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Limited benefits of organic management and fungicide reduction to ground beetles in vineyards

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Abstract

The use of fungicides in agriculture can reduce animal biodiversity. Such non-target effects could be mitigated through fungus-resistant cultivars that reduce the need for fungicide applications. Hence, we conducted a study in 32 commercial vineyards in southwest Germany. We investigated the effect of fungicide spraying intensities (susceptible vs resistant cultivars) and management (conventional vs organic) on ground beetles as a widely used indicator group in agroecological studies. In addition, we examined the effects of local habitat conditions (e.g., microclimate, vegetation) and landscape characteristics. Fungicide applications were reduced by half in conventional, and almost by two-thirds in organic vineyards with fungus-resistant cultivars, compared to susceptible grape varieties in the same management regime. While there was no evidence that fungus-resistant cultivars positively affect the diversity of ground beetles, organic management doubled the number of individuals of conservation-relevant species per vineyard. Additionally, the proportion of semi-natural habitats in the surrounding landscape, and the vegetation height significantly affected the species composition across vineyards. We conclude that local habitat conditions and landscape characteristics influence ground beetles more than the fungicide spraying intensity. Additional measures such as organic management, moderate ground vegetation management, and landscape diversification are needed for the conservation of ground beetles in viticulture.

KEYWORDS

Carabidae, carabids, fungus-resistant, organic farming, pesticides, sustainable agriculture, viticulture

1 | INTRODUCTION

Agricultural intensification is considered a major cause of global biodiversity decline (Seibold et al., 2019). One of the key drivers is the intensive use of pesticides (Ndakidemi et al., 2016). This becomes particularly evident in monocultures and thus intensively cultivated areas, as is the case with viticulture. While damaging insects or weeds play a strong role in Mediterranean climate (Paredes et al., 2021), fungal diseases are the major target of pesticide use in vineyards of oceanic and cool temperate areas (Geppert et al., 2024; Pertot et al., 2017; Winkler, 1962). Frequently, more than 10 fungicide treatments are necessary per season to protect susceptible grape varieties from the most common fungal infestations of downy mildew (*Plasmopara viticola*) and powdery mildew (*Uncinula necator*) (Reiff et al., 2023).

One remedy could be fungus-resistant varieties. Emerging from the hybridization of the common grapevine (*Vitis vinifera*) with several other *Vitis* species, these cultivars feature a hereditary resistance against fungal diseases (Bavaresco, 2019; Pedneault & Provost, 2016). Therefore, fungicide applications can be reduced by up to 85% in some multiresistant cultivars (Fischer et al., 2004). In addition to economic savings for winegrowers, several studies indicate the promotion of predator abundance and improved conditions for natural pest control (Pennington et al., 2018; Pennington et al., 2019; Reiff et al., 2021, 2023). Nevertheless, consumer demand and cultivation of fungus-resistant cultivars are still limited, and thus also scientific evidence concerning their effect on biodiversity is scarce. In terms of their oenological quality, however, fungus-resistant cultivars are comparable to susceptible cultivars (Kiefer & Szolnoki, 2023; Pedneault & Provost, 2016). Other restrictions, such as the European Protected Designations of Origin, no longer limit the planting of these cultivars (Sillani et al., 2022), which should facilitate their adoption also in southern countries. The paradigm shift towards environmentally friendly agriculture in the past years has led to a rising societal interest in the benefits of fungus-resistant cultivars for biodiversity and more sustainable consumption (Borrello et al., 2021; Vecchio et al., 2022). In addition, policies such as the European Green Deal (European Commission, 2019) focus not only on reducing pesticide use but also on increasing the proportion of organic management and semi-natural habitats (SNH) in agricultural landscapes. Species diversity is likely to benefit from the creation of greater complexity in agricultural systems both at a local and landscape scale (Tscharntke et al., 2012).

Besides the pesticide savings made possible through fungus-resistant cultivars, qualitative countermeasures against biodiversity loss can be taken through environmentally friendly farming practices such as organic management. This is characterized by mechanical weed removal and the prohibition of synthetic fertilizers and pesticides. Thereby, the results of meta-analysis indicate, on average, a 30% higher species richness and a 50% increase in abundance in organic compared to conventional management systems (Bengtsson et al., 2005; Tuck et al., 2013). Despite the overall positive effects of organic management on biodiversity (Hole et al., 2005), some researchers report negative or context-dependent effects on diversity in perennial systems (Beaumelle et al., 2022; Bruggisser et al., 2010; Schirmel et al., 2022). Both synthetic and non-synthetic fungicides exhibit negative effects on non-target organisms (Desneux et al., 2007; Pozzebon et al., 2010), but there is a controversy about some non-synthetic fungicides used in organic management exhibiting stronger negative effects than those in conventional (Bünemann et al., 2006; Milanovic et al., 2013). Commonly used as a fungicide in organic management, copper, in particular, is known to accumulate in the topsoil, significantly influencing soil organisms and thus altering degradation processes (Mackie et al., 2013; Ostandie et al., 2021). Copper has been shown to exhibit adverse effects on plant growth and physiology, especially in perennial systems (e.g., citrus: Schutte et al., 1997; cherry: Holb & Schnabel, 2005; apple: Lesnik et al., 2011; pear: Reil et al., 1974). Contrastingly, Fountain and Medd (2015) reported in their review relatively benign effects of synthetic fungicides on predatory mites in conventionally managed soft fruit crops, although active agents are so diverse that evidence of their effects on non-target organisms is often lacking. However, little is known about fungicide effects on non-target organisms and accumulation in perennial vineyard systems. Since intensive spraying is typically not only reaching the grapevine itself but also non-target areas, life in the herbaceous and ground layer is also exposed to toxicological effects (Kovacic et al., 2013).

Ground beetles (Coleoptera: Carabidae) are important agents for natural pest control, including consumption of weed seeds (Kromp, 1999; Sunderland, 2002). Thus, they often serve as indicator organisms in agroecological studies (Holland, 2002). Organic management is reported to favor ground beetles, through a lack of synthetic pesticides, and mineral fertilizers, beneficial microclimate as a result of more heterogeneous vegetation, and higher food availability (Caprio et al., 2015; Ostandie et al., 2021; Uzman et al., 2020). However, the positive effect of organic management on ground beetle diversity may be dependent on the complexity of the surrounding landscape (Schirmel et al., 2022; Tscharntke et al., 2012; Uzman et al., 2020), for example, through SNH. Especially species richness of predatory ground beetles is favored by the amount of SNH around agricultural fields with beneficial effects on natural pest control (Fusser et al., 2017, 2018). However, since heavy metals also accumulate in ground beetles (Butovsky, 2011), the reduction of non-synthetic pesticides might prove beneficial for the number of individuals as well as diversity beyond organic management practices and the surrounding landscape.

We conducted a field study to assess differences in ground beetle communities in vineyards with either susceptible or fungus-resistant grape varieties ($N_{sites} = 32$). The vineyards under investigation featured different spraying intensities, with susceptible cultivars receiving more fungicide treatments than fungus-resistant ones. Additionally, half of the sites were subject to organic and conventional management respectively. We aim to answer the following research questions: (i) Are species diversity, total number of individuals, and the number of individuals of conservation-relevant ground beetles higher in vineyards with fungus-resistant compared to fields with susceptible grape varieties? (ii) Does organic management have a positive influence on diversity, the total number of individuals and conservation-relevant ground beetles compared to conventional management? And if so, is the positive effect of organic management enhanced when the fungicide spraying intensity is reduced? (iii) Does the species composition of ground beetles vary in dependence on management and cultivar type? What proportion of the variance is explained by landscape and local parameters? (iv) Finally, does a high proportion of SNH in the surrounding landscape have a positive effect on ground beetle diversity?

2 | MATERIALS AND METHODS

2.1 | Study sites

The study was conducted between April and October 2022 in Rhineland-Palatinate, southwest Germany. In total, 32 vineyards were selected which are located in the second-largest wine-growing region of Germany ('Pfalz': cultivation area of 23,721 ha, Deutsches Weininstitut, 2022; Supporting Information, Table S1). The area is characterized by a mean annual temperature of 11.4°C and an average annual precipitation of 730.5 mm (station Landau-Nussdorf, Agrarmeteorologie Rheinland-Pfalz, 2022). Vineyards were provided by 14 commercial winegrowers. Six of the winegrowers cultivate their vineyards under conventional and the other eight under organic management standards (European Union, 2018), including the corresponding regulations for the spraying regimes. Thereby, organic farmers used varying formulations of copper, sulfur, and potassium bicarbonate, while conventional farmers sprayed mainly synthetic fungicides. Each winegrower provided at least two vineyards: one with a susceptible and another with a fungus-resistant cultivar. Hence, they differed in terms of their fungicide spraying intensity but were similar in other management practices and were thus grouped into pairs for statistical analysis (Supporting Information, Figure S1). The vineyards were selected based on their geographical location and planting history to keep the design as homogenous as possible and reduce the impact of other environmental variables.

2.2 | Sampling of ground beetles

Ground beetles were captured using pitfall traps ($N_{traps} = 512$). The setup consisted of four plastic cups with an opening diameter of 68 mm and a depth of 98 mm that were deployed at ground level in the most central row of each vineyard. Starting at 10 m into the field interior to minimize external influences from adjacent fields, traps were placed alternately in the inter-row and underneath the grapevine with 5 m to one another (i.e., placement at 10, 15, 20, and 25 m from the vineyard edge). The cups were filled with equal amounts of propylene glycol and water, with some rinsing agent as a trapping liquid. Sampling was carried out at four different time points during the vegetation period (April 21–22, June 20–21, July 25–26, and October 10–11).

Pitfall traps remained in the soil for 1 week each before the collected samples were brought to the laboratory preserved in 80% ethanol. Using a stereomicroscope (Leica Microsystems, Wetzlar, Germany), individuals were identified to the species level according to Müller-Motzfeld (2004). The conservation relevance of species was classified using the Red List of ground beetles for Germany (Schmidt et al., 2016). Species from the categories 1 ("Vom Aussterben bedroht", corresponding to the IUCN category "Critically Endangered"), 2 ("Stark gefährdet", corresponding to the IUCN category "Endangered"), 3 ("Gefährdet", corresponding to the IUCN category "Vulnerable"), V ("Vorwarnliste", roughly corresponding to the IUCN category "Near Threatened"), and R ("Extrem selten", meaning "Extremely Rare", without correspondence in the IUCN system) were considered conservation-relevant. For each site, the number of individuals of conservation-relevant species were summed up.

2.3 | Local habitat conditions and landscape characteristics

Vegetation structure was characterized within plots of 50 × 200 cm around the position of each pitfall trap. Vegetation height (cm) was measured using a drop disc (diameter = 230 mm, 80 g) at three different spots within the plots the week before each sampling period (Bransby & Tainton, 1977). During the first two samplings (April and June), one data logger (HOBO pendant UA-002-08, Onset, USA) was deployed underneath the grapevine and the inter-row respectively to measure temperature (°C) at the ground ($N = 14$ sampling days). All measures were averaged to obtain one mean value per vineyard. Vineyard characteristics, such as the duration since planting the current grapevine plants (i.e., grapevine age) and the number of pesticide applications, were provided by the winegrowers. Using QGIS v3.30.2 (QGIS Development Team, 2023) and the Google Satellite layer (©2022 GeoBasis-DE/BKG (©2009), Google; available under the Open Database License CC BY-2.0), we calculated the proportion of SNH (%) within a radius of 500 m from the center of the four pitfall traps (i.e., 17.5 m from the vineyard edge). We defined SNH as forests, hedges, shrubs, and grassland.

2.4 | Data analysis

Statistical analysis was conducted in R v4.1.1 (R Core Team, 2021). Therefore, captures of the four traps per site and the four sampling time points were aggregated to obtain one value per vineyard in the data set. The number of fungicide applications depicted a high correlation with susceptible and fungus-resistant grape varieties ($r = 0.87$, Supporting Information, Figure S2). To avoid multicollinearity, only the cultivar variable was used for further analysis. During the whole analysis, p-values <.05 were considered statistically significant.

The R package lme4 v1.1-35.1 (function glmer, Bates et al., 2015) was used to fit multiple generalized linear mixed models (GLMMs). To see whether vineyards with different management and spraying intensity differ in landscape and local habitat conditions, their effects on all environmental variables were tested using GLMMs. The vineyard pairs were included as a random effect. A Gaussian distribution was assumed for models with continuous outcome variables (SNH, temperature, and vegetation height) and a negative binomial distribution for grapevine age as overdispersed count. Age differences between vineyards with varying management or cultivar types were checked to see whether higher numbers of individuals could be attributed to longer colonization periods. The number of fungicide applications showed signs of underdispersion and its model was thus refitted using Conway–Maxwell–Poisson distribution (R package glmmTMB v1.1.8, function glmmTMB).

The dependent variables, total number of individuals, number of individuals of conservation-relevant species, species richness, and Simpson index (Hill, 1973), were regressed on the proportion of SNH, temperature, vegetation height, management (conventional vs organic), and the cultivar type (susceptible vs resistant) as well as the interaction of the latter two. To account for geographic proximity and maintenance by the same winegrower, the vineyard pairs were included as a random effect. Because nine out of 512 traps got destroyed during the field study, the logarithm of sampling days from active traps was included as an offset variable in the models to account for different sampling intensities. Since overdispersion was detected, a negative binomial distribution was used for the total number of individuals, and the number of individuals of conservation-relevant species (function glmer.nb). A Poisson GLMM was applied for species richness as equidispersed count variable, while a Gaussian distribution was chosen for the Simpson index. Statistical significance of the explanatory variables was calculated using type-II analysis-of-variance-tables based on Wald Chi^2 tests (R package car, Fox & Weisberg, 2019).

In addition, distance-based redundancy analysis (dbRDA) was performed using the R package vegan (function capscale, Oksanen et al., 2020) to assess similarities between vineyards regarding their species composition. The analysis was computed with a standardized number of individuals (individuals/sampling days) to account for different sampling intensities and a Hellinger transformation (function decostand) to give lower weights to rare species. The full model was constituted using the interaction term of management and cultivar as well as the proportion of SNH, temperature, vegetation height, and grapevine age. The vineyard pairs were included as a conditional effect. Statistical significance of the whole model, axes, and included terms was tested with the function anova.cca. Only environmental variables with $p < .05$ were included in the ordination plot.

3 | RESULTS

A total of 1769 individuals from 55 different species were caught (Supporting Information, Table S2). The most frequent species were *Nebria salina* (240), *Harpalus rufipes* (173), *Amara aenea* (171), *Harpalus affinis* (154), and *Nebria brevicollis* (145). In conventional vineyards, 724 individuals were captured belonging to 42 species. Vineyards with susceptible cultivars featured very similar individual numbers (358) and species (33) like fields with fungus-resistant cultivars (366/35). In contrast, 1045 individuals from 46 species were captured in organic vineyards. Here, more species were found in vineyards with susceptible cultivars (41) than in vineyards with fungus-resistant ones (34), but very similar number of individuals (529 in susceptible and 516 in fungus-resistant cultivars). Overall, 55 individuals from 10 conservation-relevant species were found, of which *Brachinus explodens* (category V, corresponding to "Near Threatened")

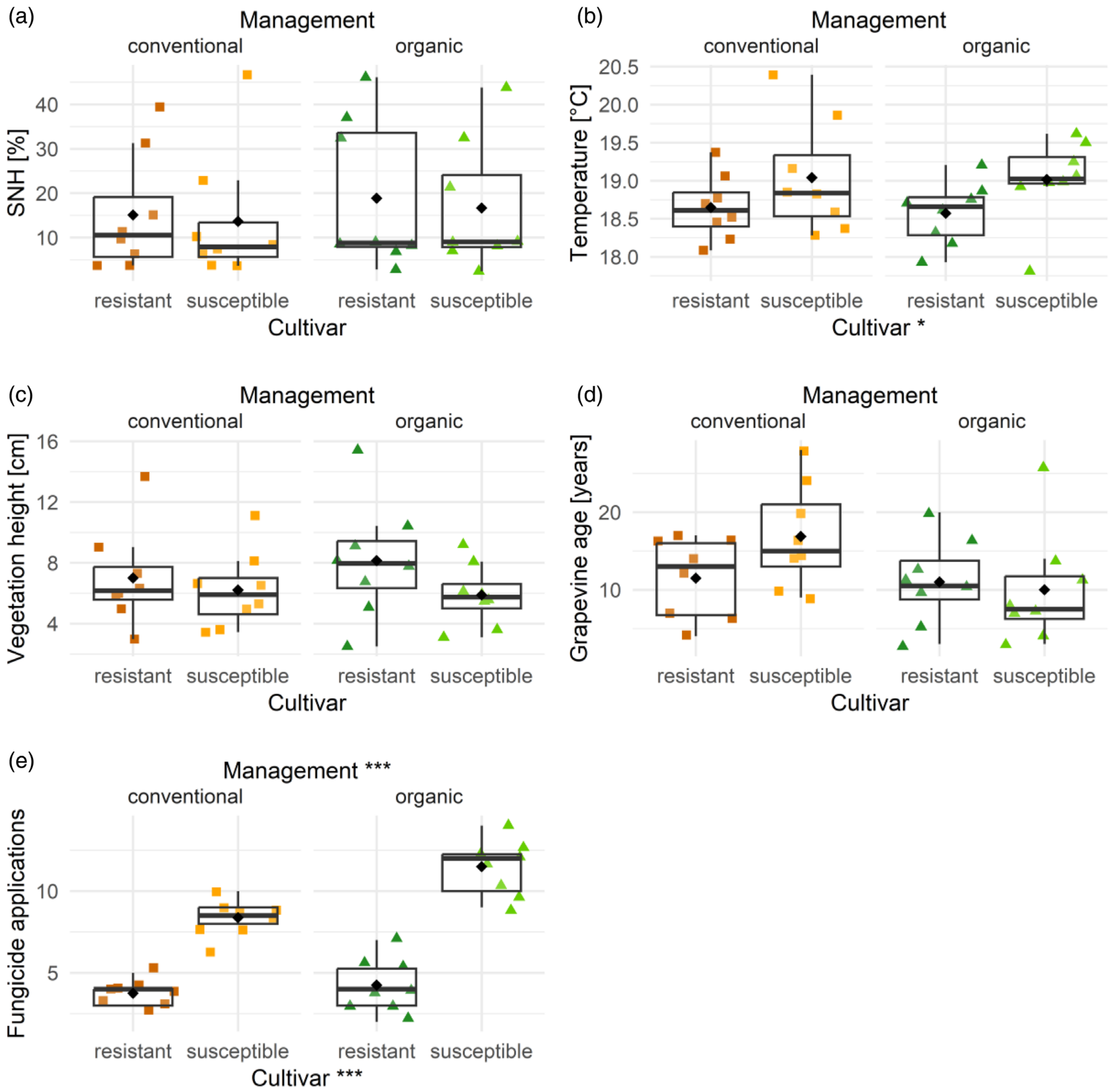

FIGURE 1 Effects of management (conventional vs organic) and cultivar type (resistant vs susceptible) on (a) proportion of semi-natural habitats (SNH), (b) temperature, (c) vegetation height, (d) grapevine age, and (e) fungicide applications. In addition to the boxplot characteristics, diamonds visualize mean values, and asterisks indicate significance levels (*$p < .05$, ***$p < .001$).

was the most abundant species (Supporting Information, Table S2).

3.1 | Local habitat conditions and landscape characteristics

The proportion of SNH in the surrounding landscape was on average 16.1% ± 14.3% and did not significantly differ among of the vineyard types under investigation (Figure 1a). Concerning the local microclimate, vineyards with susceptible cultivars had slightly but significantly higher mean ground temperatures (19.0 ± 0.6°C) than fungus-resistant cultivars (18.6 ± 0.4°C; Figure 1b). Vegetation height was on average 16% higher in vineyards with fungus-resistant than in fields with susceptible cultivars (Figure 1c), although this difference was not significant on the 0.05 level. With an average grapevine age of 13.4 ± 7.7 years, vineyards with susceptible cultivars were not significantly older than resistant cultivars with an average age of 11.3 ± 5.1 years (Figure 1d). The number of fungicide spraying events differed significantly between the management and the cultivar types, respectively (Figure 1e). Susceptible cultivars in conventionally managed vineyards received on average 8.4 fungicide sprayings, while fungus-resistant ones received 3.8 applications. In organically managed vineyards, susceptible cultivars were also sprayed more often (11.5 applications) than fungus-resistant cultivars (4.3 applications). A summary of the results is available in Table 1.

3.2 | Ground beetle diversity and number of individuals

Neither the environmental variables nor the management, cultivar type, and interaction of both predictors significantly affected the total number of ground beetle individuals, which was on average 56.5 individuals (Table 2 and Figure 2a). Management had a significant effect on the number of individuals of conservation-relevant species (Table 2) with organic vineyards

TABLE 1 Effects of management, cultivar, and their interaction on the proportion of semi-natural habitats (SNH) in the surrounding landscape, temperature, vegetation height, grapevine age, and the number of fungicide applications.

	Management				Cultivar				Management × cultivar				Variance of random term
	Est.	SE	Chi^2	*p*	Est.	SE	Chi^2	*p*	Est.	SE	Chi^2	*p*	
SNH	0.04	0.07	0.216	.642	−0.01	0.02	1.901	.168	−0.01	0.03	0.090	.764	0.021
Temperature	−0.08	0.27	0.072	.788	0.39	0.27	4.697	**.030**	0.05	0.39	0.019	.890	0.001
Vegetation height	1.14	1.49	0.110	.740	−0.80	1.21	3.224	.073	−1.46	1.71	0.733	.392	3.041
Grapevine age	−0.07	0.25	2.421	.120	0.39	0.19	1.251	.263	−0.50	0.28	3.331	.068	0.096
Fungicide applications	0.13	0.13	13.904	**<.001**	0.80	0.11	150.723	**<.001**	0.19	0.15	1.661	.197	0.002

Note: The variance of the random term accounts for the grouping into pairs. Significant *p*-values are displayed in bold. Eight study sites were investigated for each combination of management and cultivar type ($N_{sites} = 32$).

TABLE 2 Effects of management, cultivar, and their interaction as well as environmental variables (semi-natural habitats (SNH), temperature, and vegetation height) on the number of individuals, the number of individuals of conservation-relevant species, species richness, and Simpson index.

	Management				Cultivar				Management × cultivar			
	Est.	SE	Chi^2	*p*	Est.	SE	Chi^2	*p*	Est.	SE	Chi^2	*p*
Number of individuals	0.21	0.27	1.949	.163	−0.03	0.25	0.085	.770	0.17	0.34	0.257	.612
Number of individuals of conservation-relevant species	0.76	0.50	3.851	**.049**	0.22	0.50	0.431	.512	−0.03	0.60	0.002	.965
Species richness	0.06	0.14	1.883	.170	−0.14	0.15	0.500	.479	0.18	0.20	1.154	.283
Simpson index	0.01	0.05	1.969	.161	−0.06	0.05	0.548	.459	0.05	0.07	0.141	.707

	SNH				Temperature				Vegetation height				Variance of random term
	Est.	SE	Chi^2	*p*	Est.	SE	Chi^2	*p*	Est.	SE	Chi^2	*p*	
Number of individuals	1.10	0.77	2.064	.151	−0.03	0.20	0.017	.897	−0.01	0.04	0.151	.697	0.065
Number of individuals of conservation-relevant species	0.85	1.33	0.410	.522	−0.60	0.33	3.261	.071	−0.05	0.07	0.557	.456	0.210
Species richness	−0.07	0.35	0.008	.931	−0.08	0.10	0.478	.489	−0.01	0.02	0.027	.870	0
Simpson index	0.02	0.13	0.041	.839	0.00	0.04	2.106	.147	−0.00	0.01	0.011	.917	<0.001

Note: The variance of the random term accounts for the grouping into pairs. Significant *p*-values are displayed in bold. Eight study sites were investigated for each combination of management and cultivar type ($N_{sites} = 32$).

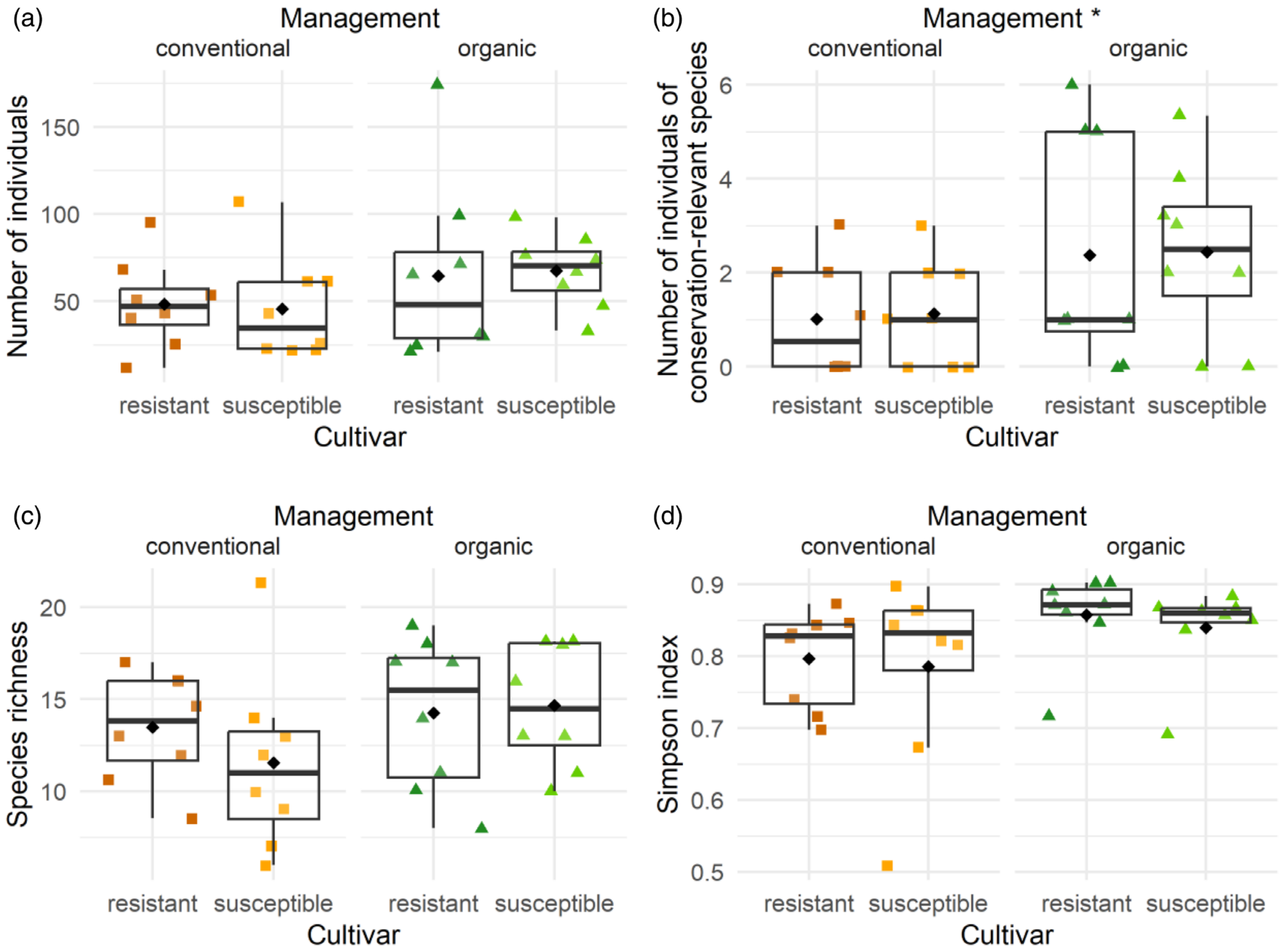

FIGURE 2 Effects of management (conventional vs organic) and cultivar type (resistant vs susceptible) on (a) the number of individuals, (b) the number of individuals of conservation-relevant species, (c) species richness, and (d) Simpson index. Count values were adjusted to account for different sampling intensities by multiplying them by the number of potential sampling days and dividing the term by the actual sampling days of active traps. In addition to the boxplot characteristics, diamonds visualize mean values and asterisks indicate significance levels (*$p < .05$).

featuring on average more than twice the number of conservation-relevant individuals than conventional fields (Figure 2b). Although organic vineyards with susceptible cultivars hosted more species (41) than other vineyards (33–35 species; Supporting Information, Table S2), none of the predictors had a significant effect on species richness (Table 2 and Figure 2c). With an average Simpson index above 0.75, all treatments were at the upper end of the biodiversity index (Figure 2d). However, the environmental variables, management, cultivar type, and the interaction of the latter two did not have a significant effect on the observed biodiversity (Table 2). The vineyard pairing as a random factor captured up to 21% of the variance in the species measures, respectively.

3.3 | Species composition

There was no distinct grouping of ground beetle assemblages according to management or cultivar (Figure 3a). This is consistent with the formal results of dbRDA, where neither management nor cultivar had a significant effect on the species composition (Table 3). An assignment of typical ground beetle species to one of those conditions is thus not possible. Nevertheless, ground beetle assemblages of conventional vineyards tended to have higher values on the first axis than those of organic vineyards (Figure 3b). Under conventional management, ground beetle assemblages were similar between susceptible and resistant grapes, as can be seen by the group centroids in Figure 3b. In comparison, ground beetle

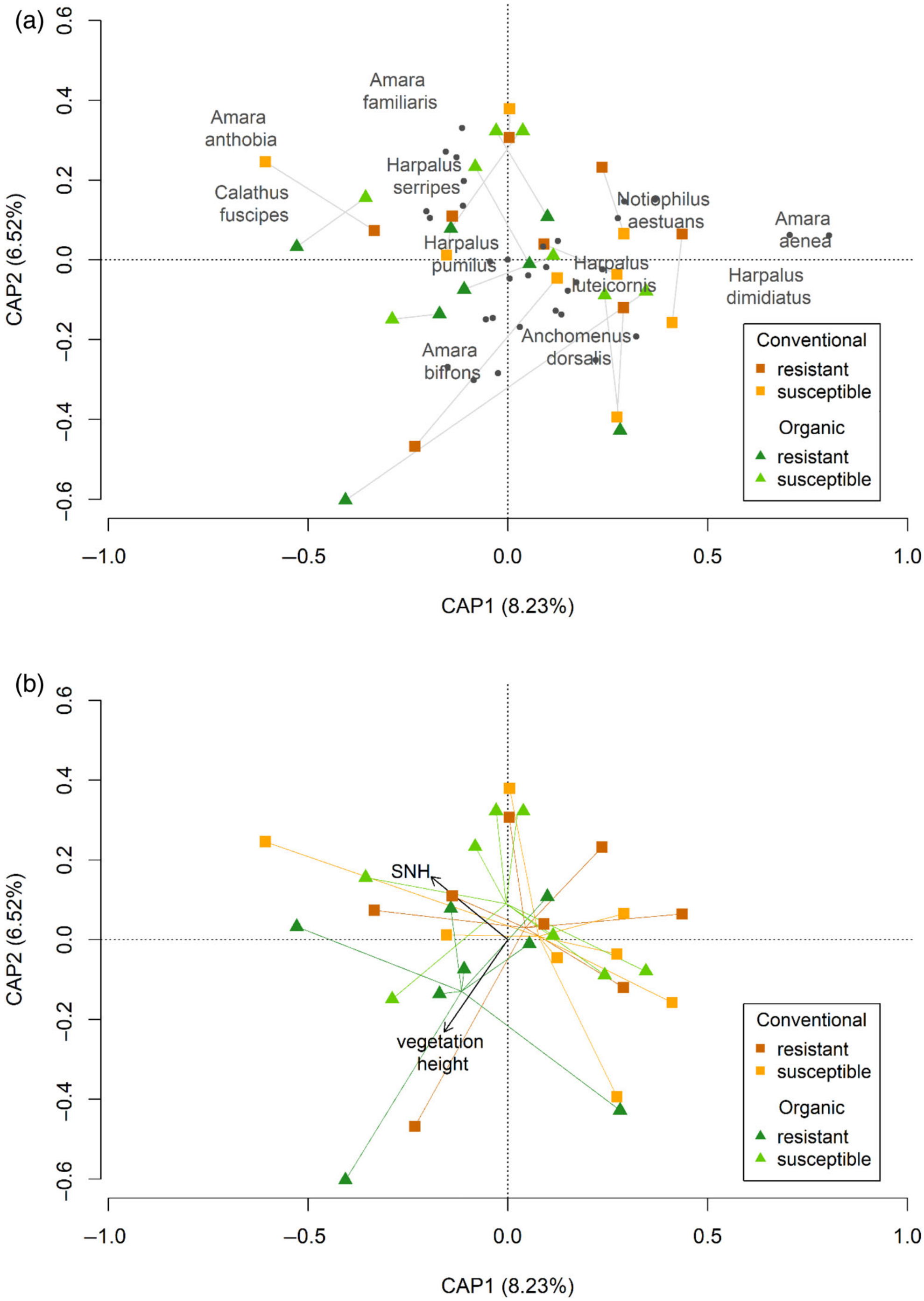

FIGURE 3 Biplots based on distance-based redundancy analysis (dbRDA) of ground beetle assemblage in the studied vineyards. Squares visualize conventional and triangles organic management, while lighter colors reflect susceptible and darker colors fungus-resistant cultivars. The first axis CAP1 explains 8.23% and the second axis CAP2 6.52% of the variance in the community composition. To aid visualization, sites are displayed with (a) species and (b) environmental variables in separate graphs. In (a), the most common taxa are shown with their species name, and less abundant ones are included with a dot to avoid graphical overlap. Gray lines indicate the grouping into vineyard pairs. Spider clusters in (b) connect sites characterized by the same management and cultivar. Here, only environmental variables with $*p < .05$ are displayed in the ordination plot.

assemblages under organic management tended to deviate between susceptible and resistant varieties. This partial separation was mostly driven by the significant effect of the vegetation height on species composition. In addition, the proportion of SNH in the surrounding landscape affected ground beetle assemblages (Table 3). Axis one significantly represents 8.23%, whereas non-significant axis two captures 6.52% of the variance in the community composition across vineyards (Table 3). In contrast, the statistically significant full model captured 23.51% and the vineyard pairs as a conditional term 8.57% of the variance in the community composition across vineyards. Consequently, 67.92% of the variance remained unexplained.

4 | DISCUSSION

In this study, we investigated the effect of reduced fungicide applications on ground beetles in conventional and organic management regimes. There was no evidence that fungus-resistant grape varieties affect diversity or the

TABLE 3 Pseudo-*F* and *p*-values of the terms (management, cultivar, management × cultivar, semi-natural habitats (SNH), temperature, vegetation height), whole model, and axes concerning distance-based redundancy analysis with the vineyard pairing as a conditional term.

	Pseudo-*F*	***p***
Management	1.495	.062
Cultivar	0.724	.828
Management × cultivar	0.801	.718
SNH	2.279	**.002**
Temperature	0.880	.645
Vegetation height	2.129	**.004**
Whole model	1.385	**.004**
Axis 1	2.659	**.046**
Axis 2	2.107	.173

total number of individuals. In contrast, organically managed vineyards significantly affected the number of individuals of conservation-relevant species, which was two times higher in organic than in conventional vineyards. The number of conservation-relevant ground beetles was low compared to the overall ground beetle abundance, which could be expected given the high management intensity of the studied vineyard landscape. Nevertheless, more conservation-relevant individuals and species were found in organic vineyards, such as *Amara lucida* and *Brachinus explodens*. Even though vineyard characteristics such as the proportion of SNH, and vegetation height drove differences in the community composition across vineyards, almost 68% of the variance remained unexplained.

Concerning the effect of reduced fungicide applications, this study does not indicate differences between fields with fungus-resistant and susceptible cultivars concerning ground beetles. While fungicide reductions are reported to favor predator abundance in the grapevine canopy (Pennington et al., 2018, 2019; Reiff et al., 2021), these effects do not seem to translate to the ground beetles in the herbaceous and ground layer. Due to their high mobility (Luff, 1987; Thomas et al., 2002), ground beetles may benefit to a smaller extent from the fungicide reductions in the studied vineyards than less mobile species. Similarly, Kaczmarek, Entling, and Hoffmann (2023) found no effects of fungicide reduction, but positive effects of SNH on highly mobile orders of flying insects. However, based on the sometimes lethal effects of fungicides on ground beetles (Bayley et al., 1995; Giglio et al., 2017), we had nevertheless expected that reductions in the spraying intensity would benefit individual numbers of ground beetles and their potential prey, such as earthworms (Duque et al., 2023), as it has recently been found for grasshoppers in organic viticulture (Kaczmarek, Gillich, et al., 2023). On the other hand, fewer spraying events also mean a lower disturbance regime through reduced traffic in vineyards with fungus-resistant cultivars (Bruggisser et al., 2010). Therefore, the vegetation community is less disturbed (Bruggisser et al., 2010), which is in line with significantly lower ground temperatures and the trend ($p < .1$) toward higher vegetation in fields with fungus-resistant cultivars. This, in turn, might indirectly affect ground beetles negatively, since they often select vineyard habitats due to their preference for xero-thermophilic microclimates (Holland, 2002). However, vegetation structure seems to influence the number of individuals and community composition more than the fungicide spraying intensity per se. Future research should thus concentrate on fungicide-induced changes in local habitat conditions and bottom–up effects on vineyard communities. In addition, it is possible that the relatively dense ground vegetation in our study region partly protected ground beetles from fungicide sprays. Therefore, the benefits of pesticide reduction are expected in vineyards with bare ground, which are common in Mediterranean climates.

Organic management had a significant positive effect on the number of individuals of conservation-relevant species compared to conventional vineyards. Contrary to our expectations, the effect of management on species-related measures did not increase when the fungicide spraying was reduced. Nevertheless, even within management types, there are large differences in management practices related to, among other things, weed control, different types of pesticides, and planting of inter-row vegetation (Ostandie et al., 2021). This may limit the generalizability of the results. Although synthetic fungicides on their own seem to be relatively harmless for non-target organisms, interactions between their active agents could still be problematic, and these are barely considered in legislation and scientific research to date (Fountain & Medd, 2015; Niedobova et al., 2016). Hence, the absence of synthetic pesticides and especially their interactions might enhance ground beetle diversity. Even though scientific evidence about the beneficial effects of organic viticulture on biodiversity is conflicting, most researchers who found positive effects attribute them to fostering vegetation structures through alternate inter-row vegetation and the absence of herbicides (see Döring et al., 2019). Plant diversity is associated with several ecosystem services such as promoting colonization by natural predators and conservation of endangered species (Nicholls et al., 2000; Paiola et al., 2020). In line with other publications (e.g., Liu et al., 2016; Rouabah et al., 2015), the effect of vegetation height on community composition confirms that vegetation is an important parameter for ground beetle diversity. Especially conservation-relevant ground beetles could benefit from vegetation management as practiced in organic viticulture.

The ordination revealed a tendency for ground beetle assemblages from resistant cultivars to differ from susceptible cultivars in organically managed vineyards, which appeared to be driven by the vegetation height. Besides microclimate and vegetation structure, the vineyard properties (e.g., altitude, planting history) and landscape characteristics are important determinants in shaping the community composition (Schirmel et al., 2022; Uzman et al., 2020). First, all vineyards studied are located no more than 9 km apart, are therefore very similar in topography, and were selected based on their planting history. Thus, we do not expect that site properties were a main driver in shaping the community composition in this study. Second, we included the proportion of SNH in the models to account for landscape effects and the vineyard pairing as random effect to account for geographical proximity. Contrary to other findings that complex landscapes have a positive effect on biodiversity in vineyards (Schirmel et al., 2022; Uzman et al., 2020), the proportion of SNH had no significant effect on any of the diversity measures in this study but shaped the community composition. Although vineyard pairing did not capture much variance in any of the GLMMs with species-related explanatory variables, it explained more than 8% of the variance in the species composition. Hence, landscape and geographical proximity had a greater impact on the species composition than on the numbers of individuals or species.

We conclude that organic management and reduced fungicide applications have limited benefits to ground beetles in our studied vineyards. However, effects may still occur in other regions where, for example, the soil is more open and direct exposure is higher. The deployment of fungus-resistant cultivars and hence the reduction of fungicides could also be important for less mobile organisms and more pesticide-exposed species in the grapevine canopy (Pennington et al., 2018, 2019; Reiff et al., 2021). In addition, climate change is predicted to cause more severe infections and more infection cycles of fungal diseases in agricultural systems (Bove et al., 2020; Salinari et al., 2006). The need for fungicide applications could therefore increase in the coming years. Multi-year studies are needed to assess how climatic fluctuations and thus the amount of fungicides needed to keep fungal infestations at bay influence the biodiversity of ground life in the long run. Hence, the cultivation of fungus-resistant grape varieties may become a necessity to maintain biodiversity without compromising economic viability in the future.

AUTHOR CONTRIBUTIONS

M. H. E., S. K., J. M. R., and K. R. conceived the ideas and designed methodology. J. T. G., S. K., and M. H. collected the samples. J. T. G. and J. S. identified species. J. T. G. analyzed the data. J. T. G. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interests.

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DATA AVAILABILITY STATEMENT

The raw data and R scripts are available upon request to the authors. Materials are stored at the RPTU Kaiserslautern-Landau.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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