcompete wild pollinators for access to abundant flower resources, such as mass flowering crops (Bernhardsson et al., 2024; Jeavons et al., 2020; Li et al., 2025); nonetheless, further research involving species-level identification of pollinators would be useful to highlight differences in terms of identity of pollinator visitors, as the use of cultivars attracting different pollinator guilds may reduce competition between insects and between plants (Burns and Stanley, 2022; Garratt et al., 2016; Grab et al., 2017).

On the other hand, flowering cover crops in agroecological orchards appeared successful in supporting a higher number of pollinators across the season than wild flowering vegetation in conventional orchards. This is consistent with available literature, often reporting the usefulness of sown flowering species for pollinators in perennial crops and agroecosystems in general (von Königslöw et al., 2022; Wilson et al., 2018). Additionally, pollinators visiting cover crops in agroecological orchards included a much higher percentage of honeybees and, most importantly, wild bees, which are regarded as key pollinators of many crops (Eeraerts et al., 2025; Reilly et al., 2024).

Some cover crop species, namely *S. alba* and *S. coronaria*, started blooming in April and thus had a partial temporal overlap with apple blooming (Table S3); this may raise concerns of competition for

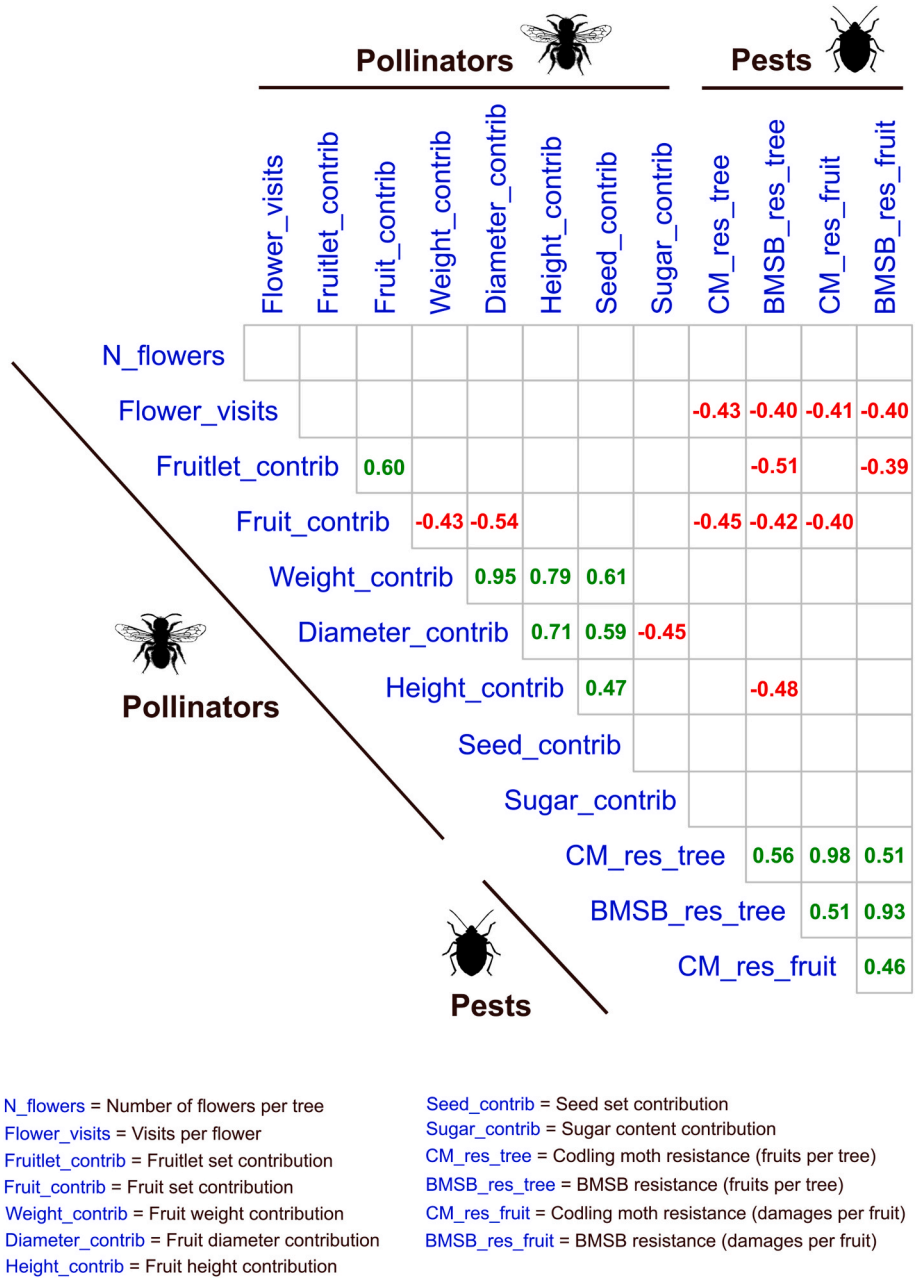

Fig. 4. Significant ($P < 0.05$) trade-offs (in red) and synergies (in green) between pollination dependence and pest resistance indicators across the studied apple cultivars. We report the values of the Pearson correlation coefficients between indicators. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

pollinators between the cash crop and the additional flowering species, as it sometimes happens (Bordoni et al., 2024; Nicholson et al., 2019); indeed, further investigations would be necessary to better confirm whether the altered patterns of apple flower visitations during the second year are partially attributable to the lack of cover crops, other than to the growth of the trees and the change in the number of available apple flowers. However, orchard management had no significant effect on the average number of visitors per apple flower in both years, and during the second year (with no cover crops) the average number of visitors per flower was lower; these facts seem to indicate that there was no significant competition for pollinators between apple trees and cover crops.

4.2. *Effects of pollinator-friendly measures on predatory arthropod abundance*

The tested agroecological measures also showed positive effects on the studied guilds of predatory arthropods. It is indeed reported that cover crops can increase the populations of both vegetation-dwelling and ground-dwelling predators, with the reasons including higher habitat complexity, additional food resources and more favourable microclimate (Beaumelle et al., 2021; Garcia et al., 2018). In our case, microclimate may have played an especially important role for ground-dwelling predators, which in arid climates usually prefer dark, moist and cool environments (Fischer et al., 2022; Gallé et al., 2024). These conditions can often be found under abundant vegetation cover (Stickley and Fraterrigo, 2021), such as the one provided by cover crops

(Kaye and Quemada, 2017); coherently with that, we recorded a significantly higher amount of these predators in agroecological orchards only during the warmest and driest sampling month (June), while interrow-dwelling predators were more abundant under agroecological management irrespective of sampling date.

Differences observed for ground-dwelling and interrow vegetation predators are in line with available literature, reporting that even microhabitats very close to each other can harbour significantly different predatory arthropod assemblages – especially if the vegetation is structurally different enough to provide unique food resources, refuges and microclimates (Masetti et al., 2018; Pérez Roig et al., 2023; Richard et al., 2020). The case of tree-dwelling predators is different, as the structural differences between apple cultivars are not nearly as strong as the structural differences between cover crops and wild vegetation; in spite of this and of the close proximity of orchards in each pair, during July we recorded a significantly higher abundance of these predators in agroecological orchards. It is however possible that this might also be linked with cover crops, rather than with cultivar diversification. It is reported that sown ground cover only occasionally leads to higher natural enemy abundance on perennial crop plants, possibly due to the marked structural diversity of the two microhabitats (Sanchez et al., 2025). In our case, the July tree sampling took place after the mowing of interrow vegetation, which could prompt the partial migration of arthropod predators from the destroyed herbaceous habitat to the crop trees (Morente and Ruano, 2025). As interrow predators were more abundant in agroecological orchards, this would result in crop trees also harbouring a higher number of predators after the mowing, as it was observed.

Overall, our data support the multifunctional value of flowering cover crops for the studied environmental context, as they suggested this measure increased not only pollinators (the main goal of this strategy), but also natural enemies, which is considered one of the most important elements for successful IPPM implementation (Egan et al., 2020; Lundin et al., 2021). Future research may also consider the abundance of generalist pest species found in cover crops as a potential ecosystem disservice, albeit this is often not a significant problem in agroecologically managed perennial crops (Markó et al., 2012; Sáenz-Romo et al., 2019).

4.3. Cultivar interactions with pollinators and pests

Cultivars differed in terms of pollinator contribution to certain aspects of production and fruit quality. These differences were likely caused by intrinsic plant biology factors, such as percentage success at self- and wind-pollinating (Ramírez and Davenport, 2013), and not by differential attractivity to pollinators, as the average number of visits per flower did not vary significantly among cultivars. Regarding yield, pollinator contribution to fruitlet set differed among cultivars, but at the fruit stage this variation disappeared, with a generally important contribution of pollinators to fruit set irrespective of variety. A likely explanation is the self-thinning undergone by apple trees (Lordan et al., 2019). Even if manual thinning was not performed on the experimental branches, self-thinning would have greatly lowered the number of fruits produced by them (Jakopic et al., 2015), reducing differences between cultivars. However, some tested varieties had lower average fruit set and higher pollinator dependence at the fruitlet stage, which caused them to drop at a near-zero yield when deprived of pollinators. The commercially successful ‘Pink Lady®’, showing these features, is an example of apple cultivar potentially extremely susceptible to pollinator loss – a worrying consideration, in light of widespread pollinator declines and crop pollination deficits (Lenzi et al., 2026; Olhnuud et al., 2022; Potts et al., 2010). Pollinator loss may also affect fruit quality: even when partially able to produce fruits, most cultivars (except ‘Campanino’ and ‘Gala 049’) had a variably reduced seed set if pollinator-deprived. Seed set influences apple size and shape (Garratt et al., 2014; Olhnuud et al., 2022), which may be why we also observed a general reduction in fruit diameter with pollinator exclusion.

As it was not possible to properly sow and grow cover crops in 2025, we could not evaluate whether this measure, through the increase in the number of natural enemies or herbivores, would have influenced pest damage incidence in agroecologically-grown ‘Pink Lady®’ apples compared with the control (Bone et al., 2009; Sanchez et al., 2025). However, we highlighted differences between cultivars in terms of pest susceptibility. ‘Pink Lady®’ itself showed a very high damage incidence from both considered pests, with a significant reduction in codling moth damage under conventional management, most likely due to the specifically planned insecticide treatments. A treatment against BMSB had been applied too, but this pest is notoriously difficult to control even with insecticides (Masetti et al., 2023; Pajač Beus et al., 2024). Most other cultivars, however, showed variable but significantly lower damage incidence even compared with the insecticide-treated ‘Pink Lady®’; this natural resistance might be linked with a variety of plant traits, including fruit ripening time, volatile chemicals, firmness, pH and size (Akroute et al., 2023; Ioriatti et al., 2025; Joshi et al., 2015), albeit pinpointing the exact drivers would be extremely hard without the gathering of specific physiological and genetic data.

4.4. Trade-offs and synergies

The observed synergies between pollination contribution metrics involved expected correlations between indicators such as fruitlet/fruit set, or between seed set and the fruit size indicators it is known to influence (Garratt et al., 2014). Trade-offs between contributions to fruit production and size indicators, or between size and sugar content, could be explained by the well-studied compromises in plant resource allocations which, for instance, may lead trees to produce a larger number of smaller fruits or vice versa (De Salvador et al., 2006). Interestingly, the positive correlations between pest resistance indicators suggest that the same apple traits (or growing environment) might simultaneously lead to a reduction of codling moth and BMSB damage. While the employed methods do not allow us to determine the specific mechanistic drivers of this synergy (Duncan et al., 2015), it would merit further study as it could have important implications in improving multifunctional pest control (Otto et al., 2025).

The frequent trade-offs between pest resistance and pollination indicators (mostly number of flower visits and contribution to yield, rather than fruit quality) deserve particular attention. It is increasingly understood that natural plant defensive compounds may reduce attractivity to pollinators (Lucas-Barbosa, 2016) and, conversely, pollinator-attracting adaptations (such as abundant nectar production) may increase herbivory as a side effect (Adler and Bronstein, 2004). The practical implication here is that it might be very hard (at least in the case of apple) to find the “perfect cultivar” for IPPM and similar frameworks – i.e., a cultivar that is simultaneously very attractive to pollinators and highly advantaged by them (and which could thus gain maximum benefit from IPPM), but also very resistant to pests (Egan et al., 2020). It should be noted that all of our tested cultivars (and apple in general), in spite of variation, are highly pollinator-dependent (Olhnuud et al., 2022); for that reason, in case of noticeable trade-offs, pest resistance should be given precedence when selecting cultivars for a fully IPPM system, in order to avoid both excessive crop losses and excessive pesticide use (Smith, 2021). Commercially important, pest-susceptible but highly pollinator-dependent varieties, like ‘Pink Lady®’, may still benefit from pollinator-friendly habitat enhancements, such as cover crops, if they are implemented until apple flowering and then mowed before the necessary insecticide applications, to prevent them from becoming ecological traps for pollinators (Ganser et al., 2019; Tarano et al., 2025). On the other hand, cultivars such as ‘Abbondanza’, ‘Rossa Precoce’ or ‘Renetta Grigia di Torriana’, being very pest resistant but also highly dependent on pollinators for seed set, are among the most promising for true IPPM management.

It is important to note that trade-offs and synergies in ecological

traits vary not only across cultivars, but also across environmental conditions (Lami et al., 2025; Tamburini et al., 2016; Yang et al., 2023); long-term trials on a wider variety of cultivars, ecological contexts and management types will be pivotal for a more detailed mapping of these patterns. Additionally, while here we focused on resistance to insect pests, future research should also consider resistance to fungi and other biotic adversities: many fungicides are regarded as relatively harmless to pollinators on their own, but it is increasingly understood that they can act synergistically with insecticides, amplifying their negative effects (Iwasaki and Hogendoorn, 2021; Sgolastra et al., 2017, 2018). An orchard with limited or zero use of fungicides would further reduce the risk to pollinators in intensified countrysides, where it is increasingly easy for them to be exposed to multiple agrochemicals from the various habitat patches they visit (Cappellari et al., 2024; Main et al., 2020). Finally, in commercial apple production, where trees are subjected to fruit thinning, a lower pollination service usually impacts more fruit quality (such as shape and size alterations due to a lower number of seeds) than yield (Olhnuud et al., 2022). It would be interesting to perform similar research on crop species that, in commercial settings, are even more dependent than apple on pollinators for yield (Turo et al., 2024); detecting a trade-off involving pollinator attractiveness in similar cases may lead to drastically different conclusions in terms of management strategies.

4.5. Limitations

To put results in perspective and inform their interpretation, it is worth mentioning some limitations. This exploratory study was designed and budgeted mainly to allow an overall comparison between the agroecological systems and the conventional systems, a goal that was partially hindered by the inclement weather and consequent lack of fully grown cover crops during the first production season. Because of that, and because of the time frame of the project funding the study, most measures were taken during a single year (either 2024 or 2025), with the exception of pollinators visiting apple flowers (sampled both years). Studies aiming at fully capturing ecological and agronomical variability are usually repeated for 5 or more years (Aldercotte et al., 2022; Jungers et al., 2021; Paredes et al., 2022), a time frame which was outside the budget of our project. Related to this, our results should be considered representative of young trees at their first productive season; further generalizability (to other environmental conditions or to mature orchards) would require additional, longer-term experiments.

The simultaneous application of different agroecological measures is also a potential confounding factor when trying to understand which measure actually caused the observed effects on arthropod communities – a problem that we partially mitigated by sampling separately different microhabitats (ground, interrow vegetation, trees) and resources (interrow flowers, apple flowers); nonetheless, future larger scale studies applying the individual agroecological measures separately may be useful for further disentangling their effects – and potentially, also to investigate the differences between agroecological and conventional management on cultivars other than 'Pink Lady®'.

5. Conclusions

This exploratory study improves our understanding of the correct management of plant diversity (both crop and non-crop) for beneficial arthropod conservation in Mediterranean apple orchards. The tested pollinator-friendly strategies, and especially the use of flowering cover crops, were indicated as useful multifunctional tools capable of increasing not only the abundance of pollinators, but also of various guilds of predatory arthropods. Cultivar choice appeared as a critical element for the creation of a productive and successful agroecological orchard. Cultivars differed in terms of both pollinator dependence and pest resistance, with some important trade-offs between one and the other; this implies that some cultivars that would greatly benefit from pollinator conservation within agroecosystems (such as the commercially important 'Pink Lady®') may be unfit for true IPPM due to pest susceptibility, and that pest-resistant cultivars should be prioritized in the establishment of sustainable agricultural systems. Promising varieties include cultivars that present both pest-resistance and high pollinator dependence for seed set, such as 'Abbondanza', 'Rossa Precoce' and 'Renetta Grigia di Torriana'. While single-year measurements would benefit from further confirmation, our results may inform future larger scale research, and find application in better informing the planning of biodiversity-friendly IPPM orchards.

CRediT authorship contribution statement

Francesco Lami: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Melissa Venturi:** Investigation, Writing – review & editing. **Lisa Cabiddu:** Investigation, Writing – review & editing. **Lucia Lenzi:** Investigation, Writing – review & editing. **Mariana Paola Mazzei:** Investigation, Writing – review & editing. **Diletta Missere:** Investigation, Writing – review & editing. **Brunella Morandi:** Funding acquisition, Project administration, Resources, Writing – review & editing. **Fabio Sgolastra:** Conceptualization, Funding acquisition, Resources, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Brunella Morandi reports financial support was provided by Partnership for Research and Innovation in the Mediterranean Area. If there are other authors, they 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. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cropro.2026.107770.

Data availability

Data will be made available on request.

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