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ORIGINAL PAPER

Organic management, reduced tillage, and increased vegetation cover promote ant abundance and diversity in Mediterranean Vineyards

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Abstract

Background Vineyards are regarded as one of the most intensively managed crops worldwide. Organic management is increasingly promoted as an ecologically friendly alternative to conventional farming and organic vineyards are expected to promote the abundance and diversity of arthropods and the associated ecosystem services. However, the effects of organic vineyards on arthropods show great variability depending on the local climate, landscape composition, and the considered taxon. Among arthropods, ants are one of the most dominant terrestrial organisms worldwide, with a multifaceted role in agriculture. Ant responses to organic management in vineyards have rarely been studied.

Methods We conducted this study in Italy, across 16 pairs of organic and conventional vineyards belonging to very different ecological and biogeographical settings, from Sicily to the southern Alps. We explored how ant communities were affected by organic management, inter-row vegetation cover, pesticide use, tillage intensity, mean annual temperature, and semi-natural habitats surrounding the vineyard. Moreover, we investigated whether ant communities showed geographic differentiation across Italy.

Results Our results highlight a significant positive effect of organic farming on both ant abundance and species richness. Moreover, ant species richness and abundance increased in vineyards with reduced tillage and a high vegetation cover in the inter-rows. The effects were consistent across different climates and landscapes, despite ant communities being highly different across Italy and showing a strong geographic characterization.

Conclusions Our study supports the positive role of organic agriculture, reduced tillage intensity, and spontaneous vegetation cover in protecting insect biodiversity. Among the diverse species pools that we identified, several species are known to play ecological roles and may provide services and disservices to winegrowers, encouraging further investigation to characterize ant role across different management systems and geographic areas.

Implications for insect conservation Organic farming proved to have a positive role promoting both the species richness and the abundance of ants as compared to conventional management. The preservation of spontaneous vegetation and reduction of tillage were identified as key biodiversity-friendly practices. The ant fauna of vineyards was found to be very different across the geographic gradient that we explored, suggesting that the characteristics of the local fauna should be taken into consideration for management and conservation actions.

Keywords Viticulture · Sustainable agriculture · Formicidae · Biodiversity · Italy

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Introduction

Vineyards are among the most economically important crops worldwide and rank among the most intensively managed crops and the most dependent on agrochemicals in Europe (Rusch et al. 2016). Viticulture is remarkably diverse, adapting to a wide spectrum of orographic and climatic conditions, from alpine cold to Mediterranean warm (Geppert et al. 2024). However, organic farming is a widespread and increasingly adopted strategy to develop more sustainable viticulture. Organic viticulture prohibits the use of synthetic inputs, including synthetic pesticides and mineral fertilizers. As part of the "Farm to Fork" strategy adopted by the European Union, organic agriculture is being strongly promoted (at least 25% of agricultural lands by 2030) (Schebesta and Candel 2020). Much evidence has already been published documenting the benefits of organic management on insect biodiversity in vineyards. However, results are sometimes complex because of the variety of agroecological contexts and taxa involved (Tscharntke et al. 2021; Beaumelle et al. 2023).

Ants stand as one of the most ecologically successful insect groups, playing an important role across terrestrial ecosystems, including agricultural lands (Parker and Kronauer 2021). Considered good bioindicators of habitat alteration (Andersen et al. 2002; Pereira et al. 2010; Carvalho et al. 2020), ants provide a handful of important ecological services and disservices to farmers. They act as important predators of insect pests (Offenberg 2015; Anjos et al. 2022; Schifani et al. 2026) and weed seeds (Baraibar et al. 2011; Evans and Gleeson 2016; Lami et al. 2020; Schifani et al. 2026), may control plant pathogens (Offenberg 2022; Schifani et al. 2026), and contribute to soil bioturbation and enrichment (De Almeida et al. 2023; Zhou et al. 2023), while also acting as mutualist partners for many honeydew-producing hemipteran pests (Anjos et al. 2022; Schifani et al. 2024a). Moreover, the same ant species often plays contrasting ecological roles, whose relative weight and balance depend on the ecological context (Styrski & Eubanks 2007; Schifani et al. 2024a). In vineyards, certain ant species have been reported as significant pests (Beltrà et al. 2017; Cocco et al. 2021; Parrilli et al. 2021; Schifani et al. 2024a), but some of the same ants may rank among the most important predatory arthropods in other contexts (Blaise et al. 2021). However, the effects of management on ant communities in vineyards have only rarely been investigated, and never on a broad geographical scale (Masoni et al. 2017).

Agricultural management can affect ant communities. For example, ant communities usually change in response to the use of synthetic or organic inputs, such as fertilizers, insecticides, and fungicides as well as to changes in vegetation, and/or soil disturbance (Oliver et al. 2005; Pihlgren et al. 2010; Masoni et al. 2017). Pesticides can directly harm ants but may also have indirect effects by suppressing other arthropods that are either prey or ant-mutualists. Altering the vegetation (e.g., mowing, fertilizing, or tilling the soil) can indirectly influence food availability for ants by affecting plants that are important for prey or mutualist insects, or by modifying the shading provided by plants, which is key to colony development in many species. On the other hand, mechanical soil disturbance can directly damage or destroy nests.

In addition to local vineyard management, environmental conditions, such as climate and landscape composition, are also expected to affect ant communities. In particular, temperature is often among the most important variables explaining ant diversity at local and global scales (e.g., Szewczyk and McCain 2016; Schifani et al. 2024b) by affecting ant metabolism, performance, and development (Parr and Bishop 2022). Concerning landscape composition, most studies find a positive effect of increasing semi-natural areas on arthropod diversity and abundance often because of spillover from semi-natural habitats (e.g., Guo et al. 2022). The few studies investigating the effect of semi-natural areas on ants showed that areas with low levels of forest cover offer limited diversity in habitats, resources, and climatic conditions and, thus, harbor a low number of ant species, although this effect might change depending on the local habitat type (Deák et al. 2021; Costa and Schmidt 2022).

Here, we aimed at (i) testing the effects of agricultural management (organic vs. conventional, inter-row vegetation, pesticide use, tillage intensity) and environmental context (temperature and semi-natural habitat area) on ant abundance and species richness across Italy; and (ii) characterizing the communities of ants across an extensive geographic range, including a spectrum of ecologically diverse vineyards representative of the Mediterranean region, ranging from the southern Alps to Sicily. We expected to find a positive effect of organic management, reduced tillage intensity, higher vegetation cover, warmer temperatures, and higher proportion of surrounding semi-natural areas on ants. Moreover, we expected the community composition to become more dissimilar over geographic distance.

Materials and methods

Study area

Ants were sampled across Italy in vineyards of the following provinces: Bari, Reggio Emilia, Nuoro, Palermo, Padua, Sondrio, and Trento (Fig. 1). Overall, we selected a total of 16 pairs of vineyards in eight areas within the above provinces. Each pair consisted of one vineyard following

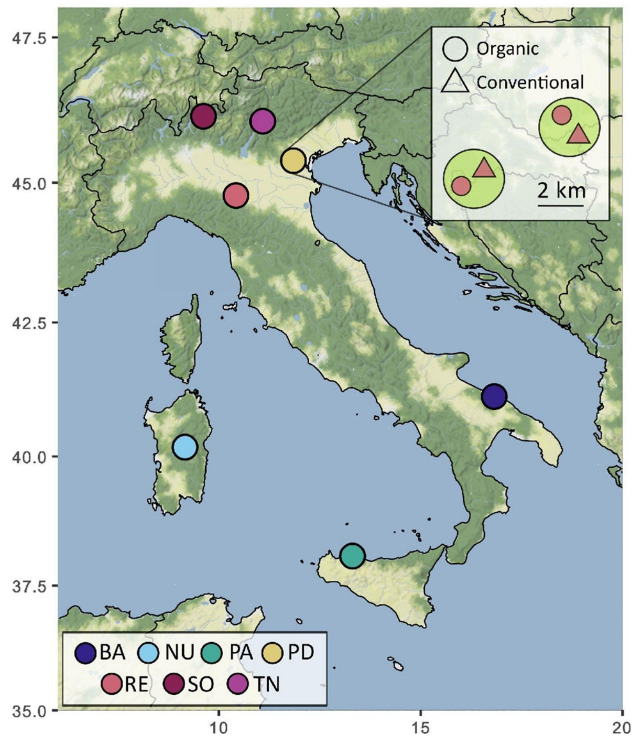

Fig. 1 Sampling sites across Italy, illustrating the approximate location of the corresponding vineyards in the provinces of Bari (BA), Nuoro (NU), Palermo (PA), Padua (PD), Reggio Emilia (RE), Sondrio (SO), and Trento (TN). Eight study areas containing 16 pairs of organic and conventional vineyards were selected in this study, for a total of 32 vineyards. Map from Stadia Maps - stadiamaps.com and Stamen Design (stamen.com), plotted using the R package "ggmap" (Kahle and Wickham 2013)

organic management practices and one under conventional agriculture, for a total of 32 vineyards. Mean distance within each pair was 728±450 m (SD). Organic vineyards were all managed according to current EU organic farming regulations. Therefore, synthetic inputs could not be used. However, the management practices within organic vineyards and within conventional ones varied depending on the environmental and socio-economic conditions (Table S1). Selected vineyards were part of a larger group of vineyards studied by Geppert et al. (2024). We extracted information on the proportion of semi-natural habitat area surrounding each vineyard in a buffer of 1 km (%), on the mean annual temperature (°C), and on pesticide use from Geppert et al. (2024). 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). The list of vineyards, their geographic location, semi-natural area, temperature, and their management characteristics is provided in the Supplementary dataset and the Table S1.

Vegetation and ant sampling

Three pitfall traps were placed per vineyard in three adjacent rows, approximately 2–3 m apart and at least 20 m from the edge of the vineyard (Figure S1). Each pitfall trap consisted of a plastic cup (400 ml capacity) buried flush with the soil surface and protected from rain by a plastic cover. Traps were activated with ≃ 150 ml of 40% ethylene glycol for 2 weeks during three rounds in 2022 (i.e., end of May, June, and July).

Taxonomic identification

Ants were identified under a Zeiss Stemi 508 stereoscopic microscope (ZEISS, Oberkochen, Germany) with an Axiocam Erc 5 s camera and the Zeiss Zen Core Software. Identification was based on Sanetra et al. (1999), Boer (2013), Seifert (2018; 2020), Csősz et al. (2024), Seifert et al. (2024), and Juvé et al. (2025).

Statistical analyses

All statistical analyses were carried out using the software R v4.2.0 and RStudio-2022.02.2–485 (R Core Team 2022). In all analyses, we pooled species abundance across the three rounds.

Influence of management practices on species richness and abundance

We explored the relationships of ant abundance and species richness with vineyard management and with the environment by first fitting two linear mixed-effects models using the lme function from the nlme R package. Management practices (organic vs. conventional), tillage intensity (i.e., annual frequency of inter-row tillage), proportion of surrounding semi-natural area, and mean annual temperature were all treated as fixed factors.The vineyard pair ID nested in the study area ID was set as a random factor to account for the biogeographic grouping of the sites (Pinheiro et al. 2024). Abundance was logarithmically transformed to fit a normal distribution.

Moreover, we separately tested the effects of vegetation cover and pesticide input (Treatment Frequency Index of fungicides, herbicides and insecticides) on ant abundance and species richness by fitting four additional linear mixed models. These were tested separately because the vegetation cover was negatively correlated to temperature (cor = −0.53, p=0.001) and to tillage intensity (cor = −0.5, p=0.001), while pesticide input was negatively correlated to temperature (cor = −0.35, p=0.06). As in the previous models, we used as random factor vineyard pair ID nested in the study area ID and we logarithmically transformed ant abundance in the analysis. The Treatment Frequency Index (TFI) is a commonly used index for calculating pesticide pressure to compare alternative pesticides across different systems (Lechenet et al. 2014; Etienne et al. 2022). The TFI takes into account the number of treatments, the dose applied relative to the recommended reference dose, and the proportion of the treated area.

Residuals of all models were checked to verify model assumptions. In all models, Variance Inflation Factor (VIF) values were close to 1, indicating little collinearity among predictors (Akinwande et al. 2015). Full models included all the two-way interactions between the fixed factors and main effects. Starting from the full model, we used a backward deletion procedure, removing 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, through stepwise model simplification. All main effects were left even if not significant. It should be noted that the fitted models test hypothesis-driven associations rather than independent effects of the different drivers.

Species composition

Non-linear Multidimensional Scaling (NMDS) was used to explore the relationship between ant communities of different sampling sites and different treatment (organic o conventional) using the abundance values of all ant species collected during this study using Bray-Curtis dissimilarity as implemented in the metaMDS function from the vegan R package (Oksanen et al. 2022). The data were automatically square-root transformed and Wisconsin double standardized within the metaMDS function to reduce the influence of highly abundant species. Moreover, to test for the influence of geographic distance on ant assemblages we used Multiple Regression on distance matrices (MRM), using the "ecodist" R package (Goslee and Urban 2007). We calculated Bray–Curtis dissimilarities on the abundance data, and Euclidean distances on coordinates and ran MRM with 999 permutations. To ensure that spatial turnover patterns were not confounded by management, analyses were then repeated separately within each management type, by subsetting the conventional vineyards and then the organic ones. Because these analyses produced results highly consistent with those from the full dataset, only the latter are reported.

Results

We identified a total of 34 ant species belonging to four subfamilies (Dolichoderinae, Formicinae, Myrmicinae, Ponerinae) and 17 genera (Supplementary material): *Aphaenogaster semipolita* (Nylander, 1856), *A. spinosa* Emery, 1878, *Camponotus aethiops* (Latreille, 1798), *C. lateralis* (Olivier, 1792), *C. nylanderi* Emery, 1921, *C. piceus* (Leach, 125), *C. vagus* (Scopoli, 1763), *Cataglyphis italica* (Fabricius, 1787), *Crematogaster scutellaris* (Olivier, 1792), *Formica cinerea* Mayr, 1853, *F. clara* Forel, 1886, *F. cunicularia* Latreille, 1798, *Hypoponera eduardi* (Forel, 1894), *Lasius emarginatus* (Olivier, 1792), *L. myops* Forel, 1894, *L. niger* (Linnaeus, 1758), *L. paralienus* Seifert, 1992, *Messor capitatus* (Latreille, 1798), *M. ibericus* (Latreille, 1798), *Monomorium monomorium* Bolton, 1987, *Myrmica hellenica* Finzi, 1926, *M. sabuleti* Meinert, 1861, *Pheidole pallidula* (Nylander, 1849), *Plagiolepis pygmaea* (Latreille, 1798), *Polyergus rufescens* (Latreille, 1798), *Tapinoma magnum* Mayr, 1861, *T. subboreale* Seifert, 2012, *Temnothorax aveli* (Bondroit, 1918), *T. unifasciatus* (Latreille, 1798), *Tetramorium immigrans* Santschi, 1927, *T. meridionale* Emery, 1870, *T. moravicum* Kratochvíl, 1941, *T. semilaeve* André, 1883, and *Solenopsis fugax* (Latreille, 1798). *Crematogaster scutellaris* was the most widely distributed species, found in six provinces, followed by *M. ibericus*, found in five (Table S1).

Linear mixed-effect models revealed a significant effect of management on ant abundance and richness across the investigated sites (Table 1). As compared to conventional

Table 1 The effects of management (conventional and organic), mean annual temperature, semi-natural area, and tillage intensity on ant abundance and species richness

Response variable	Fixed factor	Estimate	Std.Error	t-value	*p*-value
Abundance	Management (Con)	−0.774	0.238	−3.022	0.011
	Mean temperature °C	0.161	0.140	1.401	0.188
	Semi-natural %	−0.302	1.054	−0.2713	0.791
	Tillage intensity	−0.209	0.099	−2.168	0.05
Species richness	Management (Con)	−1.130	0.550	−2.024	0.06
	Mean temperature °C	−0.280	0.330	−0.850	0.414
	Semi-natural %	0.566	2.3342	0.242	0.813
	Tillage intensity	−0.191	0.206	−0,928	0.373

Abundance was logarithmically transformed

Con Conventional

ones, organic vineyards were characterized by higher abundance (F = 13.27, p = 0.017) and species richness (F = 4.68, p = 0.05) (Fig. 2a, b). Furthermore, tillage intensity had a significant negative effect on the abundance (Table 1; Fig. 2c). Moreover, vegetation cover positively affected both ant abundance and richness (Table 2; Fig. 2e, d). By contrast, pesticide input, the amount of surrounding semi-natural area, and mean annual temperature did not influence ant abundance and speciesrichness (Table 1, S2).

The NMDS had a stress value of 0.132, indicating a good fit to the data. It revealed a strong geographic structure of the ant communities of the investigated vineyards, with the ordination clearly separating the sites of Sardinia, Sicily, and southern Italy (lower scores on the first NMDS axis) from those of northern Italy (higher scores) (Fig. 3). MRM indicated a significant positive relationship between geographic distance and Bray–Curtis dissimilarity of ant communities (R^2 = 0.32, p-value = 0.001).

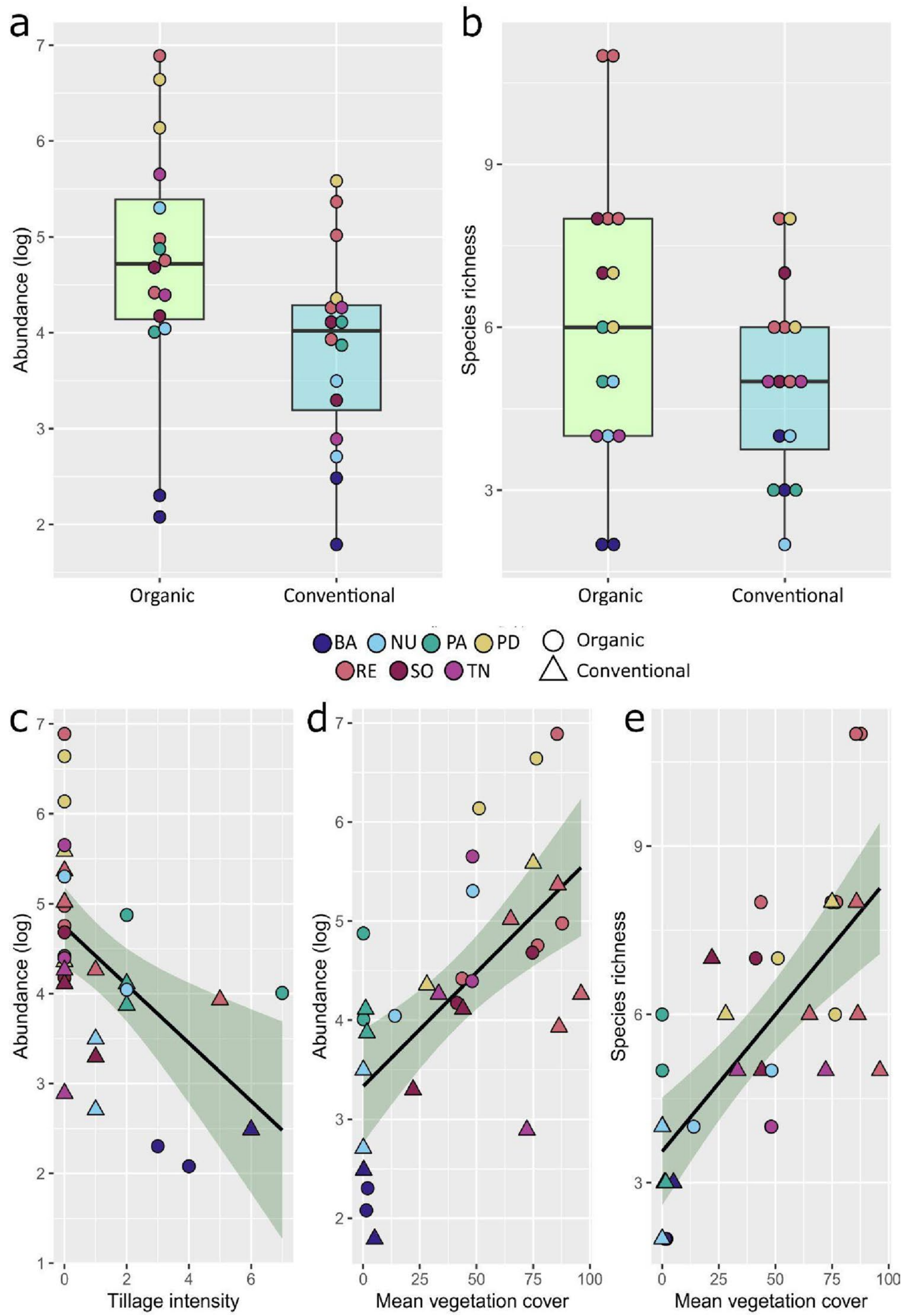

Fig. 2 Effects of organic vs. conventional management on ant abundance (**a**) and species richness (**b**), of tillage intensity on ant abundance (**c**), and of mean vegetation cover on ant abundance (**d**) and on species richness (**e**), as estimated from separate linear mixed models

Table 2 The effects of vegetation cover on ant abundance and species richness

Response variable	Fixed factor	Estimate	Std.Error	t-value	*p*-value
Abundance	Vegetation cover	0.022	0.0065	3.41	0.0039
Species richness	Vegetation cover	0.046	0.0099	4.68	0.0003

Abundance was logarithmically transformed

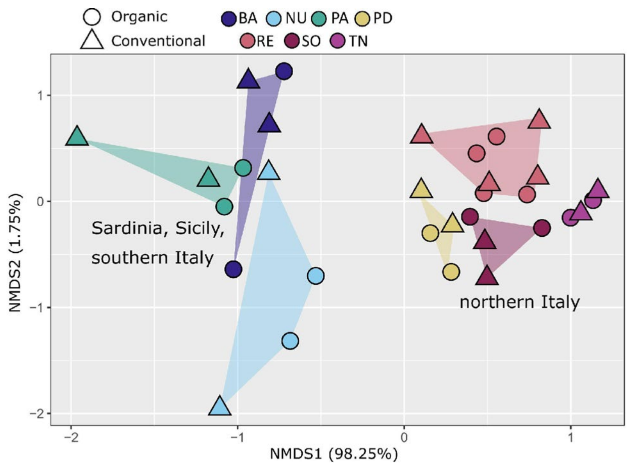

Fig. 3 Non-linear Multidimensional Scaling (NMDS) clustering of ant communities from organic and conventional orchards across Italy

Discussion

In our study, organic management consistently had a positive effect on ants, with organic vineyards supporting higher species richness and individual abundance across various climates and landscapes. Furthermore, lower tillage intensity and higher vegetation cover were associated with a greater abundance of ants, while temperature, semi-natural areas, and pesticide input did not have an effect. Moreover, we found a clear distance decay of similarity, with ant communities across organic and conventional Italian vineyards being significantly different based on biogeography, suggesting broad scale environmental effects on species composition across the same habitat type.

The significant positive effect of organic farming on ant abundance and species richness confirms and extends the pattern previously only observed at a local scale (Masoni et al. 2017). Crops managed under organic farming tend to host more predatory insects and higher species richness, with the ban of all synthetic inputs often regarded as a key factor (Bengtsson et al. 2005; Crowder et al. 2010; Galloway et al. 2021; Zielonka et al. 2024). Our results support this hypothesis, considering organic farming more sustainable than conventional for protecting ants. Still, specific management practices were highly variable within both the organic and the conventional vineyards due to the diversity of ecological conditions across Italy (Geppert et al. 2024). For example, tillage intensity did not differ between organic and conventional vineyards, but it negatively affected ant abundance, while increasing vegetation cover had a positive effect on ant abundance and species richness. This pattern has already been documented in some French vineyards: tillage intensity may directly impact ants by destroying their nests and microhabitats and contributes to the reduction of semi-natural vegetation cover which in turn offers additional microhabitats and a variety of important trophic resources (Blaise et al. 2021; Rocher et al. 2022). Contrary to our expectations, we did not find a significant negative effect of pesticides on ants, as opposed to other studies (Schläppi et al. 2021; Pohl et al. 2024). The lack of effect might be due to contrasting pesticide effects for different ant species or it might be linked to the uneven timing of pesticide applications and its relationship with trap placement or ant activity (Barbieri et al. 2013; Motzke et al. 2013). Given the collinearity among environmental and management variables, one limitation of the current study is that the observed effects do not reflect evidence for fully independent causal effects of the different drivers.

Temperature and semi-natural area did not have a significant role in determining ant abundance and species richness in our study. We expected the temperature to affect ants, because it influences nearly every aspect of ant biology, such as their metabolism, performance, and development (Parr and Bishop 2022). However, different ant species have specialized in a wide range of temperatures, showing, for example, a high degree of thermal preference in their nesting and brood-rearing behaviors (Parr and Bishop 2022). This high degree of thermal specialization is likely linked to the lack of temperature effect on metrics such as abundance and species richness, which do not consider species identity. Moreover, ants respond to warming in complex ways due to the physical characteristics of their nests (i.e., their depth, exposure, and materials modulating their microclimates), their foraging area, and their behavior (Menke et al. 2014; Roeder et al. 2022). Concerning semi-natural areas, the lack of effect on ant abundance and species richness is understandable, since natural areas are likely to host different communities that include more specialized taxa but are not necessarily characterized by more ant species or individuals. In contrast, agricultural areas may be entirely unsuitable for disturbance-sensitive ants, which limits any substantial spillover from natural areas (Bazzato et al. 2022).

A strong biogeographic characterization of the Italian ant fauna is well documented (Schmitt et al. 2021; Wang et al. 2023), but how this is transposed to agricultural settings is a largely unexplored topic (Giannetti et al. 2021; Schifani et al. 2022). Here, we found that spatial distance explained a substantial portion of the compositional variation of ant communities. The strong distance decay of similarity and biogeographic clustering confirms the informative value of ant communities in representing biogeographic and ecological differences in the region (Castracani et al. 2020; Wang et al. 2023). The Po Plain and the Prealps in northern Italy are characterized by a continental climate, while the southern regions of the peninsula, Sardinia, and Sicily are characterized by a Mediterranean climate, and correspond to different bioregions for ants (Wang et al. 2023). Even if organic viticulture emerged as a promising strategy to conserve ant diversity, the species composition changed depending on the biogeographic region, potentially complicating ant conservation and management in the region.

In agricultural habitats, arthropod communities are expected to be dominated by generalist species, which largely applies to our case (Neyret et al. 2024). However, the observed diversity in species pools suggests potential differences in the ecosystem services or disservices ants may provide in vineyards of different regions. Among the species we have found, there are seed-eating ants that may contribute to controlling weeds (*Messor* spp., Baraibar et al. 2011), ground-nesting predators (e.g., *Aphaenogaster* spp., *Lasius* spp., *T. magnum*, Campolo et al. 2015; Martínez-Núñez et al. 2021; Bulgarini et al. 2021; Schifani et al. 2023a, b, 2026), arboreal-nesting predators (e.g., *T. aveli* and *C. scutellaris*, Castracani et al. 2017; Giannetti et al. 2022; Schifani et al. 2023a, b, 2026), and some of the above are also trophobiotic species that may defend mealybug pests from their natural enemies with different degrees of ability (e.g., *Lasius* spp., *T. magnum*, *C. scutellaris*, Mansour et al. 2012; Castracani et al. 2023; Schifani et al. 2023c). Further field investigations are still needed to clarify the ecological roles that these and other ant species play in vineyards.

Recent years have witnessed a greater interest in studies focusing on the effects of organic agriculture or other agroecological practices on arthropod diversity and conservation (e.g., Tuck et a 2014; Kolb et al. 2020; Gayer et al. 2021; Raven & Wagner 2021; Stein-Bachinger et al. 2021; Outhwaite et al. 2022; Rosas-Ramos et al. 2022). Here, we could confirm the positive role of organic management, reduced tillage intensity, and vegetation cover on ant communities in vineyards. Understanding the complexity of insect assemblages in agroecosystems across large spatial and temporal scales, the interactions between different indicator taxonomic groups in response to human activities (e.g., Bazzato et al. 2023), and cascading effects on ecosystem services will be crucial to promoting sustainable management practices.

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Author contributions ES: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. CG: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Writing – original draft, Writing – review & editing. DG, GA, GB, SGC, AC, EC, IF, FL, AL, PLB, DL, SM, LMai, EP, GR, IR, SS, MS, PS, GT: Investigation, Resources, Writing – review & editing. LMar, DAG: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

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Data availability All data produced in this study are available in the Supplementary material.

Declarations

Conflict of interest The authors declare no competing interests.

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