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Arthropods on grapes benefit more from fungicide reduction than from organic farming

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Abstract

BACKGROUND: Pesticides are considered main contributors to global arthropod declines and therefore may decrease the provision of ecosystem services such as natural pest control. Organic farming and cultivating pest- and disease-resistant varieties can allow pesticide applications and their impacts on nontarget organisms and the environment to be reduced. We investigated the effects of organic *versus* conventional management and fungus-resistant *versus* susceptible wine grape varieties on arthropod biodiversity and pest control of grape berry moths in 32 vineyards in the Palatinate region, Germany. Hazard quotients of applied pesticides were calculated for each vineyard.

RESULTS: The cultivation of fungus-resistant varieties led to significantly reduced hazard quotients and in turn enhanced abundances of natural enemies, particularly theridiid and philodromid spiders. Unexpectedly, organic management resulted in higher hazard quotients than conventional management and reduced numbers of natural enemies, particularly earwigs. Pest predation rates showed no significant differences between grape varieties or management types.

CONCLUSION: Widespread benefits of organic management on arthropod biodiversity found in other crops were absent in our viticultural study region. This is likely due to the dominant role of fungal diseases in viticulture, which requires high numbers of fungicide treatments under both conventional and organic viticulture. Thus, fungicide reduction through the cultivation of fungus-resistant grape varieties is one key element to fostering the abundance of arthropods in general and beneficial arthropods in particular. Beyond vineyards, this is potentially relevant in numerous other crop types.

Supporting information may be found in the online version of this article.

Keywords: pesticide toxicity; fungus-resistant grape varieties; natural pest control; *Lobesia botrana*; spiders; *Forficula auricularia*

1 INTRODUCTION

Agricultural intensification counts as one of the main drivers of global declines in arthropods,[1–3] reducing food availability to subsequent trophic levels such as birds[4] and further decreasing the provision of ecosystem services, notably natural pest control.[5,6] Organic farming can enhance the abundance and richness of natural enemies of pest species and, consequently, their effectiveness in pest control.[7,8] However, biodiversity impacts may depend on the specific differences between organic and conventional farming, which can vary across crops and growing regions. For example, organic vineyards tend to have higher ground cover than conventional vineyards in the Mediterranean but not in the Temperate regions.[9–12] Furthermore, pest pressure varies between regions. Areas with higher humidity during summer have stronger pressure of fungal diseases, while different insect pests prevail depending on their geographic distribution.[13–15] The benefits of organic viticulture on biodiversity and natural pest control may thus be absent or even reversed depending on the study region.

Negative effects of synthetic pesticides are expected to prevail in conventional vineyards where insecticide applications are widespread[16,17] or where regulations on fungicide specificity are lax. Organic viticulture can have positive effects on biodiversity and arthropod abundance.[18–21] In particular, the abundance of predatory arthropods such as spiders, ants and coccinellid beetles has been enhanced by organic viticulture.[16,18,22–24] However, the degree to which arthropods benefit from differences in ground cover management, fertilization, or plant protection in organic viticulture is poorly known. When organic vineyards receive less pesticide input than conventional vineyards, organic management is likely to show positive effects on arthropod biodiversity and abundance.[18,19,25] Conversely, pesticide applications can be more frequent in organic than in conventional vineyards in some

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regions with high disease pressure.[9] Furthermore, fungicides such as copper and sulphur which are applied in organic viticulture can also have detrimental effects on beneficial arthropods.[26–28] In addition, plant protection products are rapidly changing and pesticide regulations in many countries are imposing increasingly strict requirements on environmental safety.[29–32] Considering all these factors, the effects of conventional *versus* organic management on biodiversity and ecosystem service provisioning are expected to vary with time and region.

Regardless of these variations, in both organic and conventional viticulture grapes are highly susceptible to several fungal diseases and thus are strongly depending on fungicide applications, which account for 70–100% of all pesticide input.[33] Thus, a vast potential to reduce pesticide inputs can be achieved by the cultivation of fungus-resistant grape varieties.[34] Field experiments suggest strong benefits of reduced plant protection in fungus-resistant varieties on arthropod biodiversity and natural pest control.[35,36] Herein, for the first time, we investigated whether organic farming and fungus-resistant grape cultivars affect the hazard quotient of plant protection regimes, the abundance of a wide range of arthropods, and their pest control potential in viticulture.

One of the major grapevine pests in Europe and beyond is *Lobesia botrana* (Denis & Shiffermüller) (Lepidoptera: Tortricidae). Predatory arthropods like Dermaptera, Hemiptera, Neuroptera, Diptera, and Coleoptera, as well as ants and several families of spiders and mites predate on *L. botrana*.[35,37,38] Furthermore, numerous parasitic hymenopterans attack different stages of *L. botrana*.[39–41] Several of these natural enemies are susceptible to fungicides like sulphur, which is applied mainly in organic viticulture, as well as to synthetic fungicides in conventional vineyards.[17,27,42,43] Consequently, Muneret *et al.*[44] found increased tortricid egg predation with decreasing pesticide use in French vineyards. This indicates a high potential by which fungus-resistant varieties facilitate the natural control of *L. botrana* using its natural enemies.

In this study, we focused on the biodiversity of the grape canopy in particular, as this is the stratum of the vineyard where natural control of grape pests occurs and exposure to pesticides is highest. Here, we hypothesize that reduced pesticide use in fungus-resistant grape varieties leads to a higher abundance of beneficial arthropods and consequently higher pest control. Our second hypothesis was that the hazard quotient (toxicity of applied pesticides), arthropod biodiversity, and pest control potential differ between organic and conventional vineyards. Third, we expect that the effects of reduced pesticide use in fungus-resistant varieties might differ between organic and conventional management.

2 MATERIALS AND METHODS

2.1 Study sites

We investigated 32 vineyards with contrasting spraying regimes in a 10-km radius around Landau in the Palatinate region (Table S1). These vineyards belonged to a total of 16 winegrowers. Nine winegrowers were organically certified and applied an organic spraying regime (mostly sulphur, copper, and potassium bicarbonate). The other seven winegrowers treated their vineyards with conventional plant protection products (mostly synthetic fungicides). Each winegrower provided two vineyards, one planted with cultivars susceptible towards powdery and downy mildew (e.g., Riesling, Pinot blanc) and one with fungus-resistant varieties (e.g., Cabernet blanc, Regent), resulting in 16 vineyard pairs with different fungicide intensity but otherwise similar management (see Table S2). To display the acute toxicity of spraying regimes, hazard quotients for applied pesticides (HQ hereafter) were calculated by dividing the amount of applied active ingredients (g or mL per ha) by their corresponding contact acute median lethal dose (LD_{50})[45] values for honeybees (µg or µL per bee) and summed over all sprayings of the sampling year for each vineyard (see Table S2). Contact acute LD_{50} values for honeybees were obtained through the Pesticide Properties DataBase.[46] Overall, 499 pesticide applications (two insecticides, 497 fungicides) were reported, of which three applications of potassium phosphonates in conventional vineyards as well as seven applications of aluminium sulphates in organic vineyards were excluded from calculation due to missing LD_{50} values.

2.2 Arthropod sampling

Arthropods were sampled monthly during the vegetation period from the end of May to mid-October 2018, resulting in six sampling dates. We sampled the whole grapevine canopy using a beat-sheet with of diameter 72 cm (beat-sheet by Dynort, bioform Dr. J. Schmidl e.K., Nürnberg, Germany). The sheet was placed under the vines, which were shaken vigorously for 5 s. All arthropods falling on the sheet were collected and stored in 70% ethanol for further identification. We repeated the shaking on 30 randomly selected vines spread throughout the vineyard, excluding a 5 m buffer from the field margins. The sampled arthropods were counted and taxonomically classified at least to the family level using a stereomicroscope (Stemi 2000; Zeiss, Jena, Germany).

2.3 Predation rate assessment

To assess the pest control potential on grape berry moths, we exposed *L. botrana* egg-baits to predation. For rearing *L. botrana* we followed Markheiser *et al.*[47] Following Pennington *et al.*,[35] we allowed the oviposition of female *L. botrana* on replaceable polyethylene strips. Egg-laden strips were harvested after 24 h and stored at 4 °C until exposure. Eggs were evenly distributed across the strips, resulting in average occupancy of 49 ± 26 eggs per strip. The predation rates were determined by randomly attaching the baits to selected 1-year-old branches and exposing them for 72 h. We exposed five baits per vineyard between the end of May and the end of August (five sampling dates), resulting in overall 25 baits per vineyard. The number of eggs was counted before and after exposure using stereomicroscopes (Zeiss). We stored the eggs that remained on the baits in a climate chamber at 70% relative humidity and 21 °C for 4 weeks to check for parasitism but did not find any parasitized eggs.

2.4 Data analysis

Data obtained were summed over all sampling dates, resulting in one observation per vineyard. All statistical analyses were executed in R version 3.6.3.[48] To identify possible predator and pest ratios, individuals were grouped according to their feeding behaviour into guilds of carnivores (including predators, parasites, parasitoids, and partly carnivorous omnivores), herbivores, and others (including detritivores, fungivores, palynivores, nectarivores, and haematophages; see Table S3 for additional information). The eight most abundant families were analysed separately.

The distribution of response and predictor variables was checked visually using 'qqp' (R package car).[49] Accordingly, HQ, spraying frequency, abundances of individuals, families, predators, and herbivore arthropods, Araneidae, Theridiidae, Salticidae, Cicadellidae, and predation rate were analysed with Gaussian distribution using linear mixed-effect models fitted with the function 'lmer' (R package lme4).[50] Abundances of other arthropods, Forficulidae, Latridiidae, Formicidae, and Philodromidae were analysed with negative binomial distribution using generalized linear mixed-effect models fitted with the function 'glmer.nb'(R package lme4).[50] The correlation of the two numeric explanatory variables 'spraying frequency' and 'hazard quotient' was evaluated using a linear mixed-effects model with 'site' as a random factor. Due to a strong correlation with HQ, spraying frequency was omitted from further analysis (Table 2). For all other variables, two models were calculated: Model 1 contained 'site' as a random factor and 'grape variety' plus 'management' as the explanatory variables, including their interaction. To test how far accumulated toxicity of applied pesticides renders an equivalent explanation to the effects of grape variety and management, we calculated a second model for each dependent variable, containing 'site' as a random factor and 'hazard quotient' as the sole explanatory variable. Some of the less abundant families were tested the same way (Table S3).

Effects on the family composition of grape variety and management type on the one hand and HQ on the other hand were analysed using the R package vegan.[51] Partial distance-based redundancy analysis (dbRDA) using the Bray–Curtis distance as a dissimilarity measure was used with the function, capscale.[51] To account for the pairwise study design, a permutation design based on 'site' and 9999 permutations was used and 'site' was added as a condition term in the dbRDA. To reduce the influence of dominant families, community data were log10 ($x + 1$) transformed. Cook's distance was used to check for outliers. Assumptions were checked for all models using graphical validation procedures.[52]

3 RESULTS

In total, we identified 17 715 individuals from 188 arthropod families. Dominant orders were Araneae (6813 individuals in 21 families), Dermaptera (3666 individuals of one species, *Forficula auricularia*), Hemiptera (2414 individuals in 25 families), Coleoptera (1461 individuals in 30 families), Trombidiformes (948 individuals in 3 families), and Hymenoptera (883 individuals in 29 families). Of all families, Forficulidae (Dermaptera) was by far the most abundant (see Table S3 for a complete list).

Spraying frequency and hazard quotient of applications differed greatly between the studied vineyard types (Tables 1 and 2). Spraying frequency was more than three times higher in susceptible than in resistant grape varieties, with higher reduction under organic than under conventional management (Fig. 1(A) and Table 2). Hazard quotients were three times higher in susceptible than in resistant grape varieties and almost twice as high under organic than under conventional management (Fig. 1(B) and Table 2). Similar to the spraying frequency, the reduction of hazard quotients in resistant varieties was higher under organic management.

Over the season, between 225 and 980 arthropods were sampled per vineyard, of which 73.5% on average were natural enemies of arthropods (predators, parasites, parasitoids, omnivores; 'carnivores' hereafter). The group of carnivores was dominated by spiders (52.2%) and earwigs (28.3%). Resistant grape varieties increased carnivore abundance by 19% (21% without Forficulidae), whereby the effects were greater in organic vineyards than in conventional vineyards. By contrast, resistant varieties had fewer herbivores (−23%) mostly in conventional vineyards

Table 1. Model outputs for plant protection parameters, arthropod abundances, and predation rates, and two tested models: (1) interactive effects of grape variety and management and (2) hazard quotient of applications

	Model 1 (df = 26)			Model 2 (df = 28)
	Grape variety (resistant/ susceptible)	Management (organic/ conventional)	Management × grape variety	Hazard quotient
Hazard quotient	<**0.001** (101.38)	**0.003** (8.92)	<**0.001** (33.65)	/
Spraying frequency	<**0.001** (500.31)	0.981 (0.00)	<**0.001** (48.52)	**+<0.001** (21.81)
Total abundance of individuals	0.283 (1.15)	**0.021** (5.32)	0.911 (0.01)	0.881 (0.02)
(Without Forficulidae)	0.196 (1.67)	0.419 (0.65)	0.783 (0.08)	0.492 (0.47)
Abundance of carnivores	**0.026** (4.98)	**0.034** (4.48)	0.811 (0.06)	**−0.005** (7.74)
(Without Forficulidae)	**0.007** (7.25)	0.462 (0.54)	0.567 (0.33)	**−0.001** (10.48)
Abundance of herbivores	**0.038** (4.30)	0.107 (2.60)	**0.016** (5.77)	0.929 (0.01)
Abundance of others	0.068 (3.33)	0.688 (0.16)	**0.023** (5.17)	**−<0.001** (21.26)
Predation rate	0.087 (2.94)	0.094 (2.81)	0.457 (0.55)	−0.0504 (3.83)
Family richness	0.827 (0.05)	0.476 (0.51)	0.809 (0.06)	0.592 (0.29)
Family composition*	**0.016** (0.06)	0.074 (0.13)	0.557 (0.04)	**0.005** (0.09)
Abundance of Araneidae	0.270 (1.22)	0.343 (0.90)	0.422 (0.64)	−0.062 (3.47)
Abundance of Philodromidae	**0.049** (3.86)	0.415 (0.66)	0.608 (0.26)	−**0.024** (5.09)
Abundance of Theridiidae	<**0.001** (16.58)	0.148 (2.09)	0.635 (0.23)	**−0.003** (8.79)
Abundance of Salticidae	0.061 (3.52)	0.646 (0.21)	0.198 (1.65)	0.906 (0.01)
Abundance of Cicadellidae	**0.007** (7.31)	0.079 (3.10)	**0.016** (5.75)	0.864 (0.03)
Abundance of Forficulidae	0.920 (0.01)	**0.010** (6.55)	0.615 (0.25)	0.477 (0.51)
Abundance of Formicidae	0.730 (0.12)	0.132 (2.27)	0.279 (1.17)	0.656 (0.20)
Abundance of Latridiidae	**0.015** (5.96)	0.768 (0.09)	0.975 (0.00)	**−<0.003** (9.11)

Note: Negative and positive correlations of hazard quotient and response variables are highlighted with +/−. Significant *P* values are displayed in bold, respective chi-squared values are given in brackets.
**F* values and respective sum of squares displayed: model 1, df = 27; model 2, df = 29.

Table 2. Plant protection parameters, arthropod abundances, and predation rates with respect to grape varieties (resistant/susceptible) and management (organic/conventional)

	Organic		Conventional	
	Resistant	Susceptible	Resistant	Susceptible
Hazard quotient	0.88 ± 0.31	4.17 ± 0.31	0.92 ± 0.35	1.67 ± 0.35
Spraying frequency	2.22 ± 0.49	10.67 ± 0.49	4.29 ± 0.56	8.57 ± 0.56
Total abundance of individuals	447.00 ± 60.64	505.78 ± 60.64	629.14 ± 68.76	676.57 ± 8.76
(Without Forficulidae)	379.77 ± 69.21	434.33 ± 69.21	438.43 ± 78.48	521.86 ± 78.48
Abundance of carnivores	377.00 ± 49.64	312.56 ± 49.64	528.29 ± 56.28	448.43 ± 56.28
(Without Forficulidae)	309.78 ± 38.89	241.11 ± 38.89	337.57 ± 44.09	293.71 ± 44.09
Abundance of herbivores	79.56 ± 12.36	79.11 ± 12.36	80.00 ± 14.02	129.00 ± 14.02
Abundance of others	37.72 ± 0.33	26.53 ± 0.33	37.72 ± 0.37	39.87 ± 0.37
Predation rate (%)	80.34 ± 2.77	73.38 ± 2.77	83.10 ± 3.14	80.54 ± 3.14
Family richness	47.33 ± 2.93	46.22 ± 2.93	44.14 ± 3.33	44.29 ± 3.33
Abundance of Araneidae	27.44 ± 4.31	22.11 ± 4.31	30.57 ± 4.89	30.00 ± 4.89
Abundance of Philodromidae	72.46 ± 0.21	45.29 ± 0.21	54.17 ± 0.24	41.47 ± 0.24
Abundance of Theridiidae	58.56 ± 10.19	40.56 ± 10.19	82.00 ± 11.55	59.29 ± 11.55
Abundance of Salticidae	24.33 ± 5.11	26.78 ± 5.11	16.86 ± 5.79	27.86 ± 5.79
Abundance of Cicadellidae	44.22 ± 10.39	49.33 ± 10.39	46.14 ± 11.78	93.29 ± 11.78
Abundance of Forficulidae	50.84 ± 0.28	56.50 ± 0.27	142.46 ± 0.31	129.94 ± 0.31
Abundance of Formicidae	5.56 ± 0.44	8.63 ± 0.44	18.44 ± 0.48	14.67 ± 0.48
Abundance of Latridiidae	9.08 ± 0.56	5.53 ± 0.56	11.64 ± 0.63	6.99 ± 0.64

Note: Model-predicted means ± standard errors ($N = 32$ vineyards) are shown.

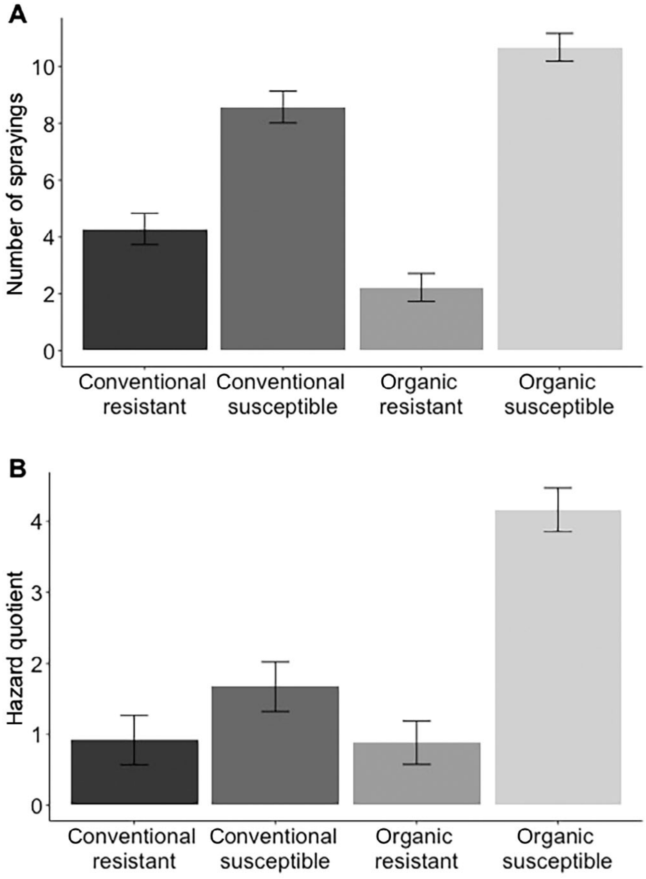

Figure 1. Differences in (A) spraying frequency and (B) hazard quotient of applications between management types (organic/conventional) and grape varieties (susceptible/resistant) in $N = 32$ vineyards (model-predicted means ± standard errors).

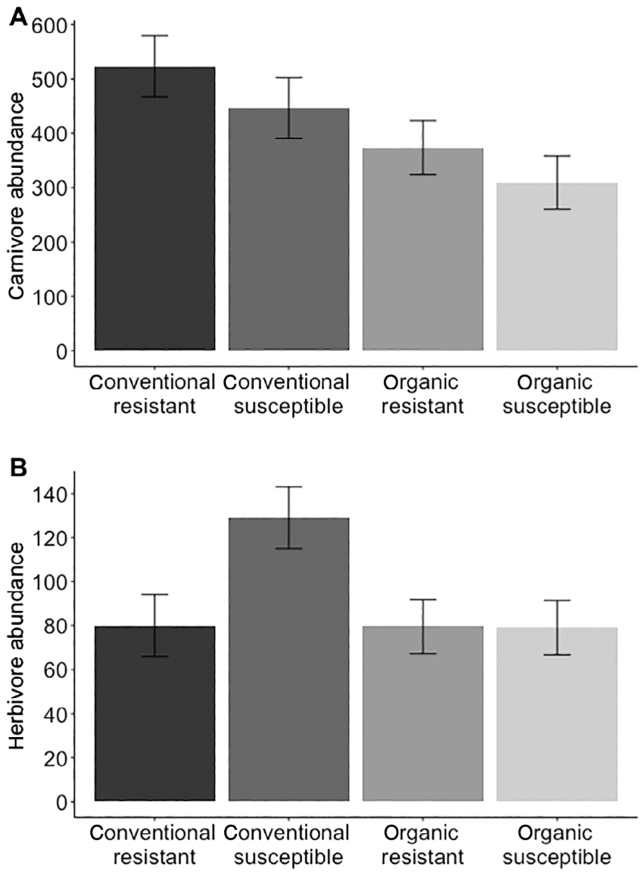

Figure 2. Differences in (A) carnivore abundance and (B) herbivore abundance between management types (organic/conventional) and grape varieties (susceptible/resistant) in $N = 32$ vineyards (model-predicted means ± standard errors).

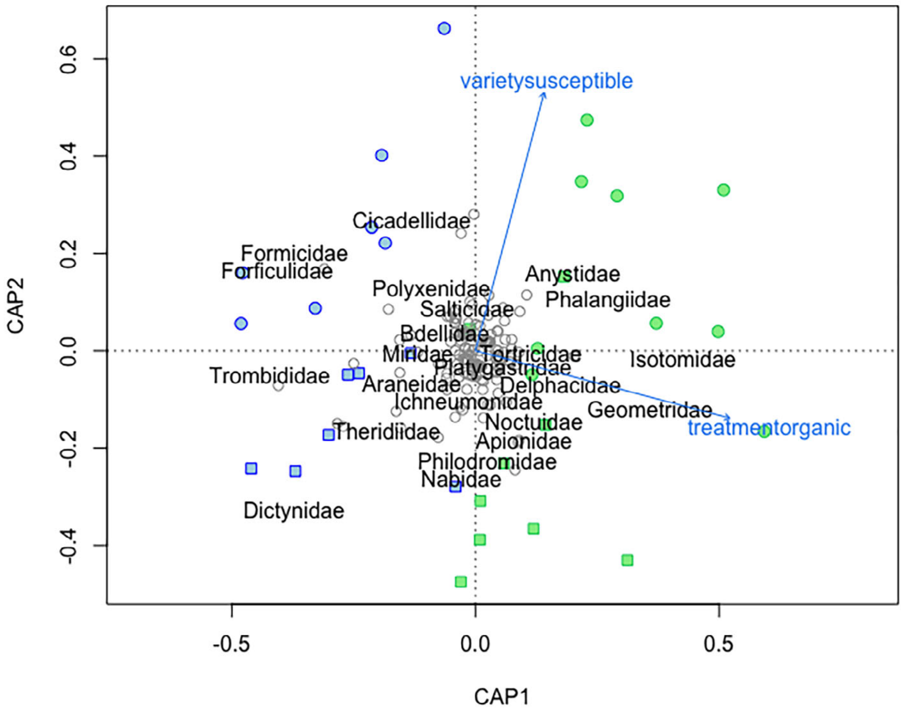

Figure 3. Relationship of arthropod families with vineyard management (organic/conventional) and grape variety (susceptible/resistant) analysed using dbRDA with Bray–Curtis distance as dissimilarity measure. Blue symbols represent conventional and green symbols organic vineyards, while circles represent susceptible and squares resistant varieties, respectively. If there were overlapping labels, more common species are displayed as text and less common species as small grey surrounded dots.

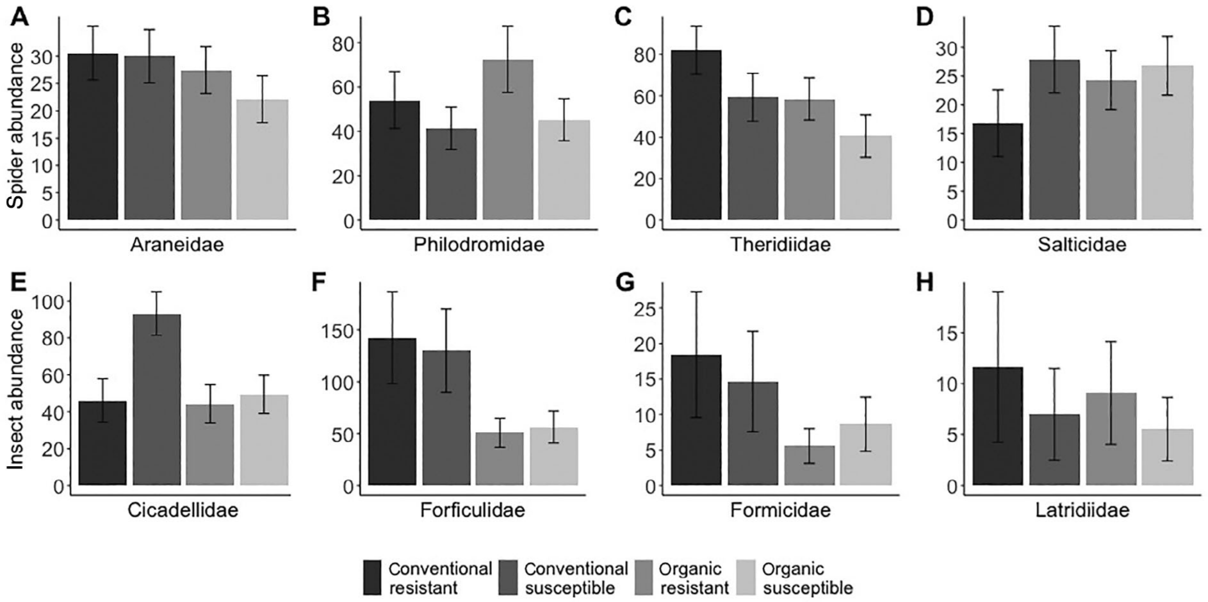

Figure 4. Abundance of the most abundant spider and insect families with respect to grape varieties (resistant/susceptible) and management types (organic/conventional) in $N = 32$ vineyards (model-predicted means ± standard errors): (A) Araneidae, (B) Philodromidae, (C) Theridiidae, (D) Salticidae, (E) Cicadellidae, (F) Forficulidae, (G) Formicidae, (H) Latridiidae.

(Tables 1 and 2, and Fig. 2(B)). Total abundance of arthropods, the abundance of other arthropods, and predation rates did not differ significantly between grape varieties (Tables 1 and 2). Conventional management increased the total abundance of arthropods by 37% and carnivore abundance by 42%, but had no effect on the abundance of carnivores other than earwigs, predation rates, and abundance of herbivores and other arthropods (Tables 1 and 2, and Fig. 2). Furthermore, the abundance of carnivores correlated negatively with hazard quotients of applied pesticides (Table 1). With a predation rate of 73.5%, the predation of *L. botrana* eggs was relatively high. However, neither resistant varieties nor organic management had a significant effect on predation rates.

On average, 46 different arthropod families were sampled per vineyard. While family richness was not affected by the investigated variables, family composition differed between resistant and susceptible grape varieties, and correlated with hazard quotients of applications (Table 1 and Fig. 3). Resistant grape varieties had higher densities of three of the dominant families (Philodromidae +46%, Theridiidae +41%, Latridiidae +65%), lower densities of Cicadellidae (−37%), and no significant difference of four of the dominant families (Araneidae, Forficulidae, Formicidae, Salticidae) (Tables 1 and 2, and Fig. 4). Conventional management had more than doubled densities of Forficulidae (+154%) compared to organic management, and showed no significant difference in any of the other seven families (Tables 1 and 2, and Fig. 4). Abundances of Theridiidae, Philodromidae, and Latridiidae were negatively correlated to hazard quotients (Table 1). Four of the less abundant families as well as two taxonomic orders showed significantly higher densities in fungus-resistant than susceptible varieties, and three taxonomic orders had higher densities in organic compared to conventional management (Table S3).

4 DISCUSSION

As expected, arthropod communities on grapes differed between fungus-resistant and susceptible grape varieties. Reduced fungicide use in resistant varieties had positive effects on arthropods and on carnivores in particular. Positive effects of lower pesticide inputs on vineyard predators are also prominent in other studies, but more likely related to insecticide use.[18,22,53–55] Nevertheless, lethal effects of single fungicides on nontarget organisms, particularly beneficial arthropods, are well documented.[46,56–58] Furthermore, sublethal effects of fungicides on predatory arthropods were observed, e.g. by reduced fecundity,[59] reduced prey consumption[60] or population decrease due to altered prey availability.[61] Consequently, higher pesticide toxicity affected predatory arthropods in Australia.[43] By contrast, we were unable to detect any clear effect of fungus-resistant varieties on the predation rates of *L. botrana* eggs in our study. However, decreased hazard quotients appeared to enhance predation rates. Positive effects of reduced fungicides on *L. botrana* egg predation were also found by Pennington *et al.*[35] in resistant grape varieties. In other viticultural areas, reduced pesticide use enhanced natural pest control of *L. botrana* regardless of organic or conventional vineyards.[38,44,62] Given the widespread empirical evidence for positive effects of predator densities and fungicide reduction on egg predation, we assume that the overall high predation rates of 73.5% in our vineyards precluded the significant effects of studied management factors on pest control.

Among the eight dominant arthropod families, four were affected by reduced fungicide applications in resistant varieties. Cicadellidae, the dominant herbivores in our study, were enhanced under increased fungicide applications in susceptible varieties. The subfamily of Typhlocybinae and particularly the species of *Empoasca vitis* is the most abundant leafhopper in vineyards and can cause severe damage.[63–65] Cicadellid abundances negatively correlated with higher predator abundances in fungus-resistant vineyards, suggesting that fungicide reduction constitutes higher levels of natural pest control (results not shown). This higher natural resistance of the vineyard ecosystem to herbivores may become important with the expected arrival of new invasive insect pests such as the phloem-feeding leafhopper *Scaphoideus titanus* or the recently arrived spotted wing drosophila *Drosophila suzukii*.[15,66] Fungivore arthropods, such as latridiid beetles, may, apart from direct effects of the applied pesticides, also indirectly benefit from reduced fungicide applications through higher availability of fungal food sources.[67] Latridiidae do not directly contribute to ecosystem services such as pest control or pollination, but they can contribute to a stable ecosystem, e.g. as detrivores or as alternative prey for carnivores. The two dominant spider families, Theridiidae and Philodromidae, benefitted from reduced fungicide applications, and both were also highly affected by hazard quotients in our study. Similar susceptibility of Theridiidae towards fungicide applications was also found by Pennington *et al.*[68] in the Palatinate study region. In contrast to other spider families, the observed species of Philodromidae and Theridiidae occur almost exclusively in the canopy of woody plants[69,70] and are therefore exposed to higher levels of fungicides. Effects of fungicides may be less prominent in other arthropods that also occur on the ground and in the inter-row vegetation of the vineyard. Ants and earwigs, for example, reproduce in the soil, have high foraging ranges, and may therefore be less affected by fungicide applications in the canopy but rather by soil management.[71–73] Both ants and earwigs play a crucial role in vineyard pest control[38,68,74,75] and tend to be susceptible to pesticides, particularly insecticide applications, in vineyards and orchards.[16,17,35,76,77] Nonetheless, neither ants nor earwigs were affected by reduced fungicide sprayings in our study.

The negative effects of organic farming on earwigs, total carnivore, and total arthropod abundance contrast with the positive effects of organic management in other crop systems. Our results contrast with a number of previous studies in vineyards where organic management enhanced the abundance of carnivores, such as spiders, earwigs, lacewings, and harvestmen.[22,24,53–55] However, it is unclear to what extent the benefit of organic farming in these studies resulted from noncrop vegetation or from the exclusion of synthetic insecticides and herbicides in organic vineyards. Overall, the effects of organic management appear less prominent in temperate viticultural areas than in warmer regions. For instance, the abundance of ground-dwelling spiders did not differ between organic and conventional vineyards in two temperate regions (Switzerland, Germany).[9,78] In both studies insecticide use was scarce and inter-row vegetation was present in both organic and conventional vineyards. It appears that if fungicides with low hazard to arthropods are used, no insecticides are applied, and inter-rows are vegetated, conventional viticulture can be equivalent or even favourable for arthropods.

Among the eight dominant arthropod families, only earwigs profited from conventional management. The positive effects of conventional management on total arthropod and carnivore abundances detected in our study resulted solely from higher earwig abundances in the conventional vineyards. Excluding earwig abundance, we found no effect of organic *versus* conventional management on total arthropod and carnivore abundance. Earwigs (exclusively the species *F. auricularia*) accounted for 20% of all sampled arthropods and almost 30% of carnivores in our study and thus dominated arthropod assemblages. Although earwigs are considered beneficial insects, they can become pests in viticulture. When occurring at high densities, earwigs may feed on grape berries and contaminate grape bunches with faeces, which decreases the must quality of the grapes.[79,80]

The abundance and richness of arthropods that we sampled in the vine canopy were similar to other viticultural regions worldwide.[55,65,81–83] The highest proportions of beneficial arthropods such as predators and parasitoids (i.e. 73.5% in this study) were also found in Spanish and Australian vineyards, with remarkably high numbers of earwigs (*F. auricularia*), ladybirds, and spiders.[65,82] Spiders were observed to be the most abundant group of predators elsewhere.[55,84,85] However, this composition of arthropod assemblages differs strongly from other cropping systems. With a comparable beat-sheet sampling method, overall arthropod abundance was higher in soy-bean and asparagus fields, with herbivores and pest species dominating these communities.[86,87] Under similar conditions, total arthropod abundance and family richness were even considerably lower in cotton fields, highlighting the dominance of herbivore guilds.[88] Vineyards therefore seem to have a higher potential for natural pest control compared to other crops. This was confirmed by a meta-analysis of spiders' effects on pest control and yield, where vineyards were the crops with the second-strongest top-down effects from spiders worldwide.[89] Furthermore, most of the sampled herbivore arthropods do not feed on vines but on noncrop vegetation in vineyards,[90] and thus offer a food supply for predators without affecting yield and grape quality.

Meanwhile, fungal diseases require the majority of plant protection treatments in our study region. Approximately 80% of the viticultural area in the investigated region is treated with mating disruption products against grape berry moths, which allows a largely insecticide-free viticulture. The subsidies for these pheromone applications are linked to the ban on insecticide use.[91] Given these insecticide-free plant protection regimes, conventional vineyards had lower HQs than organic vineyards in our study. On the one hand, organic winegrowers sprayed more frequently due to the necessity of application prior to potential disease occurrence and the mode of action of the allowed fungicides. Nonselective compounds such as copper and sulphur applied in organic viticulture resulted in high levels of toxicity towards nontarget organisms.[46] Furthermore, according to Schulz *et al.*[92] the toxicity of applied pesticides (mainly insecticides) has increased in the last few years. Moreover, studies show that the cumulative effect of multiple spray applications across one or more seasons greatly increases the adverse effects. Given this, every single spray application further contains combinations of different pesticide products with different active ingredients and adjuvants.[17,93,94] Such mixes may be more harmful to nontarget organisms than the single products.[95] To date, alternatives to chemical control of grape fungal diseases are unavailable in both organic and conventional viticulture. Thus, the most promising approach to fostering more sustainable viticulture is the avoidance of fungicide applications. This can be achieved through the cultivation of fungus-resistant grape varieties without losses in the quality or quantity of the yield.

5 CONCLUSION

To sum up, we found clear benefits of fungus-resistant varieties but not of organic farming on hazard quotients of plant protection in vineyards. Fungus-resistant varieties allowed increased densities of carnivorous arthropods along with reduced densities of leafhoppers. The intensive use of fungicides even in organic viticulture appears to preclude the otherwise often observed benefits of organic farming on arthropod biodiversity. Thus, the reduction of fungicides in vineyards through the cultivation of fungus-resistant grape varieties, under both organic and conventional management, is strongly recommended to foster functional biodiversity and natural pest control. Fungus-resistant cultivars offer a higher potential to minimise the adverse effects of intensive agriculture on ecosystems and should therefore be more widely cultivated to enhance the sustainability of agriculture.

AUTHOR CONTRIBUTIONS

MHE, CH, and JMR conceived the ideas and designed methodology. JMR and KS performed the experiments. JMR led the data analysis and writing, and designed the graphical abstract. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The authors confirm that the data supporting the findings of this study are available within the article, its supplementary material or are available on PANGAEA (doi:10.1594/PANGAEA.954752).

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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