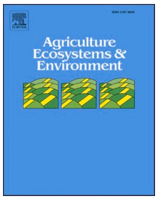
Agriculture, Ecosystems and Environment 397 (2026) 110065

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee



Taxon-specific responses to temperature, landscape, and local management challenge common strategies for pest control in vineyards

Costanza Geppert[a,*], Alberto Alma[b], Lucia Andretta[c], Gianfranco Anfora[d], Enrico Busato[b], Pierfilippo Cerretti[e], Serena Giorgia Chiesa[f], Arturo Cocco[g], Elena Costi[h], Mariana da Cruz Albertazzi[a], Carlo Duso[a], Pierluigi Forlano[i,j], Antonio Pietro Garonna[c], Nicola Grigolin[a], Francesco Lami[k], Paolo Lo Bue[l], Daniela Lupi[m], Serena Magagnoli[k], Lara Maistrello[h], Roberto Mannu[g], Gaetana Mazzeo[n], Luca Mazzon[a], Nicola Mori[o], Giacomo Ortis[o], Ezio Peri[l], Gianvito Ragone[p], Marzia Cristiana Rosi[q], Giuseppe Rotundo[r], Patrizia Sacchetti[q], Francesco Sanna[a], Sara Savoldelli[m], Pompeo Suma[n], Giovanni Tamburini[p], Vincenzo Trotta[j], Lorenzo Marini[a]

[a] *Department of Agronomy, Food, Natural Resources, Animals and Environment (DAFNAE), University of Padua, Viale dell'Università 16, Legnaro, PD 35020, Italy*
[b] *Department of Agricultural, Forest and Food Sciences (DISAFA), University of Turin, Via Verdi 8Turin, TO 10124, Italy*
[c] *Dipartment of Agriculture, University of Naples "Federico II", Piazza Carlo di Borbone, Portici, NA 80055, Italy*
[d] *C3A - Center Agriculture Food Environment, University of Trento, Via Edmund Mach 1, San Michele all'Adige, TN 38010, Italy*
[e] *Department of Biology and Biotecnologies "Charles Darwin", Sapienza Università di Roma, Piazzale Valerio Massimo 6, Rome, RO 00185, Italy*
[f] *Technological Transfer Center, Edmund Mach Foundation, Via Edmund Mach 1, San Michele all'Adige, TN 38010, Italy*
[g] *Department of Agricultural Sciences, University of Sassari, Viale Italia 39A, Sassari, SS 07100, Italy*
[h] *Department of Life Sciences, University of Modena and Reggio Emilia, Via G. Amendola 2, Pad. Besta, Reggio nell'Emilia, RE 42122, Italy*
[i] *Department of Pharmacy (DIFARMA), University of Salerno, Via Giovanni Paolo II 132, Fisciano, SA 84084, Italy*
[j] *Department of Agriculture, Environment and Food (DAFE), University of Basilicata, via dell'Ateneo Lucano 10, Potenza, PT 85100, Italy*
[k] *Department of Agricultural and Food Sciences (DISTAL), University of Bologna, Viale Giuseppe Fanin 42, Bologna, BO 40127, Italy*
[l] *Department of Agriculture, Food and Environment (SAAF), University of Palermo, Viale delle Scienze, Ed. 4, Palermo, PA 90128, Italy*
[m] *Department of Food, Environmental and Nutritional Sciences, University of Milan, Via Celoria 2, Milan, MI 20133, Italy*
[n] *Department of Agriculture, Food and Environment (Di3A), University of Catania, Via S. Sofia 100, Catania, CT 95123, Italy*
[o] *Department of Biotechnologies, University of Verona, Strada le Grazie, 15, Verona, VR 37134, Italy*
[p] *Department of Soil, Plant and Food Sciences (DiSSPA – Entomology and Zoology), University of Bari, Piazza Umberto I, Bari, BA 70121, Italy*
[q] *Department of Agriculture, Food, Environment and Forestry (DAGRI), University of Florence, Italy*
[r] *Department of Agricultural, Environmental and Food Sciences (DiAAA), University of Molise, via De Sanctis, Campobasso, CB 86100, Italy*

ARTICLE INFO

Keywords:
Ground beetles
Hoverflies
Leafhoppers
Natural enemies
Plants
Spiders
Ecosystem service
Organic

ABSTRACT

Grape is among the most pesticide treated crops in Europe. To reduce pesticide use, it is increasingly important to enhance pest control by natural enemies. However, the provision of biological control in vineyards is highly context- and taxa-dependent. Here, we selected 60 vineyards across Italy in order to explicitly explore the effect of vineyard management, temperature and landscape composition on arthropod predators, grapevine pests, dummy caterpillar predation, and seed predation. We found that plant cover in the inter-row was lower in dry-warm climates, and it positively affected only the abundance of hoverflies, while the abundance of carabids, ladybugs, harvest spiders and spiders was affected by temperature and the surrounding landscape. Organic management did not affect predators but supported more abundant populations of the pest *Erasmoneura vulnerata*. Overall, most leafhopper pests showed species specific responses to local management, temperature and the landscape. The abundance of two leafhopper species decreased with increasing semi-natural areas. By contrast, pest control rate and grape damage did not respond to any of the selected drivers. In conclusion, our findings suggest that local vineyard management significantly influences biocontrol and pests, but the effects are taxon specific and shaped by the surrounding landscape and by the temperature, challenging universal strategies.

---

* Corresponding author.
E-mail address: costanza.geppert@unipd.it (C. Geppert).

https://doi.org/10.1016/j.agee.2025.110065
Received 29 March 2025; Received in revised form 9 September 2025; Accepted 1 November 2025

Therefore, we advocate for developing regional strategies for grape protection accounting for local climate and multiple taxa responses.

1. Introduction

Vineyards are highly intensive agricultural systems, with grape being among the most pesticide treated crops in Europe (Rusch, 2024; Wolkovich et al., 2018). Because of frequent soil tillage and pesticide applications, intensively managed vineyards usually negatively impact biodiversity and related ecosystem services (Bruggisser et al., 2010; Paiola et al., 2020). However, given the temporal stability of these cropping systems, vineyards hold the potential to sustain high levels of biodiversity and ecosystem service provision. As there is large variability in vineyard management practices, it is often difficult to predict the response of different taxa and, consequently, the provision of associated ecosystem services (Beaumelle et al., 2023; Geppert et al., 2024). Therefore, identifying management strategies and environmental conditions to maximise vineyard sustainability has become an increasingly important priority (Rusch, 2024).

Besides fungal diseases, pest control of grapevine moths, leafhoppers, scales and mites is probably one of the major challenges in vineyard management. Several leafhopper species represent a concern for grape production, because they directly cause yield losses and reduction of sugar content of berries or because they are vectors of pathogens, such as of Flavescence dorée (FD) (Chuche and Thiéry, 2014; Pertot et al., 2017). Usually, pest control relies heavily on insecticides but a change from current practices is increasingly demanded, due to concern about their impact on human health and the environment (Pertot et al., 2017). This is reflected in the current EU strategies, such as the Farm to Fork Strategy, Biodiversity Strategy, and the Zero Pollution Action Plan, aiming to reduce pesticide use and associated risks by 50 % by 2030. In this framework, creating strategies to enhance biological pest control by natural enemies becomes increasingly important. Several nature-based solutions operating at different spatio-temporal scales can limit pest infestations by increasing predators and parasitoids (Rusch, 2024).

A key driver of vineyard natural enemies and biocontrol is the inter-row management (Winter et al., 2018). Inter-row management practices are used for weed control and water conservation, and can include herbicide applications, tillage, alternating tillage, or no tillage with a permanent vegetation cover. Inter-row management has been shown to affect the number, diversity and activity of arthropods, with cascading effects on ecosystem services (Beaumelle et al., 2021; Dainese et al., 2019; Zanettin et al., 2021). Overall, most studies highlight the benefits of vegetated inter-rows for pest control (Puig-Montserrat et al., 2017; Winter et al., 2018). For example, vegetated inter-rows supported higher abundance of hoverflies, spiders and ground beetles, and lower abundance of pests (Gaigher et al., 2024; Kratschmer et al., 2018; Ostandie et al., 2021; Rusch et al., 2017). In contrast, bare soil was found to harbour few arthropods, especially when maintained by herbicides (Masoni et al., 2017; Sanguankeo and León, 2011). Plant cover in the inter-row, however, can also produce disservices related to pests, by increasing their abundance (Danne et al., 2010).

In addition to the role of the inter-row management, the effect of organic farming on biocontrol in vineyards has been widely investigated (Beaumelle et al., 2023; Muneret et al., 2018). On average, organic vineyards host higher diversity and abundance of arthropods and provide higher ecosystem services than conventional ones (Beaumelle et al., 2023). For example, they can favour the diversity and abundance of plants, ants and spiders, and natural pest control, pollination, or carbon sequestration (Beaumelle et al., 2023; Gattinger et al., 2012; Masoni et al., 2017; Muneret et al., 2018; Nascimbene et al., 2012; Puig-Montserrat et al., 2017). However, results are often inconsistent (Beaumelle et al., 2023; Muneret et al., 2019; Paiola et al., 2020), with most studies finding large variation and taxon-specific responses. For example, it has been shown that beetles, earthworms and grasshoppers tend to be reduced by organic viticulture, while birds and moths are not affected (Beaumelle et al., 2023; Bruggisser et al., 2010; Caprio et al., 2015). Most studies investigating arthropods and pest control in vineyards focus on the effect of agricultural management, irrespective of underlying environmental gradients, such as climate and landscape structure.

Both landscape structure and climate are strong predictors of vineyard management, influencing, for example, the frequency of insecticide and fungicide treatments, and the amount of N-fertilization (Geppert et al., 2024). Besides the indirect effects through changes in agricultural practices, landscape and climate can have direct effects on predator taxa and pests (Paiola et al., 2020). For instance, increasing the amount of non-crop habitats around the vineyard, such as forests, grasslands or hedgerows, usually enhances the abundance and diversity of true bugs, birds and bats, as well as pest control services (Gaigher et al., 2024; Ostandie et al., 2021; Rusch et al., 2016b). Concerning climate, temperature is one of the main drivers of arthropod abundance and diversity, since it affects the physiology, performance, and fitness of ectotherms (Frazier et al., 2006). Also vegetation cover is affected by temperature and rainfall due to the direct effect of weather conditions on water availability and vegetation growth (Wilschut et al., 2022; Wittwer et al., 2023). Understanding how local management practices affect both pests and natural enemies depending on climate and landscape is needed.

Depending on agricultural management, landscape, and climate, both beneficial organisms and pests show very high variability in vineyards (Paiola et al., 2020). This variability hinders general recommendations and emphasizes the importance of focusing on multiple functional groups. Here, our experimental design enabled the comparison of conventional and organic vineyards along statistically independent gradients in landscape and climate. We selected 60 vineyards across Italy and tested the effect of vineyard management (organic vs. conventional), landscape composition and temperature on plant cover, arthropod predators, pest control, seed predation, leafhopper pests and grape damage. We hypothesized that: i) multiple arthropod taxa would co-vary along the landscape and temperature gradients; ii) plant cover would increase pest control; iii) organic management would increase plant cover, predators and pest control; iv) landscape composition would affect the abundance of most arthropods, with a positive effect of semi-natural areas on pest control and a negative effect on pests; and v) increasing temperatures would increase the abundance of most arthropods.

2. Methods

2.1. Study area

The study area covers multiple locations across Italy, where we selected 30 landscapes of 1 km radius (Fig. 1a). Landscapes were chosen along two statistically independent gradients: a climatic gradient related to latitude and a landscape composition gradient, ranging from areas dominated by viticulture to mostly natural areas. In each landscape, we selected a pair of vineyards, consisting of one organic and one conventional vineyard (for a total of N = 60 vineyards) (Fig. 1b). The vineyards belonging to a pair were close to each other with a maximum distance of approximately 1 km between them (mean distance within pair = 0.885 km ± 0.526 SD, ranging from 0.08 to 2 km). In addition, the vineyards in each pair shared the same red grape variety (except for one pair with a white variety). The most common grape varieties were Merlot (N = 8) and Primitivo (N = 8). Selected vineyards were a subsample of the vineyards studied in (Geppert et al., 2024); from which, we retrieved information on mean annual temperature (°C), and rainfall during the growing season (mm), and on the insecticide use (obtained through face-to-face questionnaires to winegrowers). Organic vineyards were all managed according to organic regulations, for detailed information refer to Table S1 and Geppert et al., 2024.

2.2. *Landscape composition*

To quantify landscape composition as accurately as possible, we used the program Google Earth Pro 7.3.4.8642 and manually drew polygons representing vineyard and semi-natural habitat cover around each focal vineyard. We calculated the semi-natural area and the vineyard area at multiple spatial scales, i.e., 250, 500, 1000 m radii, as it was shown previously that landscape properties at such spatial scales affect predator and pest arthropods (Martin et al., 2013). Semi-natural area was defined as the total area covered by forests (including coniferous, broadleaved and mixed forests) and grasslands (including pastures, meadows and other permanent grasslands). In our experimental design, we decided to focus on a gradient of semi-natural areas, as its effect on arthropods is the most commonly considered in agroecological studies and environmental policies. However, additional land-use categories (such as urban area or subcategories of semi-natural areas) and landscape configuration (such as patch density) could be taken into account to have a more comprehensive understanding of landscape influences on arthropod communities.

2.3. *Sampling of vegetation cover percentage*

To measure plant cover, we used the quadrat method. In each vineyard, we placed three 1 m x 1 m plots on the ground in three different inter-rows. In each vineyard, we took one photo of the quadrat from above of each plot. This sampling procedure was repeated a total of four rounds, corresponding to the key phenological stages of the grapevine: winter dormancy, flowering, fruit set, and veraison. This results in a total of 12 images for each vineyard. Finally, we quantified total plant cover for each picture using ImageJ (Schneider et al., 2012).

2.4. *Sampling of pest control indicators*

Different sampling techniques were used to monitor the arthropods belonging to the taxa of spiders (Araneae), carabids (Coleoptera: Carabidae), ladybugs (Coleoptera: Coccinellidae), harvest spiders (Opiliones, also known as "harvestmen") and hoverflies (Diptera: Syrphidae). We selected these taxa because they include important predator species. Abundance is considered for many arthropods a simple but important proxy for the associated ecosystem service, for example the abundance of carabids can be used to measure pest control and the abundance of wild bees to measure pollination (Winfree et al., 2015). In each vineyard, arthropod sampling was carried out at three phenological stages of the grapevine: flowering, fruit set, and veraison (Table S2), in 2022. Sampling was not performed during winter dormancy because most arthropods are not active at that time of the year. All taxa were sampled in the centre of the vineyards, i.e. at least 20 m distant from the edge (Fig. 1c). For each taxon, the number of sampled vineyards (N) is reported, as it may vary slightly among taxa, due to practical field constraints (e.g., occasional trap loss or sample damage).

2.4.1. *Carabid, harvest spider and spider sampling*

Three pitfall traps per vineyard were placed in three adjacent rows for three rounds. Each pitfall trap consisted of two plastic cups (400 ml capacity), placed one on top of the other, buried in the soil with the edge at the same level as the ground, and filled with 150 ml of 75 % propylene glycol. In addition, plastic plates were put on top of the traps to reduce the risk of the glasses being flooded by rain or debris. After 2 weeks in the field, the contents of the traps were taken to the laboratory to be sorted. Carabids were successfully collected in all vineyards for all rounds except for one vineyard during the third round, where traps were destroyed (N = 59 vineyards), while spiders and harvest spiders were collected in 52 vineyards.

2.4.2. *Ladybug sampling*

In each vineyard, three yellow sticky traps (40 ×24.5 cm) were positioned near the foliage of the vines at a height of around 1.5 meters for three rounds: flowering, fruit set and veraison. The traps were collected 2 weeks later. Sticky traps were initially positioned to capture leafhoppers but given the high amount of ladybugs collected, we

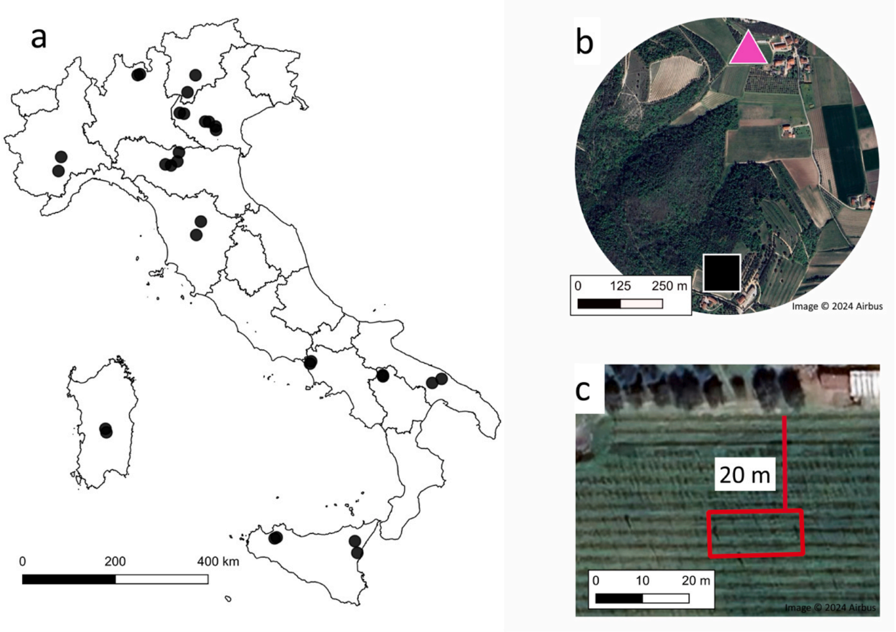


Fig. 1. Map of the 30 landscapes selected across Italy (a); one landscape including a pair of vineyards managed according to conventional (black square) and organic (purple triangle) farming, for a total of 60 vineyards (b); and the area within a vineyard where sampling took place (c).

decided to measure their abundance. Ladybugs were collected in N = 44 vineyards.

2.4.3. Hoverfly sampling

In each vineyard, we placed a total of nine pan traps (three white, three blue, three yellow) for three rounds. In particular, we positioned three traps, one per colour, in one inter-row at a distance of approximately 1.5 m, and repeated this combination three times in three different inter-rows. Pan traps were filled with water and a drop of organic dish soap and were exposed for 48 h during sunny, windless days with at least 20°C. Collected specimens were preserved in 70 % ethanol and brought to the laboratory for identification. Pan-traps were retrieved in 47 vineyards during the flowering, 41 vineyards during the fruit set and 42 during the veraison, as some traps were destroyed.

2.5. Sampling of pest control functions

The efficacy of pest control was evaluated through the use of dummy caterpillars. Dummy caterpillars are commonly used to assess the intensity of pest predation by actively hunting sight predators (Howe et al., 2009). We moulded 30 mm × 3 mm dummy caterpillars using green plasticine and glued the caterpillars on green cardboard. We placed eight dummy caterpillars at each vineyard. In particular, we placed two caterpillars on the lower part of the vine trunk and two on the leaves,1 m above the ground, on two different plants. They were exposed for 48 h. The sampling was carried out once during the fruit set phase and was successfully completed in 52 vineyards. We then checked all predation marks on caterpillars and determined the total number of caterpillars reporting predation marks by arthropods in each vineyard.

In addition, to assess the intensity of potential predation of weed seeds, we measured seed removal. We used seed cards, made of small rectangles (8 × 3 cm) of P80 grit sandpaper, on which seeds were glued using a repositionable glue (3 M Spray Mount) (Westerman et al., 2003). On each seed card, we glued thirty seeds of poppy, *Papaver rhoeas* (L., 1753). In addition, we used Petri dishes containing thirty seeds of sunflower, *Helianthus annuus* L., 1753, as too large to successfully be glued to the sandpaper. We used two plant species with very different seeds, as we expected, from previous studies, poppy seeds to indicate invertebrate seed predation, and sunflower both invertebrate and vertebrate predation (Farwig et al., 2009; Lami et al., 2020). At each vineyard, we placed three Petri dishes and three seed cards in the sub-row, ensuring they were spaced at least 1 m apart. The seed cards were secured to the ground with nails and positioned next to the Petri dishes. Each Petri dish was buried so that its rim was in level with the soil surface and then filled with soil to match the surrounding ground level. The seeds were placed directly on the soil surface within the Petri dishes. Seeds were exposed for 48 h, during sunny days with low wind speed. Then, we collected the seed cards and the Petri dishes and counted the remaining seeds of each species. The sampling was carried out once during the veraison phase in all vineyards (N = 60).

2.6. Sampling of pests and grape damage

We sampled leafhopper species (Hemiptera: Auchenorrhyncha) that are known vine pests because of their direct damage to the plant or their role as pathogen vectors. As species causing direct damage, we considered: *Empoasca vitis* Göethe, 1875 (*Hebata vitis* (Göethe, 1875))*, Erasmoneura vulnerata* (Fitch, 1851), and *Zygina rhamni* Ferrari, 1882; while as vectors of pathogens: *Dictyophara europaea* (Linnaeus, 1767), *Hyalesthes obsoletus* Signoret, 1865, *Orientus ishidae* (Matsumura, 1902) and *Scaphoideus titanus* Ball, 1932. In each vineyard, three yellow sticky traps (40 ×24.5 cm) were positioned near the foliage of the vines at a height of around 1.5 m. The traps were exposed for 2 weeks and the sampling took place three times in the three rounds (flowering, fruit set and veraison). Traps were brought to the laboratory and pests causing direct damage were counted on ¼ of the sticky trap, while vectors of phytoplasmas on the whole trap. Leafhopper pests were collected in all vineyards and were the only taxon studied at the species level.

Moreover, we visually estimated the grape damage by the grape moth, *Lobesia botrana* (Denis & Schiffermüller, 1775). The estimate was carried out during two sampling rounds in the phenological phases most affected, i.e. fruit set and veraison. We carried out a visual estimate of damage on 100 randomly selected grape bunches per vineyard. Each grape bunch belonged to a different plant. We classified the damage according to an infestation scale with 3 classes: 0: healthy bunch, absence of eggs or larvae; 1: infested bunch, traces of larval damage and/or presence of eggs or larvae; 2: severely infested bunch, presence of erosions/holes on the berries, silk threads, excrement, and/or exuviae.

2.7. Statistical analyses

2.7.1. Correlation among predictors

We estimated correlations among explanatory variables: mean plant cover (%), mean annual temperature (°C), rainfall during the growing season (mm), semi-natural area in a 1 km buffer (%), vineyard area in a 1 km buffer (%), semi-natural area in a 500 m buffer (%), vineyard area in a 500 m buffer (%), semi-natural area in a 250 m buffer (%), vineyard area in a 250 m buffer (%), and slope (degrees) (Supplementary Figure 1). Mean annual temperature and rainfall during the growing season were highly negatively correlated; vineyard area at 1000 m, 500 m and 250 m were highly positively correlated and semi-natural area at 1000 m, 500 m and 250 m too. Moreover, slope was positively correlated with semi-natural areas and negatively with temperature. We excluded highly correlated predictors ($r \geq 0.5$), keeping the more ecologically relevant to arthropods. Therefore, we removed rainfall and slope from the analysis and retained temperature, semi-natural area and vineyard area at only one spatial scale.

2.7.2. Cross-taxon congruence

To observe if predator taxa co-varied in conventional and organic vineyards, for each pair of taxa, we calculated pairwise correlations for abundance, including also plant cover (Pearson's correlations). We calculated correlations separately for conventional and organic vineyards. First, we aggregated the data by vineyard ID and calculated the mean abundance over the three sampling rounds. For leafhoppers, we summed the abundance of all species considered. Then, we transformed abundances using natural-logarithm transformation to linearize the relationship.

2.7.3. Effect of landscape, temperature and management

We fitted linear mixed models to investigate the responses of plant cover, arthropod abundance, pest control, seed removal and grape damage, using the R package "glmmTMB" (Magnusson et al., 2017). For plant cover, we fitted linear mixed model with vineyard ID nested in landscape ID as random structure, and management (conventional and organic), mean annual temperature, semi-natural area, and sampling round as fixed factors. Concerning arthropod abundance, we used as response variables the abundance of carabids, ladybugs, hoverflies, harvest spiders, and spiders. We fitted generalised linear mixed models with vineyard ID nested in landscape ID as random structure assuming a negative binomial distribution for all arthropods but ladybugs. For ladybugs, we assumed a poisson error distribution. Mean plant cover, management (conventional and organic), mean annual temperature, semi-natural area and sampling round were used as fixed factors. In addition, as fixed factor, we considered insecticide application using the treatment frequency index (TFI), an index frequently used to compare different active ingredients, that includes the dose sprayed relative to the recommended dose and its frequency of application (Lechenet et al., 2014).

For pest control, we fitted generalised linear mixed models assuming a beta distribution with landscape ID as the random factor and mean plant cover, management (conventional and organic), mean annual temperature, and semi-natural area as fixed factor, and pest control, i.e. the ratio of predated dummy caterpillars per site over the total number of dummy caterpillar exposed (also referred to as "attack rate"), as response variable (see, for example, Cappellari 2023). Moreover, for seed predation rate, i.e. the ratio of predated seeds over the initial total, we fitted a linear mixed model with the same fixed factors and the addition of the fixed factor of seed species (poppy or sunflower) and of the random factor vineyard ID nested in landscape ID, because we exposed three seed-cards for seed species for each vineyard.

For leafhopper pests, we fitted one generalised linear mixed model assuming negative binomial distribution for each species with vineyard ID nested in landscape ID as random structure. We used the count of the individuals of each species as response variable and as fixed factors mean plant cover, management (conventional or organic), mean annual temperature, semi-natural area, insecticide TFI and sampling round. To compare the model estimates, we standardized the predictors to mean = 0 and SD = 1. For three leafhopper species (i.e. *E. vulnerata*, *O. ishidae* and *S. titanus*), Sardinia and Sicily were excluded from the analysis as these exotic species have not yet been recorded there. Finally, we tested the effect of mean plant cover, management (conventional and organic), mean annual temperature, semi-natural area and sampling round on grape damage percent. We pooled the total number of damaged grape bunches belonging to class 1 and 2 (infested and severely infested). This represents the percentage of grape bunches per vineyard. We used it as a response variable, and we fitted linear mixed models with vineyard ID nested in landscape ID as random structure.

2.7.4. Model selection and diagnostics

To select the most appropriate spatial scale, for all response variables (i.e. carabids, ladybugs, hoverflies, harvest spiders, spiders, pest control, seed predation, *E. vitis*, *E. vulnerata*, *Z. rhamni*, *D. europaea*, *H. obsoletus, O. ishidae*, *S. titanus* and grape damage*)*, we fitted three different models using semi-natural area at 250, 500 and 1000 m as predictors, and selected the model with the lowest AICc value. To do so, we used the "AICc" function of the R package "MuMIn" (Bartoń, 2023). In a set of n models, each model i can be ranked using its difference in AICc with the best-fitting model (ΔAICci = AICci − AICcMIN). A model in a set was considered plausible if its ΔAICc was below 2. When models were equally supported we reported results at 250 m (see Table S3 for AICc results of all models). Moreover, we run the same process using as a predictor vineyard area at 250, 500 and 1000 m. We did not use semi-natural area and vineyard area as predictors in the same model, to avoid overfitting the models and because they were weakly negatively correlated. We report in the main text results of the best fitting model with semi-natural area as predictor, while in the supplementary materials results from the best fitting model using vineyard area (Table S4).

After selecting the most appropriate spatial scale with AICc comparison, we used a backward deletion procedure starting from the full model. Full models described above included all of the two-way interactions between the fixed factors and main effects. We removed one-by-one the interactions if the p-value was higher than 0.05 and re-ran the model to avoid overfitting and to correctly interpret the main effects. All main effects were left even if not significant. Variance Inflation Factors' (VIFs) values for all models were close to 1, showing low correlations among variables (Akinwande et al., 2015). Residuals were visually estimated using diagnostic plots to check that no pattern occurred, using the R package "DHARMa" (Hartig, 2019).

3. Results

3.1. Cross-taxon congruence

In total, we collected 2013 specimens of carabids, 716 of harvest spiders, 1733 of ladybugs, 2808 of spiders, 300 of hoverflies, and 26,083 of leafhoppers, including pests and vectors, the vast majority belonging to the species *E. vitis* (approximately 90 %) (Table S5). We detected only positive or non-significant pairwise correlations among the abundance of arthropod taxa (Fig. 2). In both conventional and organic vineyards, carabids and ladybugs, hoverflies and ladybugs, and hoverflies and plant cover were positively correlated. In addition, in conventional vineyards, carabids were positively correlated also with spiders; and so were leafhoppers and ladybugs. By contrast, in organic vineyards, carabids were positively correlated with hoverflies.

3.2. Effects of landscape, temperature and management on plant cover, pest control indicators, pests and grape damage

We found that plant cover in the inter-row decreased with increasing mean annual temperature but this trend varied across sampling rounds, with the sharpest decline observed during the first round (i.e. winter dormancy) and the weakest during the fourth round (i.e. veraison) (Figure S2a, Table S6). Moreover, plant cover decreased with increasing area of semi-natural habitats (Figure S2 b).

The abundance of carabids and ladybugs decreased with increasing semi-natural areas and were lower in the second sampling round (Fig. 3a and 3 b, Table S7). Moreover, ladybugs decreased with increasing plant cover percentage (Fig. 3c). By contrast, hoverfly abundance responded only to plant cover, increasing with increasing percentage of plant cover in the inter-row (Fig. 3d). Harvest spiders increased with increasing temperature, they increased with increasing semi-natural area and decreased in the last sampling round (Fig. 4a and 4 b). Spiders responded to an interaction between management and semi-natural area, i.e. their abundance increased with increasing semi natural areas in organic vineyards (Fig. 4c). Moreover, they showed a trend for increasing with increasing temperature and they decreased over the last sampling round (Fig. 4d). Dummy caterpillar control was not significantly affected by any of the selected factors, but it showed a trend for decreasing with increasing plant cover and in conventional management, and for increasing with increasing semi-natural area (Table S8). Seed predation rate was affected only by the plant species, with poppy seeds showing a higher predation rate than sunflower seeds (Table S8).

Empoasca vitis was not affected by plant cover, management, temperature and insecticide TFI, but it decreased with increasing semi-natural area and over the sampling rounds (Fig. 5, Table S9). *Erasmoneura vulnerata* was more abundant in organic than conventional vineyards. *Zygina rhamni* increased in warm dry climates. *Dictyophora europaea* responded only to the sampling rounds, increasing over time. *H. obsoletus* decreased with increasing semi-natural area. *Orientus ishidae* decreased in warm-dry climates and increased over the sampling rounds. *Scaphoideus titanus* increased over the sampling rounds, while it showed a marginally significant trend for decreasing with increasing insecticide TFI. Mean grape damage by *L. botrana* did not respond to sampling round, mean plant cover, management, mean annual temperature and semi-natural area (Table S10).

4. Discussion

Our results showed high heterogeneity and taxon specific responses to vineyard management, landscape and temperature. We found that a higher cover of inter-row vegetation was maintained in cold and wet climates. Organic management did not have any positive direct effect on the plant cover, on the abundance of beneficial predator taxa, nor on seed predation. Both beneficial predator arthropods and leafhopper pests showed taxon-specific responses to local management, landscape and temperature. In particular, the significant effect of semi-natural areas and temperature on several groups adds to the evidence supporting the need of integrating landscape composition in vineyard management and adapting grape production to current climate change.

As hypothesized, we mostly observed positive cross-taxon congruence between different arthropods. In particular, carabids and ladybugs, hoverflies and ladybugs and hoverflies and plant cover were positively

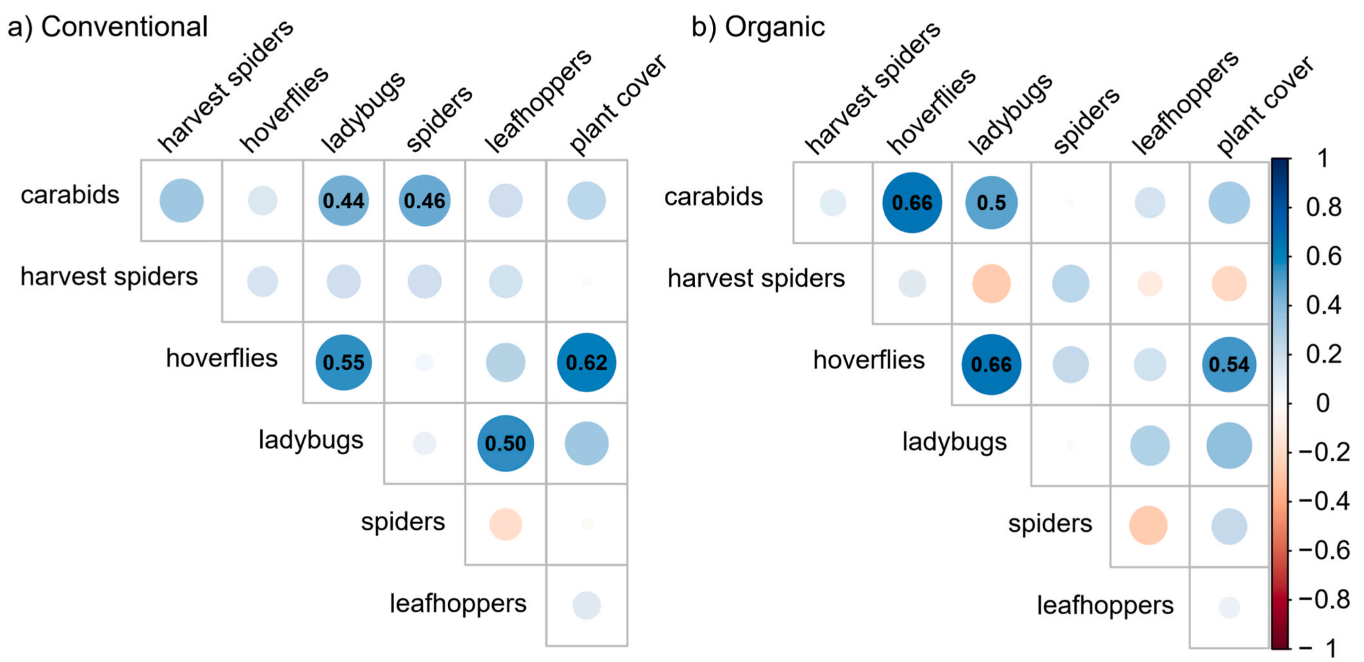


Fig. 2. Pairwise Pearson's correlation among natural-logarithmic transformed abundance of arthropod taxa and percentage of plant cover in the inter-row in a) conventional and b) organic vineyards. Blue represent positive correlations, red negative correlations. The circle size is proportional to the magnitude of the correlation. Only significant correlations with r ≥ 0.4 are shown.

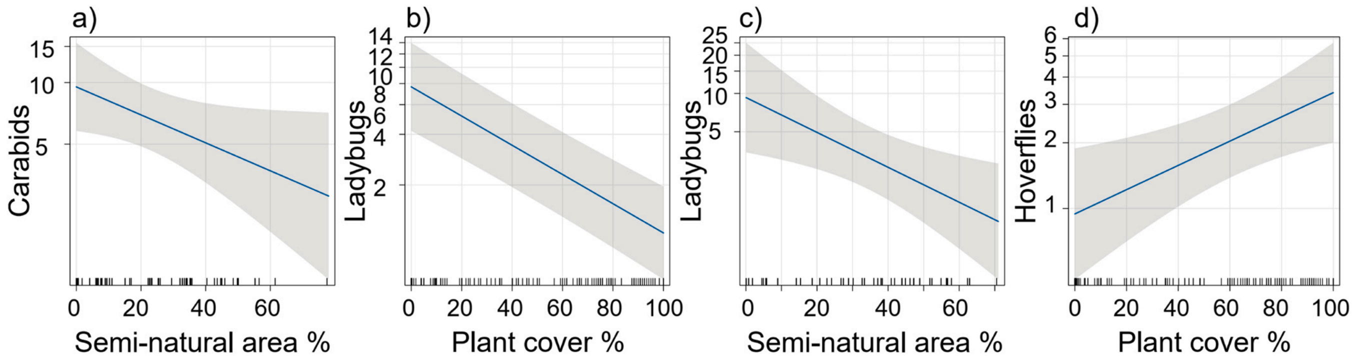


Fig. 3. The effect of a) semi-natural area (%) on carabid abundance; b) plant cover (%) on ladybug abundance; c) semi-natural area (%) on ladybug abundance; and d) plant cover (%) on hoverfly abundance. Only significant effects are showed and shaded areas represent confidence intervals at 95 %. The significant effect of sampling round is not shown.

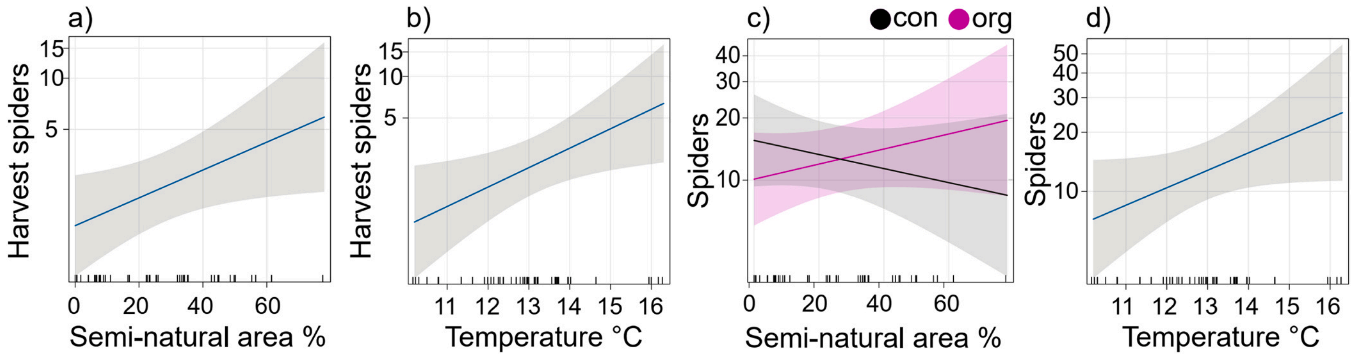


Fig. 4. The effect of a) semi-natural area (%) on harvest spider abundance; b) temperature (°C) on harvest spider abundance; c) the interaction of management and semi-natural area (%) on spider abundance; and d) temperature (°C) on spider abundance. Con = conventional and org = organic. Significant and marginally significant effects are showed and shaded areas represent confidence intervals at 95 %. The significant effect of sampling round is not shown.

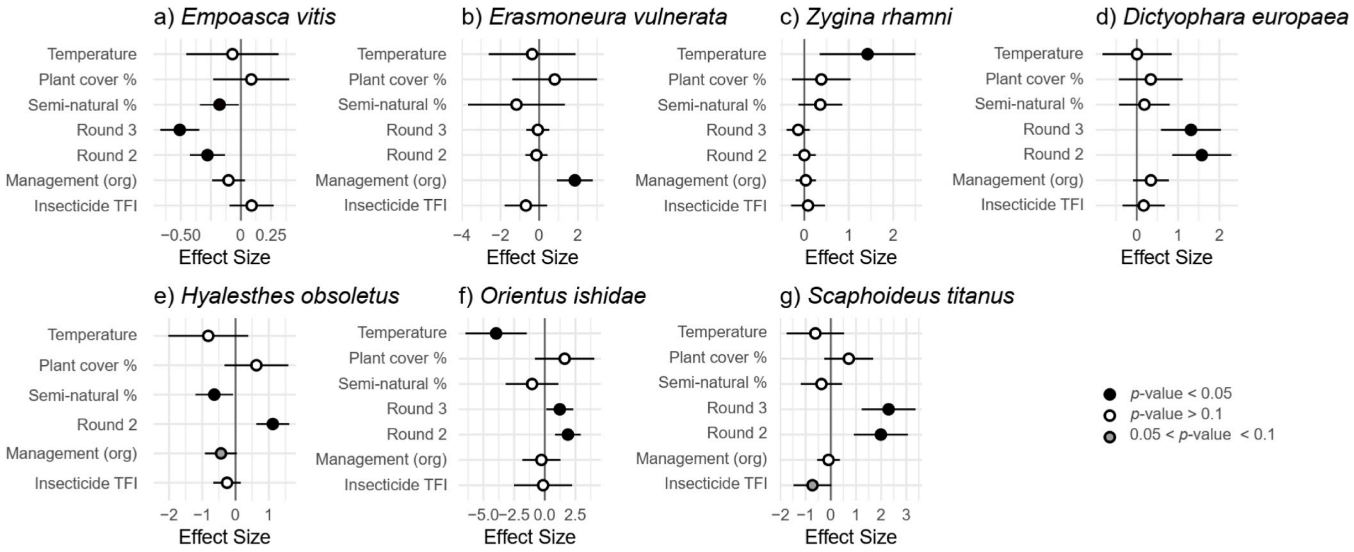


Fig. 5. Forest plot showing model-averaged effect sizes (points) and 95 % confidence intervals (bars) for leafhopper pest abundance. The plot includes the scaled effects of plant cover, management, semi-natural area, temperature, insecticide TFI, and sampling rounds. For *Hyalesthes obsoletus* only round 1 and 2 are included because no individuals were collected in round 3.

correlated. However, conventional and organic vineyards showed a few different correlations. For example, carabids were positively correlated with spiders only in conventional vineyards, while they were correlated with hoverflies only in organic vineyards. Overall, we could confirm the importance of carabid beetles as surrogate group for other ground-dwelling predators (Bohan et al., 2011; Rainio and Niemelä, 2003). In addition, carabid beetles seem to hold the ability to be bioindicators in a variety of habitat types both natural and agricultural (Corcos et al., 2021).

Plant cover in the inter-row changed according to temperature and sampling round. The negative effect of temperature on inter-row plant cover was expected, because hot and dry conditions (temperature was negatively correlated with rainfall) reduce vegetation growth (Eziz et al., 2017; Wilschut et al., 2022). In addition, the decrease in plant cover with warming was more pronounced during the winter than in the summer. This might be related to the traditional practice of reducing inter-row vegetation during the summer in Mediterranean regions, to reduce competition for water. We found no difference in the plant cover of conventional and organic vineyards. This lack of difference may be due to the fact that mechanical operations and mowing regime did not differ between conventional and organic farming. Finally, plant cover decreased with the amount of semi-natural area surrounding the vineyard. As plant cover in the inter-row usually benefits biodiversity and ecosystem services, and prevents soil erosion (Winter et al., 2018), it is important to consider strategies to counteract the predicted negative effects of climate warming on inter-row vegetation.

Concerning arthropod predators, the abundance of carabids, ladybugs, harvest spiders and spiders changed in response to landscape composition. Carabid and ladybug abundance increased with decreasing semi-natural areas, which corresponds to increasing perennial and annual crops. Carabid and ladybug abundance are often reported to be positively affected by the amount of agricultural area, because agricultural habitats support several ruderal species, often feeding on crop pests (Honek et al., 2017; Lami et al., 2021; Vanbergen et al., 2005). By contrast, semi-natural area had a positive effect on harvest spiders. Usually, microclimate and vegetation type and structure shape harvest spider community characteristics, with a positive effect of the amount of woody vegetation (Papura et al., 2020; Stašiov et al., 2021). The same positive effect of semi-natural areas was found for spiders in organic vineyards but not in conventional vineyards. Organic and conventional vineyards usually sustain spider communities strongly differing in their composition (Caprio et al., 2015; Kolb et al., 2020). Therefore, this result might be due to species specific responses to the landscape drivers. In addition, as expected because of the well-known effect of temperature on arthropod physiology and fitness of ectotherms (Frazier et al., 2006), harvest spiders and spiders increased with increasing temperatures. Finally, increasing plant cover in the inter-row had a negative effect on ladybugs and a positive on the abundance of hoverflies. The positive effect on hoverflies is linked to the overall quantity of floral resources for adults (Biella et al., 2025; Kratschmer et al., 2019, 2018). Plant cover is not a direct measure of food availability; however, flower cover in vineyards increases with plant cover because floral resources are destroyed by frequent soil tillage, mowing or herbicide use (Kratschmer et al., 2019). The negative effect on ladybugs as well as the lack of effect on other predator taxa were unexpected, as a positive effect is frequently reported in the literature (Blaise et al., 2022, 2021; Hanna et al., 2003; Puig-Montserrat et al., 2017; Winter et al., 2018).

Similar levels of abundance for arthropod predators were sustained by conventional and organic vineyards. Overall, several studies did not find a positive effect of organic vineyards on arthropods (Beaumelle et al., 2023; Bruggisser et al., 2010; Caprio et al., 2015). The lack of effect can be explained by the extremely high variability within organic and conventional management (Geppert et al., 2024). In addition, the absence of beneficial effects of organic farming in vineyards compared to the well-known positive effect in cereals or other annual crops, can be explained by different levels of disturbance in annual vs. perennial cropping systems, following the argumentation of the intermediate disturbance hypothesis or the intermediate landscape-complexity hypothesis (Bruggisser et al., 2010; Connell, 1978; Tscharntke et al., 2012). In annual systems, the level of disturbance is much higher than in perennial systems, such as vineyards, which provide more stable habitats and resource continuity, thereby reducing the relative advantage of organic management in enhancing arthropods. Moreover, our results focused on the abundance and did not consider the diversity of predator species, which may respond more sensitively to organic management.

Concerning pest control and seed predation, we expected plant cover in the inter-row to positively affect biological control. Usually, diverse cover crops and permanent green cover enhance the abundance of natural enemies and the rates of predation, especially in simplified landscapes (Beaumelle et al., 2021; Menalled et al., 2007; Sanguankeo and León, 2011; Zanettin et al., 2021). However, we found no effect on seed predation and a trend for a negative effect on pest control. It is known that higher predation rates depend on higher activity density and the activity-density may vary spatially and temporally while predators search for suitable microclimates, shelter and prey or in response to changing weed density (Thomas et al., 2006). This means that a lower predation rates does not necessarily imply low activity density but it might be due to a dilution effect. Moreover, we found a trend for a positive effect of organic farming on pest control, which might be linked to the lower applications of synthetic pesticides (Puliga et al., 2024; Tortosa et al., 2025). However, the lack of a strong and clear management effect on both predation metrics considered (i.e. pest control and seed predation) has already been reported in the literature in vineyards and it is partly explained by the large variability in agricultural practices, both within organic and within conventional systems (Geppert et al., 2024; Rusch et al., 2016a). Concerning landscape effects, there is a large inconsistency of such effects on pest populations and crop damages (Karp et al., 2018; Muneret et al., 2019; Petit et al., 2017; Rusch et al., 2016a). However, in our study, we considered semi-natural and vineyard areas, without exploring additional, more specific land-use categories or landscape configuration metrics. Finally, concerning seed predation, rates were higher for poppy than sunflower seeds, which could suggest a higher predation by invertebrates than vertebrates.

Concerning leafhopper pests, we found species specific responses to the considered drivers (Trivellone et al., 2012). Only one species, *E. vulnerata*, was more abundant in organic than conventional vineyards, as reported in other studies (Duso et al., 2020). *Empoasca vitis* and *H. obsoletus* were both negatively affected by increasing semi-natural areas. This negative effect might be due to the barrier effects of unsuitable natural habitat types, and/or due to the higher pest suppression capacity of the semi-natural landscapes, that usually sustain a higher abundance of predators and parasitoids (Ragone et al., 2025; Rusch et al., 2016a; Veres et al., 2013). However, this is in contrast with previous studies on *E. vitis*, that reported a positive effect of semi-natural areas on its abundance (Veres et al., 2013). Moreover, *Zygina rhamni,* and *O. ishidae* were significantly affected by the temperature with opposite responses, i.e. *Z. rhamni* increased in warm dry climates and *O. ishidae* decreased. The frequency of use of insecticides had a marginally significant negative effect on *S. titanus* (Tirello et al., 2021; Trivellone et al., 2012), but not on the other species. *Scaphoideus titanus* is the main vector of the phytoplasma associated to Flavescence dorée (FD), a disease causing severe damage in European vineyards and in several regions in Northern Italy it is mandatory to spray insecticides against it. The lack of a strong effect of insecticides on *S. titanus* might be related to the fact that the control is legally required in the presence of the vector, regardless of its density. In addition, the lack of the expected negative effect of warm dry climates on *E. vitis* might be related to the mandatory control of FD in Northern Italy. These results highlight the need of integrating multiple strategies to contain leafhopper pests.

5. Conclusions

Enhancing natural enemy abundance and activity in agroecosystems is a major challenge for future agriculture. However, predicting pest control is notably difficult (Alexandridis et al., 2021; Karp et al., 2018; Petit et al., 2020). Here, we found high heterogeneity and taxon specific responses of both predators and pests. Concerning the local management, we did not find any beneficial effect of organic management on predators, and organic vineyards showed a higher abundance of the leafhopper species *E. vulnerata*. We highlight that for future viticulture it is crucial to consider landscape and climate change effects to tailor local efficient control strategies. Temperature affected the plant cover in the inter-row, the abundance of harvest spiders, spiders and several leafhopper species, while semi-natural areas affected carabids, ladybugs, harvest spiders, and two species of leafhoppers (i.e. *E. vitis* and *H. obsoletus*). Further research on pest control along environmental gradients is needed to be able to promote the transformation of grape production, including additional research on what influences winegrowers' decisions, such as their attitudes, beliefs, and the specific management needs (Chen et al., 2022).

CRediT authorship contribution statement

Costanza Geppert: Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Alberto Alma:** Writing – review & editing, Investigation. **Lucia Andretta:** Writing – review & editing, Investigation. **Gianfranco Anfora:** Writing – review & editing, Investigation. **Enrico Busato:** Writing – review & editing, Investigation. **Pierfilippo Cerretti:** Writing – review & editing, Investigation. **Serena Giorgia Chiesa:** Writing – review & editing, Investigation. **Arturo Cocco:** Writing – review & editing, Investigation. **Elena Costi:** Writing – review & editing, Investigation. **Mariana da Cruz Albertazzi:** Writing – review & editing, Investigation. **Carlo Duso:** Writing – review & editing, Investigation. **Pierluigi Forlano:** Writing – review & editing, Investigation. **Antonio Pietro Garonna:** Writing – review & editing, Investigation. **Nicola Grigolin:** Writing – review & editing, Investigation. **Francesco Lami:** Writing – review & editing, Investigation. **Paolo Lo Bue:** Writing – review & editing, Investigation. **Daniela Lupi:** Writing – review & editing, Investigation. **Serena Magagnoli:** Writing – review & editing, Investigation. **Lara Maistrello:** Writing – review & editing, Investigation. **Roberto Mannu:** Writing – review & editing, Investigation. **Gaetana Mazzeo:** Writing – review & editing, Investigation. **Luca Mazzon:** Writing – review & editing, Investigation. **Nicola Mori:** Writing – review & editing, Investigation. **Giacomo Ortis:** Writing – review & editing, Investigation. **Ezio Peri:** Writing – review & editing, Investigation. **Gianvito Ragone:** Writing – review & editing, Investigation. **Marzia Cristiana Rosi:** Writing – review & editing, Investigation. **Giuseppe Rotundo:** Writing – review & editing, Investigation. **Patrizia Sacchetti:** Writing – review & editing, Investigation. **Francesco Sanna:** Writing – review & editing, Investigation. **Sara Savoldelli:** Writing – review & editing, Investigation. **Pompeo Suma:** Writing – review & editing, Investigation. **Giovanni Tamburini:** Writing – review & editing, Investigation. **Vincenzo Trotta:** Writing – review & editing, Investigation. **Lorenzo Marini:** Writing – original draft, 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.

Acknowledgments

This work was part of the "Climvit" initiative promoted by the SEI-SEA (the Agricultural Entomology section of the Italian Entomological Society). We thank all farmers, students, and scientists involved in the study. In particular, we thank Prof. Giovanni Burgio for financial support to FL and SM, Prof. Andrea Lentini for financial support to AC and RM, and Dr. Daniele Giannetti, Silvio Pepe, Guerino Pescara, Martino Salvetti, Dr. Roberto Catania and Dr.Luca Girgenti for their fundamental help during field work. This study was carried out within the Agritech National Research Center funded by the European Union - Next Generation EU, Mission 4 Component 2 CUP C93C22002790001.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2025.110065.

Data availability

Data will be made available on request.

References

Akinwande, M.O., Dikko, H.G., Samson, A., 2015. Variance inflation factor: as a condition for the inclusion of suppressor variable(s) in regression analysis. Open J. Stat. 05, 754–767. https://doi.org/10.4236/ojs.2015.57075.

Alexandridis, N., Marion, G., Chaplin-Kramer, R., Dainese, M., Ekroos, J., Grab, H., Jonsson, M., Karp, D.S., Meyer, C., O'Rourke, M.E., Pontarp, M., Poveda, K., Seppelt, R., Smith, H.G., Martin, E.A., Clough, Y., 2021. Models of natural pest control: towards predictions across agricultural landscapes. Biol. Control 163, 104761. https://doi.org/10.1016/j.biocontrol.2021.104761.

Bartoń, K., 2023. MuMIn: Multi-Model Inference.

Beaumelle, L., Auriol, A., Grasset, M., Pavy, A., Thiéry, D., Rusch, A., 2021. Benefits of increased cover crop diversity for predators and biological pest control depend on the landscape context. Ecol. Solut. Evid. 2, e12086. https://doi.org/10.1002/2688-8319.12086.

Beaumelle, L., Giffard, B., Tolle, P., Winter, S., Entling, M.H., Benítez, E., Zaller, J.G., Auriol, A., Bonnard, O., Charbonnier, Y., Fabreguettes, O., Joubard, B., Kolb, S., Ostandie, N., Reiff, J.M., Richart-Cervera, S., Rusch, A., 2023. Biodiversity conservation, ecosystem services and organic viticulture: a glass half-full. Agric. Ecosyst. Environ. 351, 108474. https://doi.org/10.1016/j.agee.2023.108474.

Biella, P., Ramazzotti, F., Parolo, G., Galimberti, A., Labra, M., Brambilla, M., 2025. Vineyard footprint on pollinators is mediated by flower vegetation, organic farming, seasonal and weather factors, a case study from North Italy. Agric. Ecosyst. Environ. 378, 109297. https://doi.org/10.1016/j.agee.2024.109297.

Blaise, C., Mazzia, C., Bischoff, A., Millon, A., Ponel, P., Blight, O., 2021. The key role of inter-row vegetation and ants on predation in Mediterranean organic vineyards. Agric. Ecosyst. Environ. 311, 107327. https://doi.org/10.1016/j.agee.2021.107327.

Blaise, C., Mazzia, C., Bischoff, A., Millon, A., Ponel, P., Blight, O., 2022. Vegetation increases abundances of ground and canopy arthropods in Mediterranean vineyards. Sci. Rep. 12, 3680. https://doi.org/10.1038/s41598-022-07529-1.

Bohan, D.A., Boursault, A., Brooks, D.R., Petit, S., 2011. National-scale regulation of the weed seedbank by carabid predators. J. Appl. Ecol. 48, 888–898. https://doi.org/10.1111/j.1365-2664.2011.02008.x.

Bruggisser, O.T., Schmidt-Entling, M.H., Bacher, S., 2010. Effects of vineyard management on biodiversity at three trophic levels. Biol. Conserv. 143, 1521–1528. https://doi.org/10.1016/j.biocon.2010.03.034.

Caprio, E., Nervo, B., Isaia, M., Allegro, G., Rolando, A., 2015. Organic versus conventional systems in viticulture: comparative effects on spiders and carabids in vineyards and adjacent forests. Agric. Syst. 136, 61–69. https://doi.org/10.1016/j.agsy.2015.02.009.

Chen, Y., Herrera, R.A., Benitez, E., Hoffmann, C., Möth, S., Paredes, D., Plaas, E., Popescu, D., Rascher, S., Rusch, A., Sandor, M., Tolle, P., Willemen, L., Winter, S., Schwarz, N., 2022. Winegrowers' decision-making: a pan-European perspective on pesticide use and inter-row management. J. Rural Stud. 94, 37–53. https://doi.org/10.1016/j.jrurstud.2022.05.021.

Chuche, J., Thiéry, D., 2014. Biology and ecology of the Flavescence dorée vector Scaphoideus titanus: a review. Agron. Sustain. Dev. 34, 381–403. https://doi.org/10.1007/s13593-014-0208-7.

Connell, J.H., 1978. Diversity in tropical rain forests and coral reefs. Science 199, 1302–1310. https://doi.org/10.1126/science.199.4335.1302.

Corcos, D., Lami, F., Nardi, D., Boscutti, F., Sigura, M., Giannone, F., Pantini, P., Tagliapietra, A., Busato, F., Sibella, R., Marini, L., 2021. Cross-taxon congruence between predatory arthropods and plants across Mediterranean agricultural landscapes. Ecol. Indic. 123, 107366. https://doi.org/10.1016/j.ecolind.2021.107366.

Dainese, M., Martin, E.A., Aizen, M.A., Albrecht, M., Bartomeus, I., Bommarco, R., Carvalheiro, L.G., Chaplin-Kramer, R., Gagic, V., Garibaldi, L.A., Ghazoul, J., Grab, H., Jonsson, M., Karp, D.S., Kennedy, C.M., Kleijn, D., Kremen, C., Landis, D.A., Letourneau, D.K., Marini, L., Poveda, K., Rader, R., Smith, H.G., Tscharntke, T., Andersson, G.K.S., Badenhausser, I., Baensch, S., Bezerra, A.D.M., Bianchi, F.J.J.A., Boreux, V., Bretagnolle, V., Caballero-Lopez, B., Cavigliasso, P., Ćetković, A., Chacoff, N.P., Classen, A., Cusser, S., da Silva e Silva, F.D., de Groot, G.A., Dudenhöffer, J.H., Ekroos, J., Fijen, T., Franck, P., Freitas, B.M., Garratt, M.P.D., Gratton, C., Hipólito, J., Holzschuh, A., Hunt, L., Iverson, A.L., Jha, S., Keasar, T., Kim, T.N., Kishinevsky, M., Klatt, B.K., Klein, A.-M., Krewenka, K.M., Krishnan, S., Larsen, A.E., Lavigne, C., Liere, H., Maas, B., Mallinger, R.E., Martinez Pachon, E., Martínez-Salinas, A., Meehan, T.D., Mitchell, M.G.E., Molina, G.A.R., Nesper, M., Nilsson, L., O'Rourke, M.E., Peters, M.K., Plećaš, M., Potts, S.G., Ramos, D. de L., Rosenheim, J.A., Rundlöf, M., Rusch, A., Sáez, A., Scheper, J., Schleuning, M., Schmack, J.M., Sciligo, A.R., Seymour, C., Stanley, D.A., Stewart, R., Stout, J.C., Sutter, L., Takada, M.B., Taki, H., Tamburini, G., Tschumi, M., Viana, B.F., Westphal, C., Willcox, B.K., Wratten, S.D., Yoshioka, A., Zaragoza-Trello, C., Zhang, W., Zou, Y., Steffan-Dewenter, I., 2019. A global synthesis reveals biodiversity-mediated benefits for crop production. Sci. Adv. 5, eaax0121. https://doi.org/10.1126/sciadv.aax0121.

Danne, A., Thomson, L.J., Sharley, D.J., Penfold, C.M., Hoffmann, A.A., 2010. Effects of native grass cover crops on beneficial and pest invertebrates in Australian Vineyards. Environ. Entomol. 39, 970–978. https://doi.org/10.1603/EN09144.

Duso, C., Zanettin, G., Gherardo, P., Pasqualotto, G., Raniero, D., Rossetto, F., Tirello, P., Pozzebon, A., 2020. Colonization patterns, phenology and seasonal abundance of the nearctic leafhopper Erasmoneura vulnerata (Fitch), a New Pest in European Vineyards. Insects 11, 731. https://doi.org/10.3390/insects11110731.

Eziz, A., Yan, Z., Tian, D., Han, W., Tang, Z., Fang, J., 2017. Drought effect on plant biomass allocation: A meta-analysis. Ecol. Evol. 7, 11002–11010. https://doi.org/10.1002/ece3.3630.

Farwig, N., Bailey, D., Bochud, E., Herrmann, J.D., Kindler, E., Reusser, N., Schüepp, C., Schmidt-Entling, M.H., 2009. Isolation from forest reduces pollination, seed predation and insect scavenging in Swiss farmland. Landsc. Ecol. 24, 919–927. https://doi.org/10.1007/s10980-009-9376-2.

Frazier, M.R., Huey, R.B., Berrigan, D., 2006. Thermodynamics constrains the evolution of insect population growth rates: "Warmer Is Better.". Am. Nat. 168, 512–520. https://doi.org/10.1086/506977.

Gaigher, R., Pryke, J.S., Kratschmer, S., Zaller, J.G., Winter, S., Samways, M.J., Pachinger, B., Geldenhuys, M., Van Schalkwyk, J., 2024. Area and configuration of both semi-natural habitats and vineyards influence arthropods in South African and central European agricultural landscapes. Insect Conserv. Divers. 17, 702–718. https://doi.org/10.1111/icad.12741.

Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., Mäder, P., Stolze, M., Smith, P., Scialabba, N.E.-H., Niggli, U., 2012. Enhanced top soil carbon stocks under organic farming. In: Proceedings of the National Academy of Sciences, 109, pp. 18226–18231. https://doi.org/10.1073/pnas.1209429109.

Geppert, C., da Cruz, M., Alma, A., Andretta, L., Anfora, G., Battaglia, D., Burgio, G., Caccavo, V., Chiesa, S.G., Cinquatti, F., Cocco, A., Costi, E., D'Isita, I., Duso, C., Garonna, A.P., Germinara, G.S., Bue, P.L., Lucchi, A., Maistrello, L., Mannu, R., Marchesini, E., Masetti, A., Mazzon, L., Mori, N., Ortis, G., Peri, E., Pescara, G., Prazaru, S.C., Ragone, G., Rigamonti, I.E., Rosi, M.C., Rotundo, G., Sacchetti, P., Savoldelli, S., Suma, P., Tamburini, G., Garzia, G.T., Marini, L., 2024. Climate and landscape composition explain agronomic practices, pesticide use and grape yield in vineyards across Italy. Agric. Syst. 215, 103853. https://doi.org/10.1016/j.agsy.2024.103853.

Hanna, R., Zalom, F.G., Roltsch, W.J., 2003. Relative impact of spider predation and cover crop on population dynamics of Erythroneura variabilis in a raisin grape vineyard. Èntomol. Exp. Et. Appl. 107, 177–191. https://doi.org/10.1046/j.1570-7458.2003.00051.x.

Hartig, F., 2019. DHARMa: Residual Diagnostics for Hierarchical (multi-level / mixed) regression models.

Honek, A., Dixon, A.F., Soares, A.O., Skuhrovec, J., Martinkova, Z., 2017. Spatial and temporal changes in the abundance and compostion of ladybird (Coleoptera: Coccinellidae) communities. Curr. Opin. Insect Sci. 20, 61–67. https://doi.org/10.1016/j.cois.2017.04.001.

Howe, A., Lövei, G.L., Nachman, G., 2009. Dummy Caterpillars as A Simple Method to Assess Predation Rates on Invertebrates in A Tropical Agroecosystem. https://doi.org/10.1111/j.1570-7458.2009.00860.x.

Karp, D.S., Chaplin-Kramer, R., Meehan, T.D., Martin, E.A., DeClerck, F., Grab, H., Gratton, C., Hunt, L., Larsen, A.E., Martínez-Salinas, A., O'Rourke, M.E., Rusch, A., Poveda, K., Jonsson, M., Rosenheim, J.A., Schellhorn, N.A., Tscharntke, T., Wratten, S.D., Zhang, W., Iverson, A.L., Adler, L.S., Albrecht, M., Alignier, A., Angelella, G.M., Zubair Anjum, M., Avelino, J., Batáry, P., Baveco, J.M., Bianchi, F.J.J.A., Birkhofer, K., Bohnenblust, E.W., Bommarco, R., Brewer, M.J., Caballero-López, B., Carrière, Y., Carvalheiro, L.G., Cayuela, L., Centrella, M., Ćetković, A., Henri, D.C., Chabert, A., Costamagna, A.C., De la Mora, A., de Kraker, J., Desneux, N., Diehl, E., Diekötter, T., Dormann, C.F., Eckberg, J.O., Entling, M.H., Fiedler, D., Franck, P., Frank van Veen, F.J., Frank, T., Gagic, V., Garratt, M.P.D., Getachew, A., Gonthier, D.J., Goodell, P.B., Graziosi, I., Groves, R.L., Gurr, G.M., Hajian-Forooshani, Z., Heimpel, G.E., Herrmann, J.D., Huseth, A.S., Inclán, D.J., Ingrao, A.J., Iv, P., Jacot, K., Johnson, G.A., Jones, L., Kaiser, M., Kaser, J.M., Keasar, T., Kim, T.N., Kishinevsky, M., Landis, D.A., Lavandero, B., Lavigne, C., Le Ralec, A., Lemessa, D., Letourneau, D.K., Liere, H., Lu, Y., Lubin, Y., Luttermoser, T., Maas, B., Mace, K., Madeira, F., Mader, V., Cortesero, A.M., Marini, L., Martinez, E., Martinson, H.M., Menozzi, P., Mitchell, M.G.E., Miyashita, T., Molina, G.A.R., Molina-Montenegro, M.A., O'Neal, M.E., Opatovsky, I., Ortiz-Martinez, S., Nash, M., Östman, Ö., Ouin, A., Pak, D., Paredes, D., Parsa, S., Parry, H., Perez-Alvarez, R., Perović, D.J., Peterson, J.A., Petit, S., Philpott, S.M., Plantegenest, M., Plećaš, M., Pluess, T., Pons, X., Potts, S.G., Pywell, R.F., Ragsdale, D.W., Rand, T.A., Raymond, L., Ricci, B., Sargent, C., Sarthou, J.-P., Saulais, J., Schäckermann, J., Schmidt, N.P., Schneider, G., Schüepp, C., Sivakoff, F.S., Smith, H.G., Stack Whitney, K., Stutz, S., Szendrei, Z., Takada, M.B., Taki, H., Tamburini, G., Thomson, L.J., Tricault, Y., Tsafack, N., Tschumi, M., Valantin-Morison, M., Van Trinh, M., van der Werf, W., Vierling, K.T., Werling, B.P., Wickens, J.B., Wickens, V.J., Woodcock, B.A., Wyckhuys, K., Xiao, H., Yasuda, M., Yoshioka, A., Zou, Y., 2018. Crop pests and predators exhibit inconsistent responses to surrounding landscape composition. Proc. Natl. Acad. Sci. 115, E7863–E7870. https://doi.org/10.1073/pnas.1800042115.

Kolb, S., Uzman, D., Leyer, I., Reineke, A., Entling, M.H., 2020. Differential effects of semi-natural habitats and organic management on spiders in viticultural landscapes. Agric. Ecosyst. Environ. 287, 106695. https://doi.org/10.1016/j.agee.2019.106695.

Kratschmer, S., Pachinger, B., Schwantzer, M., Paredes, D., Guernion, M., Burel, F., Nicolai, A., Strauss, P., Bauer, T., Kriechbaum, M., Zaller, J.G., Winter, S., 2018. Tillage intensity or landscape features: What matters most for wild bee diversity in vineyards? Agric. Ecosyst. Environ. 266, 142–152. https://doi.org/10.1016/J.AGEE.2018.07.018.

Kratschmer, S., Pachinger, B., Schwantzer, M., Paredes, D., Guzmán, G., Goméz, J.A., Entrenas, J.A., Guernion, M., Burel, F., Nicolai, A., Fertil, A., Popescu, D., Macavei, L., Hoble, A., Bunea, C., Kriechbaum, M., Zaller, J.G., Winter, S., 2019. Response of wild bee diversity, abundance, and functional traits to vineyard inter-row management intensity and landscape diversity across Europe. Ecol. Evol. 9, 4103–4115. https://doi.org/10.1002/ece3.5039.

Lami, F., Bartomeus, I., Nardi, D., Beduschi, T., Boscutti, F., Pantini, P., Santoiemma, G., Scherber, C., Tscharntke, T., Marini, L., 2021. Species–habitat networks elucidate landscape effects on habitat specialisation of natural enemies and pollinators. Ecol. Lett. 24, 288–297. https://doi.org/10.1111/ele.13642.

Lami, F., Boscutti, F., Masin, R., Sigura, M., Marini, L., 2020. Seed predation intensity and stability in agro-ecosystems: role of predator diversity and soil disturbance. Agric. Ecosyst. Environ. 288, 106720. https://doi.org/10.1016/j.agee.2019.106720.

Lechenet, M., Bretagnolle, V., Bockstaller, C., Boissinot, F., Petit, M.-S., Petit, S., Munier-Jolain, N.M., 2014. Reconciling pesticide reduction with economic and environmental sustainability in arable farming. PLOS ONE 9, e97922. https://doi.org/10.1371/journal.pone.0097922.

Magnusson, A., Skaug, H., Nielsen, A., Berg, C.W., Kristensen, K., Maechler, M., Benthem, K.J. van, Sadat, N., Bolker, B., Brooks, M., 2017. Package 'glmmtmb.' Package 'glmmtmb' R Package Version 0.2. 0 25.

Martin, E.A., Reineking, B., Seo, B., Steffan-Dewenter, I., 2013. Natural enemy interactions constrain pest control in complex agricultural landscapes. Proc. Natl. Acad. Sci. 110, 5534–5539. https://doi.org/10.1073/pnas.1215725110.

Masoni, A., Frizzi, F., Brühl, C., Zocchi, N., Palchetti, E., Chelazzi, G., Santini, G., 2017. Management matters: a comparison of ant assemblages in organic and conventional vineyards. Agric. Ecosyst. Environ. 246, 175–183. https://doi.org/10.1016/j.agee.2017.05.036.

Menalled, F.D., Smith, R.G., Dauer, J.T., Fox, T.B., 2007. Impact of agricultural management on carabid communities and weed seed predation. Agric. Ecosyst. Environ. 118, 49–54. https://doi.org/10.1016/j.agee.2006.04.011.

Muneret, L., Auriol, A., Bonnard, O., Richart-Cervera, S., Thiéry, D., Rusch, A., 2019. Organic farming expansion drives natural enemy abundance but not diversity in vineyard-dominated landscapes. Ecol. Evol. 9, 13532–13542. https://doi.org/10.1002/ece3.5810.

Muneret, L., Mitchell, M., Seufert, V., Aviron, S., Djoudi, E.A., Pétillon, J., Plantegenest, M., Thiéry, D., Rusch, A., 2018. Evidence that organic farming promotes pest control. Nat. Sustain 1, 361–368. https://doi.org/10.1038/s41893-018-0102-4.

Nascimbene, J., Marini, L., Paoletti, M.G., 2012. Organic farming benefits local plant diversity in vineyard farms located in intensive agricultural landscapes. Environ. Manag. 49, 1054–1060. https://doi.org/10.1007/s00267-012-9834-5.

Ostandie, N., Giffard, B., Bonnard, O., Joubard, B., Richart-Cervera, S., Thiéry, D., Rusch, A., 2021. Multi-community effects of organic and conventional farming practices in vineyards, 2021 11 Sci. Rep. 1 (11), 1–10. https://doi.org/10.1038/s41598-021-91095-5.

Paiola, A., Assandri, G., Brambilla, M., Zottini, M., Pedrini, P., Nascimbene, J., 2020. Exploring the potential of vineyards for biodiversity conservation and delivery of biodiversity-mediated ecosystem services: a global-scale systematic review. Sci. Total Environ. 706, 135839. https://doi.org/10.1016/j.scitotenv.2019.135839.

Papura, D., Roux, P., Joubard, B., Razafimbola, L., Fabreguettes, O., Delbac, L., Rusch, A., 2020. Predation of grape berry moths by harvestmen depends on landscape composition. Biol. Control 150, 104358. https://doi.org/10.1016/j.biocontrol.2020.104358.

Pertot, I., Caffi, T., Rossi, V., Mugnai, L., Hoffmann, C., Grando, M.S., Gary, C., Lafond, D., Duso, C., Thiery, D., Mazzoni, V., Anfora, G., 2017. A critical review of plant protection tools for reducing pesticide use on grapevine and new perspectives for the implementation of IPM in viticulture Crop Protection, Pesticide use and risk reduction with IPM, pp. 70–84. https://doi.org/10.1016/j.cropro.2016.11.025 vol 97.

Petit, S., Muneret, L., Carbonne, B., Hannachi, M., Ricci, B., Rusch, A., Lavigne, C., 2020. Landscape-scale expansion of agroecology to enhance natural pest control: a systematic review. In: Bohan, D.A., Vanbergen, A.J. (Eds.), Advances in Ecological Research, The Future of Agricultural Landscapes, Part I. Academic Press, pp. 1–48. https://doi.org/10.1016/bs.aecr.2020.09.001.

Petit, S., Trichard, A., Biju-Duval, L., McLaughlin, Ó.B., Bohan, D.A., 2017. Interactions between conservation agricultural practice and landscape composition promote weed seed predation by invertebrates. Agric. Ecosyst. Environ. 240, 45–53. https://doi.org/10.1016/j.agee.2017.02.014.

Puig-Montserrat, X., Stefanescu, C., Torre, I., Palet, J., Fàbregas, E., Dantart, J., Arrizabalaga, A., Flaquer, C., 2017. Effects of organic and conventional crop management on vineyard biodiversity. Agric. Ecosyst. Environ. 243, 19–26. https://doi.org/10.1016/j.agee.2017.04.005.

Puliga, G.A., Sprangers, T., Huiting, H., Dauber, J., 2024. Management practices influence biocontrol potential of generalist predators in maize cropping systems. Èntomol. Exp. Et. Appl. 172, 132–144. https://doi.org/10.1111/eea.13395.

Ragone, G., Laterza, I., Tedone, B., Otlu, A., Yüksel, D., Cornara, D., Addante, R., de Lillo, E., Tamburini, G., 2025. Seminatural habitats support both grapevine pests and their parasitoids in Mediterranean organic vineyards. Oecologia 207, 22. https://doi.org/10.1007/s00442-024-05661-5.

Rainio, J., Niemelä, J., 2003. Ground beetles (Coleoptera: Carabidae) as bioindicators. Biodivers. Conserv. 12, 487–506. https://doi.org/10.1023/A:1022412617568.

Rusch, A., 2024. Nature-based solutions to increase sustainability and resilience of vineyard-dominated landscapes. Basic Appl. Ecol. https://doi.org/10.1016/j.baae.2024.12.005.

Rusch, A., Binet, D., Delbac, L., Thiéry, D., 2016a. Local and landscape effects of agricultural intensification on Carabid community structure and weed seed predation in a perennial cropping system. Landsc. Ecol. 31, 2163–2174. https://doi.org/10.1007/s10980-016-0390-x.

Rusch, A., Chaplin-Kramer, R., Gardiner, M.M., Hawro, V., Holland, J., Landis, D., Thies, C., Tscharntke, T., Weisser, W.W., Winqvist, C., Woltz, M., Bommarco, R., 2016b. Agricultural landscape simplification reduces natural pest control: a quantitative synthesis. Agric. Ecosyst. Environ. 221, 198–204. https://doi.org/10.1016/j.agee.2016.01.039.

Rusch, A., Delbac, L., Thiéry, D., 2017. Grape moth density in Bordeaux vineyards depends on local habitat management despite effects of landscape heterogeneity on their biological control. J. Appl. Ecol. 54, 1794–1803. https://doi.org/10.1111/1365-2664.12858.

Sanguankeo, P.P., León, R.G., 2011. Weed management practices determine plant and arthropod diversity and seed predation in vineyards. Weed Res. 51, 404–412. https://doi.org/10.1111/j.1365-3180.2011.00853.x.

Schneider, C.A., Rasband, W.S., Eliceiri, K.W., 2012. NIH Image to ImageJ: 25 years of image analysis. Nat. Methods 9, 671–675.

Stašiov, S., Kubovčík, V., Čiliak, M., Diviaková, A., Lukáčik, I., Dovciak, M., 2021. Harvestmen (Opiliones) community structure varies across forest-meadow ecotones in a biodiverse karst region. Biodivers. Conserv 30, 1101–1117. https://doi.org/10.1007/s10531-021-02135-5.

Thomas, C.F.G., Brown, N.J., Kendall, D.A., 2006. Carabid movement and vegetation density: Implications for interpreting pitfall trap data from split-field trials. Agric. Ecosyst. Environ. 113, 51–61. https://doi.org/10.1016/j.agee.2005.08.033.

Tirello, P., Marchesini, E., Gherardo, P., Raniero, D., Rossetto, F., Pozzebon, A., Duso, C., 2021. The Control of the American Leafhopper Erasmoneura vulnerata (Fitch) in European vineyards: impact of synthetic and natural insecticides. Insects 12, 85. https://doi.org/10.3390/insects12020085.

Tortosa, A., Vialatte, A., Laroche, F., Rusch, A., Entling, M.H., Giffard, B., 2025. Landscape heterogeneity and pesticide reduction favor predation, but also grape infestation by Lobesia botrana. Ecol. Appl. 35, e70045. https://doi.org/10.1002/eap.70045.

Trivellone, V., Paltrinieri, L.P., Jermini, M., Moretti, M., 2012. Management pressure drives leafhopper communities in vineyards in Southern Switzerland. Insect Conserv. Divers. 5, 75–85. https://doi.org/10.1111/j.1752-4598.2011.00151.x.

Tscharntke, T., Tylianakis, J.M., Rand, T.A., Didham, R.K., Fahrig, L., Batáry, P., Bengtsson, J., Clough, Y., Crist, T.O., Dormann, C.F., Ewers, R.M., Fründ, J., Holt, R. D., Holzschuh, A., Klein, A.M., Kleijn, D., Kremen, C., Landis, D.A., Laurance, W., Lindenmayer, D., Scherber, C., Sodhi, N., Steffan-Dewenter, I., Thies, C., van der Putten, W.H., Westphal, C., 2012. Landscape moderation of biodiversity patterns and processes - eight hypotheses. Biol. Rev. 87, 661–685. https://doi.org/10.1111/j.1469-185X.2011.00216.x.

Vanbergen, A.J., Woodcock, B.A., Watt, A.D., Niemelä, J., 2005. Effect of land-use heterogeneity on carabid communities at the landscape scale. Ecography 28, 3–16. https://doi.org/10.1111/j.0906-7590.2005.03991.x.

Veres, A., Petit, S., Conord, C., Lavigne, C., 2013. Does landscape composition affect pest abundance and their control by natural enemies? A review. Agriculture, Ecosystems & Environment, Landscape Ecology and Biodiversity in Agricultural Landscapes, pp. 110–117. https://doi.org/10.1016/j.agee.2011.05.027 vol. 166.

Westerman, P.R., Wes, J.S., Kropff, M.J., Van Der Werf, W., 2003. Annual losses of weed seeds due to predation in organic cereal fields. J. Appl. Ecol. 40, 824–836. https://doi.org/10.1046/j.1365-2664.2003.00850.x.

Wilschut, R.A., De Long, J.R., Geisen, S., Hannula, S.E., Quist, C.W., Snoek, B., Steinauer, K., Wubs, E.R.J., Yang, Q., Thakur, M.P., 2022. Combined effects of warming and drought on plant biomass depend on plant woodiness and community type: a meta-analysis. In: Proceedings of the Royal Society B: Biological Sciences, 289. https://doi.org/10.1098/rspb.2022.1178.

Winfree, R., W. Fox, J., Williams, N.M., Reilly, J.R., Cariveau, D.P., 2015. Abundance of common species, not species richness, drives delivery of a real-world ecosystem service. Ecol. Lett. 18, 626–635. https://doi.org/10.1111/ele.12424.

Winter, S., Bauer, T., Strauss, P., Kratschmer, S., Paredes, D., Popescu, D., Landa, B., Guzmán, G., Gómez, J.A., Guernion, M., Zaller, J.G., Batáry, P., 2018. Effects of vegetation management intensity on biodiversity and ecosystem services in vineyards: A meta-analysis. J. Appl. Ecol. 55, 2484–2495. https://doi.org/10.1111/1365-2664.13124.

Wittwer, R.A., Klaus, V.H., Miranda Oliveira, E., Sun, Q., Liu, Y., Gilgen, A.K., Buchmann, N., van der Heijden, M.G.A., 2023. Limited capability of organic farming and conservation tillage to enhance agroecosystem resilience to severe drought. Agric. Syst. 211, 103721. https://doi.org/10.1016/j.agsy.2023.103721.

Wolkovich, E.M., García de Cortázar-Atauri, I., Morales-Castilla, I., Nicholas, K.A., Lacombe, T., 2018. From Pinot to Xinomavro in the world's future wine-growing regions. Nat. Clim. Change 8, 29–37. https://doi.org/10.1038/s41558-017-0016-6.

Zanettin, G., Bullo, A., Pozzebon, A., Burgio, G., Duso, C., 2021. Influence of vineyard inter-row groundcover vegetation management on arthropod assemblages in the vineyards of north-eastern Italy. Insects 12, 349. https://doi.org/10.3390/insects12040349.