

ARTHROPOD FUNCTIONAL BIODIVERSITY IN VINEYARDS UNDER REDUCED FUNGICIDE SPRAYINGS

by
Jo Marie Reiff
from Duisburg

Accepted Dissertation thesis for the partial fulfilment of the requirements for a
Doctor of Natural Sciences
Fachbereich Natur- und Umweltwissenschaften
Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau

Thesis examiners:
Prof. Dr. Martin H. Entling,
Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau
Dr. Christoph Hoffmann,
Julius Kühn-Institut

Date of the oral examination:
12 October 2023



This thesis was conducted within the scope of the project NoViSys funded by the German Federal Ministry of Education and Research (BMBF).

TABLE OF CONTENTS

ABSTRACT.....	I
ZUSAMMENFASSUNG.....	I
CHAPTER I.....	2
General introduction	
CHAPTER II.....	7
Consistent benefits of fungicide reduction on arthropod predators and predation rates in viticulture: a five-year experiment	
CHAPTER III.....	22
Fungicide reduction favors the control of phytophagous mites under both organic and conventional viticulture	
CHAPTER IV.....	34
Arthropods on grapes benefit more from fungicide reduction than from organic farming	
CHAPTER V.....	49
Dominant effects of fungicide sprayings on spiders in the vineyard canopy	
CHAPTER VI.....	62
Arthropods in the spotlight – identifying predators of vineyard pest insects with infrared photography	
CHAPTER VII.....	69
Selected poster publications	
CHAPTER VIII.....	72
Conclusion and Outlook	
REFERENCES.....	77
DANKSAGUNG.....	100
APPENDIX.....	I
SUPPLEMENTARY MATERIALS.....	II
STATUS AND AUTHOR CONTRIBUTIONS OF PUBLICATIONS.....	XIX
CURRICULUM VITAE.....	XXI
DECLARATION.....	XXIV

ABSTRACT

The intensive use of pesticides is one of the main causes for global arthropod decline which can subsequently affect ecosystem services such as pollination, natural pest control, and soil fertility and cascade to higher trophic levels including bats and birds. However, agriculture in large parts is strongly dependent on pesticides, and viticulture in particular is one of the major consumers of fungicides. Fungus-resistant grape varieties offer a very good opportunity to reduce fungicide applications by more than 80 % while maintaining healthy grapes. Here, the effects of fungicide reduction on arthropods and natural pest control were investigated on the one hand in a long-term study in an experimental vineyard and on the other hand in 32 commercially managed vineyards in southwestern Germany. In both designs, fungicide reduction resulted in mostly positive effects on arthropods and natural pest control. Particularly beneficial arthropods such as predatory mites and spiders were promoted by reduced fungicide applications. Contrastingly, potential vineyard pests such as phytophagous mites and leafhoppers decreased under fungicide reduction. Fungus-resistant grape varieties are thus a promising approach to foster resilient agroecosystems and a more sustainable viticulture.

ZUSAMMENFASSUNG

Die intensive Anwendung von Pestiziden ist einer der Hauptgründe für den Rückgang von Arthropoden. Dies kann entsprechend Folgen für Ökosystemleistungen wie Bestäubung, natürliche Schädlingskontrolle und Bodenfruchtbarkeit haben und auch höhere trophische Ebenen wie Fledermäuse und Vögel betreffen. Weite Teile der Landwirtschaft sind jedoch stark von Pestiziden abhängig und insbesondere der Weinbau ist einer der größten Fungizidanwender. Pilzwiderstandsfähige Rebsorten bieten eine sehr gute Möglichkeit die Anwendung von Fungiziden um mehr als 80 % zu reduzieren und trotzdem gesunde Trauben zu erhalten. In dieser Studie wurden die Effekte von reduziertem Fungizideinsatz auf Arthropoden und die natürliche Schädlingskontrolle einerseits als Langzeitversuch in einem Versuchsweinberg und andererseits in 32 kommerziell bewirtschafteten Weinbergen in Südwestdeutschland untersucht. Die Fungizidreduktion hatte in beiden Untersuchungen meist positive Effekte auf Arthropoden und die natürliche Schädlingskontrolle. Insbesondere Nützlinge wie Raubmilben und Spinnen wurden unter geringerem Fungizideinsatz gefördert. Im Gegensatz dazu verringerte sich die Zahl der möglichen Weinbergsschädlinge wie Schadmilben oder Zikaden. Pilzwiderstandsfähige Rebsorten sind somit ein vielversprechender Ansatz, um resiliente Agro-Ökosysteme und einen nachhaltigeren Weinbau zu fördern.

CHAPTER I

GENERAL INTRODUCTION

Jo Marie Reiff

The world population is currently reaching eight billion people and is estimated to reach over ten billion by 2060 (Statista Research Department, 2023a). Hence, the demand for food production and agricultural area grows. In 2020 the farmland already accounted for 36.5 % of the earth's terrestrial surface (The World Bank Group, 2023). Over the last decade the global cropland increased by 9 % with a simultaneous increase in land productivity as a result of agricultural intensification (Potapov et al., 2022). However, intensive agriculture is one of the main causes for biodiversity decline (Sánchez-Bayo and Wyckhuys, 2019; Seibold et al., 2019; Raven and Wagner, 2021; Uhler et al., 2021; Caro et al., 2022). Globally, 58 % of the endangered and critically endangered species are threatened amongst others by agriculture (IUCN, 2023). In Europe, 41 % of 1675 species currently listed as endangered and critically endangered are also threatened by agriculture (IUCN, 2023). Particularly strong declines were found for arthropods (Hallmann et al., 2017). For instance, recent pollinator extinctions in the UK were associated with agricultural intensification (Ollerton et al., 2014). Similarly, butterfly species richness and abundance decreased in intensified agricultural landscapes in Germany (Habel et al., 2019). Ecosystems are shaped by complex networks of interspecies interactions and the loss of one species can result in cascading extinctions (Kehoe et al., 2021). In a very simplified presentation, the impact of arthropod decline on subsequent trophic levels is evident in the decline of insectivorous birds and bats in agricultural landscapes (Newton, 2004; Bowler et al., 2019; Put et al., 2019).

Ecosystems harbouring high levels of biodiversity are shown to be more resilient, also in terms of ecosystem services, such as pollination, natural pest control and soil nutrient cycling (Oliver et al., 2015). For instance, the fruit sets of crops increased with the visit of a higher diversity of pollinators including bees and non-bees (Rader et al., 2016). Furthermore, natural pest control was promoted by agro-ecosystems with high plant diversity resulting in less pest damage to crops (Letourneau et al., 2011). Put the other way round: intensive agriculture impairs ecosystem services such as pollination and pest control. Moreover, agricultural intensification can affect soil biodiversity and consequently decomposition rates and soil fertility (de Graaff et al., 2019). It appears rather ironic that a majority of the agricultural sector is, however, dependent on ecosystem services. For instance, 35 % of global agricultural production comes from crops that depend on pollinators (Klein et al. 2006). Pollination services by wild and managed bees were estimated at \$ 518 billion per year (IPBES, 2016), while natural pest control was estimated at \$ 4.5 billion per year in the United States alone (Losey and Vaughan, 2006). Preserving healthy agro-ecosystems with high arthropod biodiversity should therefore be our vital interest. Unfortunately, healthy crops do not simultaneously imply a healthy ecosystem¹. On the contrary, plant protection products are among the main causes of biodiversity loss (Gibbs et al., 2009; Geiger et al., 2010; Sánchez-Bayo and Wyckhuys, 2019).

The worldwide pesticide consumption accounted for 2.66 million tons in 2020. In other words, on average 1.81 kg of pesticides were applied per hectare cropland and year (Statista Research Department, 2023b). A large part of the applied pesticides, however, generally does not remain there. Approximately 99 % of an applied pesticide ends up in the environment but not at the aimed target² (Sun et al., 2018) where some of them persist and bioaccumulate (Shama et al., 2019). Large parts of the sprayed pesticides are already dispersed as aerosols during the

1 Actually, a lack of ecological knowledge in agriculture fosters the dependency upon pesticides by farmers (Wyckhuys et al., 2019).

2 The aimed target can be very small (e.g. pest mites, seedlings, fungal spores), thus the non-target environment can comprise crops, agricultural soils and non-agricultural areas.

application (van Lexmond et al., 2015). For instance, pesticides and their residues were detected in the majority of public sites (e.g. playgrounds) within the intensively managed agricultural area of South Tyrol (Linhart et al., 2021). Approximately 70 % of sprayed pesticides are contaminating soils where they harm soil invertebrates and impact soil fertility (Aktar et al., 2009; Sun et al., 2018; Shama et al., 2019; Gunstone et al., 2021). Further, pesticide contaminated runoff from agricultural surfaces also pollutes water bodies. Pesticides and their residues are meanwhile found in many surface waters where they exceed legal threshold levels (Herrero-Hernández et al., 2013; Stehle and Schulz, 2015; Umweltbundesamt, 2020). To sum up with the words of Jaques-Yves Cousteau:

Water and air, the two essential fluids on which all life depends, have become global garbage cans.

Consequently, it does not appear surprising that pesticide pollution globally affects non-target arthropods in terrestrial and aquatic systems (Biondi et al., 2012; Sánchez-Bayo, 2021). Regarding aquatic systems, abundances of vulnerable arthropods were drastically decreased in German streams with contamination of different pesticides which resulted in a shift in community composition (Liess and von der Ohe, 2005). Further, arthropod species and family richness were decreased in European streams even under pesticide concentrations which were considered environmentally safe (Beketov et al., 2013). Comparable patterns were found for terrestrial systems. Pesticides are suspected to be one major cause of pollinator decline (Potts et al., 2010). There is evidence, that pesticides, although applied at recommended rates, strongly affect soil invertebrate communities (Beaumelle et al., 2023a). Similarly, pesticide seed treatments affected above-ground arthropods although residual amounts of those pesticides in soils were below detection threshold (Dubey et al., 2020). And it has long been understood that disturbances of arthropod communities by pesticides affect overall ecological interrelationships in agricultural systems (Ripper, 1956). Disruption of arthropod communities and predators in particular can result in turn in the promotion of pest species (Hanna et al., 1997; Nash et al., 2010; Hill et al., 2017). Trophic interactions within ecosystems can be complex and boundaries between them are blurred (Schulz et al., 2015). Thus, impacts of pesticides on aquatic systems may in return also affect terrestrial systems and consequently also agriculture.

Although single pesticides undergo a strict risk assessment when they are registered the regulations fail to adequately protect the environment (Brühl and Zaller, 2019). For instance, mixtures of different pesticides with different active ingredients and adjuvants are more toxic than the single product evaluated for risk assessment (Chen and Stark, 2010; Mullin et al., 2015; Jansen et al., 2017). And although sublethal effects on non-target organisms are rarely considered during risk assessment, pesticides are certainly known to have them (Desneux et al., 2007, Niedobová et al., 2016). We are thus only beginning to suspect the extent of the consequences of intensive pesticide use.

With growing environmental awareness, society, governments and scientists are also becoming more concerned about the effects of intensive pesticide use (Jaquet et al., 2022). Within the EU Green Deal the European Commission is willing to reduce the current use of pesticides³ by 50 % by 2030 (European Commission, 2023). Moreover, there is demand for a pesticide-free agriculture by 2035 (PAN Europe, 2023). However, it seems unlikely that these objectives will be achieved in the current context (Guyomard et al., 2020). Many crops are still depending on pesticides to ensure or improve productivity and quality of yield (Aktar et al. 2009; Shama et al.,

3 However, this accounts only for the synthetic and hazardous pesticides.

2019). Grapevine is no exception to that. On the contrary, it is the second intensively pesticide treated crop in Germany with a particularly high consumption of fungicides (JKI, 2022). Powdery mildew (*Erysiphe necator*) and downy mildew (*Plasmopara viticola*) were accidentally introduced to Europe in the second half of the 19th century and have been among the most important diseases of grapevine ever since (Töpfer and Trapp, 2022). Without an adequate plant protection with fungicides wine production would be seriously threatened. In contrast to arable crops, organic viticulture offers no solution and contrarily consumes equal or even higher amounts of pesticides (Bengtsson et al., 2005; Muneret et al., 2018; Beaumelle et al., 2023b; Kaczmarek et al., 2023). Thus, there is need for alternative approaches to reduce pesticides. The most promising strategy is the cultivation of fungus-resistant grape varieties. Cross-breedings between the susceptible European grapevine *Vitis vinifera* and resistant grapevine species from North America and Asia (e.g. *V. riparia*, *V. amurensis*, *V. rupestris*) and marker-assisted selection with additional reverse cross-breedings allowed for varieties with fungus resistance and good wine quality (Sivčev et al., 2020; Töpfer and Trapp, 2022). Depending on climatic conditions and resulting pathogen pressure a reduction of fungicide applications by 85-100 % is possible in fungus-resistant varieties with multiple resistance loci although not recommended for the sake of resistance durability (Wingerter et al., 2022). Consequently, a reduction in fungicide applications not only enables savings in purchase costs of plant protection products, but also in labour hours and machine hours. For instance, the cultivation of fungus-resistant varieties allowed fuel savings of approximately 200 litres per hectare and year in a Swiss winery (Strasser and Coray, 2009). In total the adoption of fungus resistant varieties can result in annual cost reductions of 400-1000 € per hectare (Schwab et al., 2001; Fuller et al., 2014). It should be noted that external costs arising with pesticide pollution were not yet internalised in these calculations. Fungus-resistant varieties thus seem to be a win-win solution for winegrowers and environment.

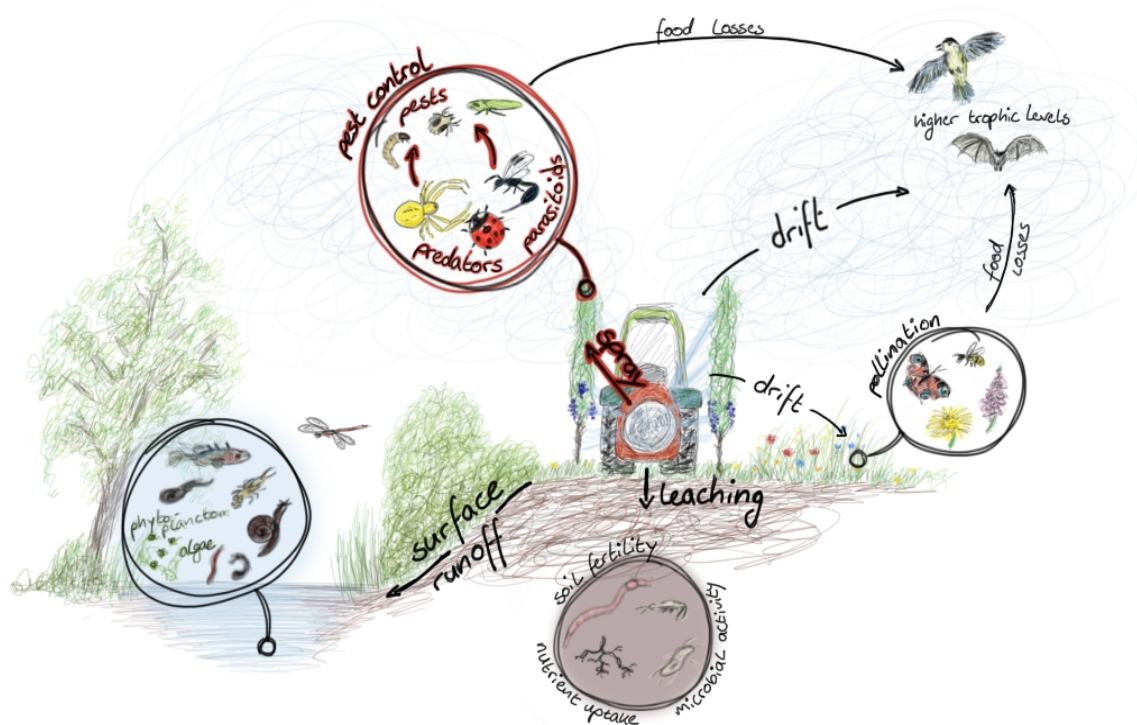


Figure 1 Schematic illustration of pesticide impacts on trophic interactions in ecosystems and their consequences for agriculture. The aspects covered in this study are highlighted in red. Note, the illustration is certainly not exhaustive (for more insight in pesticide sublethal effects compare e.g. Sánchez-Bayo, 2021).

Figure 1 provides a schematic illustration of the described complex relationships within and between ecosystems exposed to pesticides. The aspects to be elaborated in this work are highlighted in red in this illustration to contextualise the relevance of this research. The aim of this work was to investigate the effects of reduced fungicide applications on arthropod biodiversity and natural pest control in the grapevine canopy with the following hypotheses:⁴

(1) Fungicide reduction enhances arthropod abundance and richness. This point is relevant for nature conservation and to maintain resilient agro-ecosystems.

(2) Fungicide reduction particularly enhances beneficial arthropods and consequently fosters natural pest control, which should be of particular interest for winegrowers.

In the first step, the effects of reduced fungicide applications were investigated under experimental conditions over a study period of five years. However, results from one standardized experimental vineyard cannot be readily extrapolated to viticulture in general. Consequently, in the second step, 32 commercially managed vineyards were investigated to clarify the extent of reduced fungicide applications under actual viticultural practice.

Chapter II of this dissertation focusses on the experimental vineyard planted with four fungus-resistant grape varieties. This allowed a determined reduction of fungicide sprayings by approximately 85 % and 70 %. The management was standardized as far as possible and only fungicides certified for organic production were sprayed. The study comprises the predator-prey-interaction of mites inhabiting grapevine leaves as well as the abundance of canopy dwelling arthropods and the predation rates on one major grapevine pest, the European grapevine moth *Lobesia botrana*. The results highlight that benefits of reduced fungicide sprayings are consistent over the five consecutive study years despite of varying weather conditions.

Contrasting Chapter II, all experiments in Chapters III-VI were conducted in commercially managed vineyards in the same study year. However, in this case organic and conventionally managed vineyards of self-marketing wineries were investigated. Under both management types half of the vineyards were planted by either susceptible or fungus-resistant grape varieties. This 2×2 design resulted in a gradient of fungicide sprayings as well as in varying toxicity of plant protection products. Within this setting Chapter III analyses densities of different beneficial and phytophagous mites on the grapevine leaves. The study focusses on the generalist phytoseiid predator *Typhlodromus pyri* as well as the tydeid mite *Tydeus götzi*, and the two eriophyid pest mites *Colomerus vitis* and *Calepitrimeus vitis*, and further incorporates two other predatory mite families, Anistidae and Trombidiidae. Chapter IV illustrates the abundance of canopy dwelling arthropods and the pest control potential on *L. botrana* eggs. The analysis comprises arthropod family richness and composition, differences in functional groups, and highlights the impact of fungicides on several abundant families. In Chapter V the effects on spiders in different taxonomic levels are addressed in more detail. Spider communities were analysed at family, genus, and species level, revealing different patterns at the three taxonomic levels. Several families and genera are affected by fungicide sprayings and the varying toxicity of the sprayed products. Finally, Chapter VI emphasises natural enemies of grapevine pests. Camera observations of sentinel cards with eggs and pupae of *L. botrana* and the spotted wing drosophila (*Drosophila suzukii*) highlight the predatory potential of particularly earwigs.

⁴ Effects of reduced fungicide applications on infestations with fungal diseases were covered in the same project by Kraus et al. (2018). Furthermore, amongst others physical aspects of fungus-resistant varieties for future grapevine breeding (Herzog et al., 2022), the consumers' acceptance of wines from fungus-resistant varieties (Nesselhauf et al., 2020), and new technologies for phenotyping of vineyards (Rose et al., 2016; Bömer et al., 2020) were covered within the same project.

CONSISTENT BENEFITS OF FUNGICIDE REDUCTION ON ARTHROPOD PREDATORS AND PREDATION RATES IN VITICULTURE: A FIVE-YEAR EXPERIMENT

Jo Marie Reiff ^{a,b}, Theresa Pennington ^{a,b}, Sebastian Kolb ^{a,b}, Konrad Theiss ^{a,b},
Ekaterina Alakina ^{a,b}, Marvin Ehringer ^{a,b}, Paul Mason ^{a,b}, Rosalie Shrestha ^{a,b},
Martin H. Entling ^a, Christoph Hoffmann ^b

*a RPTU Kaiserslautern-Landau, iES Landau, Institute for Environmental Sciences,
Fortstraße 7, D-76829, Landau in der Pfalz, Germany*

*b Julius Kühn-Institute, Federal Research Institute for Cultivated Plants,
Institute for Plant Protection in Fruit Crops and Viticulture,
Geilweilerhof, D-76833 Siebeldingen, Germany*

ABSTRACT

For reliable pest suppression, benefits of habitat management for natural enemies of agricultural pests need to be consistent over time. Unfortunately, most research projects allow only for 1 or 2 years of data collection. Here, we present a five-year study on effects of fungicide reduction and altered plant architecture on arthropod abundances and natural pest control in an experimental vineyard. The vineyard rows were divided into eight groups, half of which were trained in vertical shoot position (“trellis system”) and the other half as semi-minimal pruned hedge (“minimal pruning”). Every row was divided in three sections receiving three different plant protection intensities, respectively, with fungicides certified for organic viticulture. In each year we sampled arthropods from the grapevine canopy by standardized leaf collection and beat-sheet sampling, and exposed baits of a major grapevine pest (*Lobesia botrana*) to assess natural pest control. Arthropods, in particular predators, benefited from reduced fungicide sprayings and in turn promoted natural pest control. In contrast, effects of minimal pruning were less strong, and restricted to the leaf mesofauna, earwigs and leafhoppers. Across the five study years with their variable weather conditions, we conclude that the advantages of reduced fungicide sprayings in fungus-resistant varieties are consistent over time.

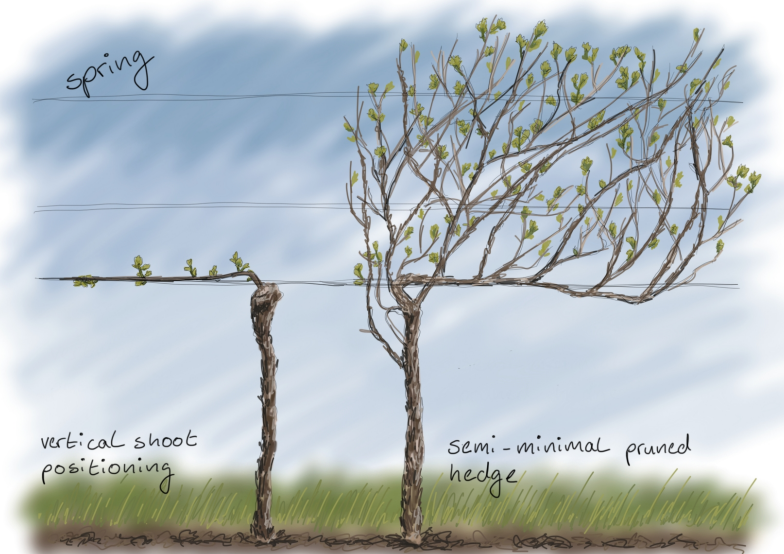
KEYWORDS

organic viticulture, fungus-resistant grape varieties, minimal pruning, natural pest control, *Lobesia botrana*, Phytoseiidae, Eriophyidae

I INTRODUCTION

Arthropods are involved in important ecosystem services such as natural pest regulation. However, many species are sensitive to agricultural practices. For example, soil disturbances such as tillage, chemical inputs like pesticides and fertilizers, and mechanical harvesting strongly impair arthropod communities (Attwood et al., 2008; Sánchez-Bayo and Wyckhuys, 2019). Nonetheless, habitat management can improve environmental conditions such as the availability of alternative food and shelter, particularly for beneficial arthropods (Landis et al., 2000). In contrast to annual crops, perennial crops such as orchards and vineyards are stable habitats with continuous vegetation cover. However, they can receive high levels of pesticide input (Bakker et al., 2022). In temperate regions with humid climate where pathogen pressure is high, vineyards typically receive 12-15 fungicide sprayings per year (Pertot et al., 2017; Reiff et al., 2023). Beneficial arthropods like parasitic wasps, ants, spiders, as well as predatory mites and beetles, are susceptible to fungicides (Nash et al., 2010; Thomson and Hoffmann, 2006). Thus, frequent fungicide treatments may impede natural pest control in vineyards. A promising approach to fostering arthropod biodiversity and natural pest control is the cultivation of fungus-resistant grape varieties which allows to reduce fungicide applications by 60-100 % (Pertot et al., 2017; Reiff et al., 2021a; Thiollet-Scholtus et al., 2021). However, the amount of wine produced from fungus-resistant varieties is still low, due to limited acceptance of new varieties by consumers (Borrello et al., 2021; Nesselhauf, 2018; Wiedemann-Merdinoglu and Hoffmann, 2010).

Another approach for a more sustainable viticulture is minimal pruning. While in traditional trellis systems 85-98 % of the annual growth are pruned in winter (Sommer et al., 1995), minimally pruned vineyards are characterized by high amounts of wooded shoots that persist over the years. Thereby, canopies of minimally pruned vines sprout more quickly, develop a full leaf canopy sooner, and have higher volumes due to increased numbers of shoots and nodes



compared to plants in traditional trellis systems (Intrieri et al., 2011; Kraus et al., 2018; Sommer et al., 1995). However, denser canopies can be less permeable to pesticide applications. Further, this shift in vine architecture results in altered microclimatic conditions (Kraus et al., 2018; Pangga et al., 2013). As a consequence, minimal pruning may amplify pathogen pressure of fungal diseases such as powdery mildew (*Erysiphe necator*) and downy mildew (*Plasmopara viticola*). Arthropods may also be affected by microclimatic conditions. A denser and more complexly-structured canopy may provide additional shelter for beneficial arthropods and promote top-down effects on herbivores (Langellotto and Denno, 2004). For instance, some spiders and mites overwinter in tree bark and on branches (Bower and Snetsinger, 1985; Duso and Vettorazzo, 1999) and their densities may thus be enhanced by higher abundance of wooded branches in minimal pruned vineyards.

For reliable pest suppression, effects of habitat management on natural enemies need to be consistent over time. Unfortunately, most research projects allow only for one or two years of data collection (Estes et al., 2018). Some snapshots already highlight the benefits of reduced fungicide sprayings and minimal pruning on arthropod predators and natural pest suppression (Pennington et al., 2017, 2018, 2019). However, these studies lack evidence for long-term validity. To fill this gap, we investigate the single and combined effects of reduced fungicide sprayings in fungus-resistant grape varieties and altered grapevine architecture in minimally pruned vineyards on arthropods in five successive years. Since exposure to pesticides is highest in the grapevine canopy, we focussed on biodiversity sampling from the foliage, including both mesofauna and macrofauna. We hypothesize that arthropod abundances and natural pest control in the grapevine canopy is enhanced by both fungicide reduction and minimal pruning.

2 MATERIALS AND METHODS

2.1 Study site

The experiments took place in an experimental vineyard of the Julius Kühn-Institute in Siebeldingen, Germany (N 49.218950, E 8.040500). Inter-row distance was 2 m and grapevine spacing was 1 m. The vineyard was planted with four different *Vitis vinifera* cultivars: ‘Reberger’ (red), ‘Villaris’ (white), ‘Felicia’ (white) and ‘Gf 84-58-988’ (red) which are resistant against powdery mildew and downy mildew. Cultivating fungus-resistant varieties allowed for reduced plant protection regimes while maintaining healthy plants. The varieties were used as replicates of the pruning and plant protection treatments and to represent a diversity of cultivars. Specific differences between these four varieties were beyond the scope of this study. Each variety was cultivated in six to ten rows, half of which were trained in vertical shoot position (VSP; “trellis system” hereafter) and half were trained in semi-minimal pruned hedge (SMPH; “minimal pruning” hereafter). Each of these rows was again divided into three sections which received different plant protection regimes by using a plot sprayer to avoid spray drift to adjacent rows (Tunnel plot sprayer ABS 6/25-TU, Christian Schachtner Fahrzeug- und Gerätebau, Ludwigsburg, Germany). Thus, each combination of plant protection intensity and pruning system was replicated four times in the different varieties, resulting in 24 treatment plots (see supplementary Figure S1 for a detailed plan). We chose a spraying regime with products certified for organic viticulture. The regime consisted of standard (10–13), reduced (4–7) or minimal (2–4) sprayings of Funguran progress® (350 g copper per kg [copper hydroxide]), Netzschwefel Stulln (796 g sulfur per kg) and VitiSan® (9949 g potassium bicarbonate per kg) per season. Under standard sprayings, fungicides were applied weekly between May and August following a standardized scheme. The number of sprayings and spraying intervals varied between years depending on phenological stages of the grapes and pathogen pressure, following recommendations of viticultural advisory authorities (supplementary Table S1). While conventional spraying regimes require a change of products between sprayings, the use of an organic spraying regime allowed us to spray the same products every time. This way, the impact of one spraying on the arthropod fauna was as standardized as possible. However, organic spraying products must be applied before disease incidence to allow adequate protection, which leads to relatively frequent

spraying in the studied region. No insecticides, acaricides or any other foliage spray (e.g., growth regulators, fertilizers) were applied in the vineyard, which allowed us to ascribe spraying effects solely to fungicide applications.

2.2 Leaf mesofauna

Mites were sampled during the vegetation period between May and October. Sampling frequency differed between study years, resulting in two sampling dates in 2015, seven sampling dates in 2016, five sampling dates in 2017, and four sampling dates in 2018 and 2019 (supplementary Table S2). At each sampling, we randomly selected 25 leaves from different vines in each of the 24 plots. Collected leaves were washed onto a filter paper following Hill and Schlamp (1984). All mites were counted and identified to family level using a stereomicroscope (Stemi 2000, Zeiss, Jena, Germany). As the focus of our study was mostly on functional aspects, we identified only a subsample of adult individuals to species level every year using the preparation method described by Krantz (1978) and the keys introduced by Schruft (1972), Karg (1994), Schliesske (1995), and Tixier et al. (2013). After the mites were washed off, the leaf area was determined using a leaf area meter (Li-COR, Modell 3100 area meter, Lincoln, NE, USA). Leaf area was used to calculate mite densities per square meter of leaf area, which was necessary due to differing leaf sizes of the four varieties being affected by the pruning method. We counted beneficial mites (Acari:Tydeidae and Phytoseiidae), the phytophagous mites *Colomerus vitis* Pagenstecher and *Calepitrimerus vitis* Nalepa (Acari:Eriophyiidae), thrips (Thysanoptera) and immature leafhoppers (*Empoasca* sp., Hemiptera:Cicadellidae).

2.3 Macrofauna

Arthropods were sampled during the vegetation period between April and October. Sampling frequency differed between study years, resulting in three sampling dates in 2015, five sampling dates in 2016 and 2018, nine sampling dates in 2017, and four sampling dates in 2019 (supplementary Table S2). We took samples of the whole grapevine canopy using a beat-sheet with a diameter of 72 cm (beat-sheet by Dynort, bioform Dr. J. Schmidl e.K., Nürnberg, Germany). The sheet was placed under the vines while they were shaken vigorously. All arthropods falling on the sheet were collected and stored in 70 % ethanol for further identification. We repeated the shaking on 10 vines per plot in 2015–2017 and 20 vines per plot in 2018 and 2019, respectively. All arthropods were counted and identified at least to order level using a stereomicroscope (Stemi 2000, Zeiss, Jena, Germany) and the identification key by Schaefer (2017).

2.4 Predation rate assessment

To assess the natural pest control potential in the vineyard, we used eggs of the grape berry moth (*Lobesia botrana* Denis & Schiffermüller)(Lepidoptera:Totricidae) as a proxy, since it is of major concern in a global context (Benelli et al., 2023). Viticulture in the study area was more or less insecticide-free because the grape berry moth was controlled with mating disruption, and *Scaphoideus titanus* Ball (Hemiptera: Cicadellidae), a vector of the grapevine phytoplasma disease flavescence dorée, was not present. For rearing of *L. botrana* we

followed Markheiser et al. (2018). Inside of the rearing containers, retainers were installed to allow for oviposition on exchangeable polyethylene strips. Egg-laden strips were harvested after 24 h and stored at 4 °C for a maximum of four days until exposure. Strips contained 45 ± 16 eggs on average. To determine predation rates, baits were attached to randomly selected one-year-old branches and were exposed there for 72 hours. We exposed five baits per plot between May and September. Sampling frequency differed between study years, resulting in two sampling dates in 2015 and 2017, four sampling dates in 2016 and 2019, and five sampling dates in 2018. The eggs were counted before and after exposition using stereomicroscopes (Zeiss, Jena, Germany). We stored eggs that remained on the baits in a climate chamber at 70 % rh and 21 °C for two weeks to check for parasitism, but did not find any parasitised eggs.

2.5 Data analysis

All statistical analyses were done in R version 3.6.3 (R Core Team, 2023). To account for the different sampling intensities, data were combined for each year. Densities of mites, thrips and leafhoppers on leaves were averaged over all sampling dates of each year to obtain one observation per year per plot. Numbers of sampled arthropods by beat-sheet were averaged to obtain one observation per year per 10 vines shaken per plot. To obtain a general predator abundance, abundances of spiders, earwigs, ants, lacewings, harvestmen and ladybirds were summed. Percentages of predated *L. botrana* eggs were averaged to obtain one observation per year per plot.

The distribution of response variables was checked visually using ‘qqp’ (R package car) (Fox and Weisberg, 2019). Accordingly, all variables were analyzed with negative binomial distribution using generalized linear models fitted with the function ‘glm.nb’ and log link (R package MASS; Venables and Ripley, 2002). Models contained pruning (2 categories), spraying frequency (continuous), year (5 categories) and variety (4 categories) as well as the interactions pruning*year, spraying frequency*year, and pruning*spraying frequency as explanatory variables. No further model simplification was done. Post hoc tests were conducted if there was a significant effect of the variables ‘year’, ‘variety’ and the interaction ‘year*pruning’ using the function ‘emmeans’ (R package emmeans). *P* values were adjusted with the Tukey method. Effects of densities of the two beneficial mite families (Phytoseiidae, Tydeidae) on densities of phytophagous mites (*Cal. vitis*, *Co. vitis*), thrips and *Empoasca* sp. were analyzed using generalized linear models fitted with the function ‘glmer.nb’ and log link (R package MASS; Venables and Ripley, 2002). Models contained Phytoseiidae and Tydeidae as explanatory variables and year as a random factor. Cook’s Distance was used to check for outliers. Assumptions were checked for all models using graphical validation procedures (Zuur et al., 2009).

3 RESULTS

Climatic conditions varied greatly over the five studied years. Highest sums of cumulative precipitation during the study period occurred in 2017 with more than 272 mm. Average leaf moisture was highest in 2016 (41 %). Average temperatures varied between 18.3 °C in 2017 and 19.8 °C in 2018, while highest temperature maxima occurred in 2015 (39.8 °C). Similarly, pathogen pressure varied over the five studied years. Downy mildew occurred in 2016 only, with lowest incidences under full fungicide applications and in trellis system (Kraus et al., 2018). Powdery mildew mostly occurred in 2019 with lowest incidences under full fungicide applications and in trellis system (Kraus, personal communication).

Arthropod abundances, mite densities, and predation rates differed over the study period, with no clear overall temporal trend (Fig. 1, 2, and 3; supplementary Table S3). For instance, phytoseiid density was significantly higher in 2018 and 2019 compared to 2015-2017, while densities of *Cal. vitis* differed in all years except for 2017 and 2018 (supplementary Table S4). Furthermore, seven arthropod taxa were affected by the grape variety with no clear overall trend. Densities of the leaf mesofauna were similar in the varieties Villaris and Gf 84-58-988 but differed in the other two varieties. Cicadellid abundances were higher in red than in white varieties (supplementary Table S4).

Table 1 Effects of minimal pruning and reduced fungicide spraying on arthropod densities and predation rates. Significant *p*-values (< 0.05) are displayed in bold.

	pruning (df 1)		spraying frequency (df 1)		year (df 4)		variety (df 3)		interaction (year * pruning) (df 4)		interaction (year * spraying frequency) (df 4)		interaction (spraying frequency * pruning) (df 1)	
	<i>X</i> ²	<i>p</i>	<i>X</i> ²	<i>p</i>	<i>X</i> ²	<i>p</i>	<i>X</i> ²	<i>p</i>	<i>X</i> ²	<i>p</i>	<i>X</i> ²	<i>p</i>	<i>X</i> ²	<i>p</i>
Leaf mesofauna														
Phytoseiidae	30.07	< 0.001	44.42	< 0.001	82.16	< 0.001	17.09	< 0.001	27.15	< 0.001	18.27	0.001	1.26	0.263
Tydeidae	11.20	< 0.001	30.23	< 0.001	259.55	< 0.001	7.01	0.072	8.03	0.091	4.16	0.385	0.99	0.321
<i>Cal. vitis</i>	2.28	0.131	8.67	0.003	185.90	< 0.001	89.04	< 0.001	15.06	0.005	7.59	0.108	10.34	0.001
<i>Co. vitis</i>	4.61	0.032	7.68	0.006	175.05	< 0.001	98.03	< 0.001	9.70	0.046	4.93	0.295	4.66	0.031
<i>Empoasca</i> sp.	0.65	0.419	1.21	0.271	136.65	< 0.001	2.23	0.527	7.80	0.099	0.73	0.948	0.53	0.467
Thrips	31.83	< 0.001	0.14	0.707	213.28	< 0.001	18.18	< 0.001	5.03	0.284	2.71	0.607	1.14	0.286
Macrofauna														
total abundance	1.73	0.188	27.67	< 0.001	123.57	< 0.001	5.84	0.120	6.15	0.188	2.31	0.679	1.43	0.232
predators	1.63	0.202	14.90	< 0.001	84.50	< 0.001	1.83	0.608	5.29	0.259	2.88	0.578	1.74	0.187
spiders	0.59	0.441	11.42	< 0.001	96.69	< 0.001	7.44	0.059	4.19	0.381	3.48	0.481	0.02	0.881
earwigs	30.23	< 0.001	0.04	0.838	13.74	0.008	10.85	0.013	1.28	0.864	0.46	0.977	2.68	0.101
ants	0.43	0.511	5.08	0.024	137.79	< 0.001	13.12	0.004	9.29	0.054	1.52	0.823	2.60	0.107
leafhoppers	8.61	0.003	2.20	0.138	77.71	< 0.001	26.95	< 0.001	17.15	0.002	1.06	0.901	0.06	0.809
Predation rates														
<i>L. botrana</i> eggs	0.67	0.412	10.89	< 0.001	156.84	< 0.001	2.23	0.526	12.32	0.015	4.15	0.386	5.30	0.021

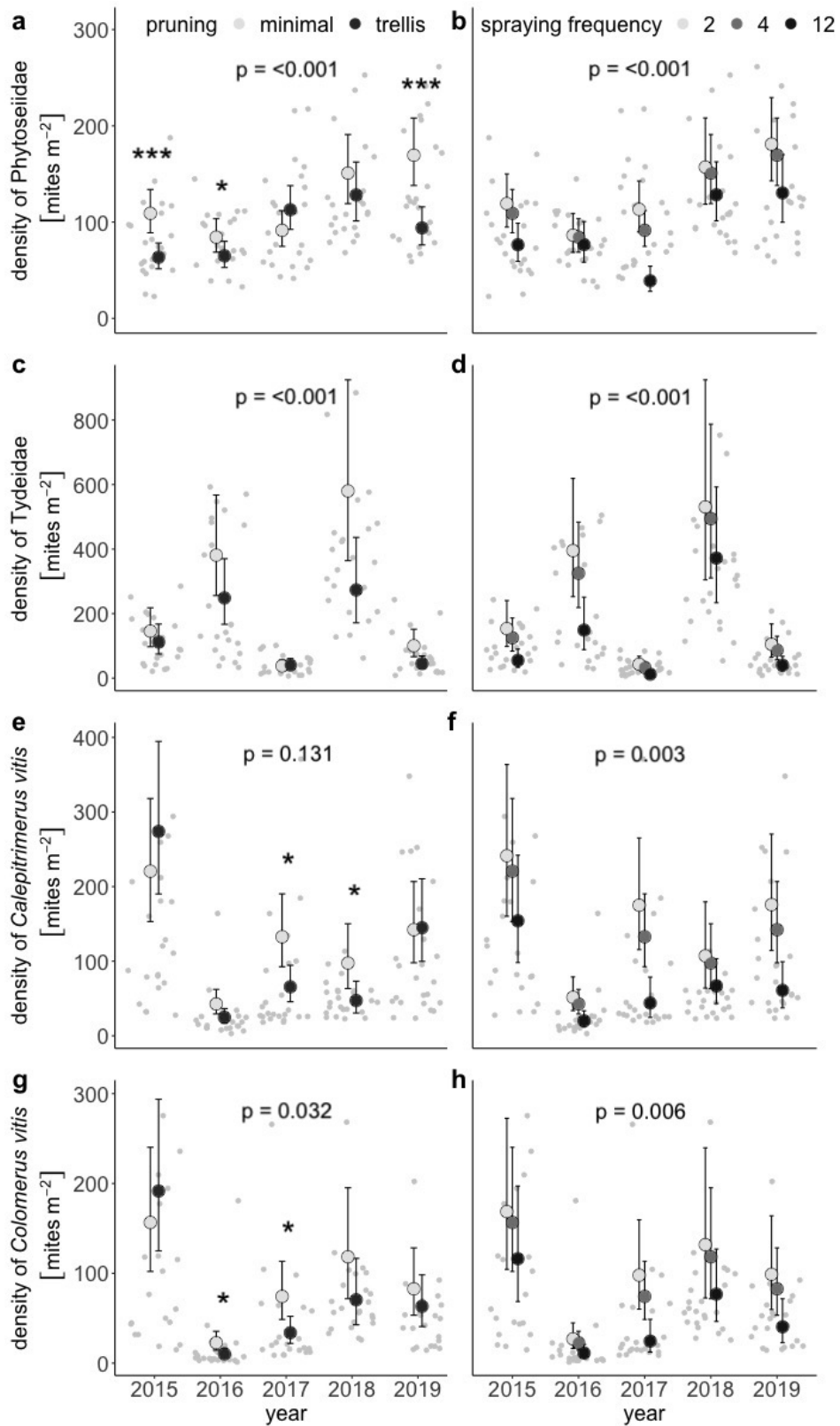


Figure 1 Mite densities of Phytoseiidae (a, b), Tydeidae (c, d), and the two eriophyid mites *Cal. vitis* (e, f) and *Col. vitis* (g, h) in five consecutive years with respect to pruning system (a, c, e, g) and spraying frequency of fungicides (b, d, f, h). Larger dots show model predicted means with respective error bars (95 % confidence interval), while smaller grey dots represent individual plots of the experimental vineyard. *P*-values for the impact of pruning and spraying frequency are indicated in the upper middle of the panels, respectively. Differences between the pruning systems were indicated with asterisks ($p < 0.001$ ‘***’; $p < 0.05$ ‘*’) for the respective year when overall interactive effects between pruning system and year occurred. The significance of the differences between spraying frequencies are not displayed since no interactive effects between spraying frequency and year occurred.

3.1 Leaf mesofauna

The densities of the two beneficial mite families, Phytoseiidae and Tydeidae, as well as the two phytophagous mites, *Co. vitis* and *Cal. vitis*, were higher in reduced fungicide sprayings (Tab. 1, supplementary Table S3, Fig. 1). Phytoseiid and tydeid mite densities were 37 % and 45 % higher under minimal compared to standard sprayings, respectively. These effects were strongest in 2017 for Phytoseiidae (68 % increase under minimal sprayings). Smallest effects of reduced sprayings were found in 2016 for Phytoseiidae (17 % increase under minimal sprayings). *Co. vitis* and *Cal. vitis* densities were 26 % and 27 % higher, respectively, under minimal compared to standard sprayings.

Both beneficial mite families as well as *Co. vitis* benefitted from minimal pruning (Tab. 1, supplementary Table S3, Fig. 1). Phytoseiid mite densities were 25 % higher in minimal pruning, with strongest effects in 2019 (46 % increase in minimal pruning). Tydeid mite densities were 41 % higher in minimal pruning. Densities of *Co. vitis* were 10 % higher in minimal pruning, with strongest effects in 2017 (53 % increase in minimal pruning). Although densities of *Cal. vitis* were significantly higher in 2017 and 2018 (37-49 % increase in minimal pruning) there was no clear temporal trend. Densities of both phytophagous mites were higher in reduced fungicide sprayings under minimal pruning. In contrast, *Co. vitis* and *Cal. vitis* densities were higher under intensive fungicide sprayings in trellis system (Tab. 1, supplementary Table S3).

Thrips densities were 38 % higher in trellis system. Densities of Phytoseiidae and Tydeidae were not related to thrips densities (supplementary Table S5). Densities of *Empoasca sp.* were neither affected by pruning system nor by spraying frequency, but decreased with increasing phytoseiid mite densities (Tab. 1, supplementary Tables S3, S5). Densities of both phytophagous mite species were higher when tydeid mite densities were low (supplementary Table S5).

3.2 Macrofauna and predation rates

In five years, we identified a total of 12590 arthropods that belonged to 20 orders. Highest arthropod abundances were observed in 2015 (21.2 ± 8.8 individuals per 10 vines) and lowest in 2017 (9.4 ± 2.0). Predation rates of *L. botrana* eggs were highest in 2019 (67.6 ± 10.7 %) and lowest in 2017 (42.3 ± 15.6 %). Reduced fungicide sprayings enhanced total arthropod abundance, predator abundance, and predation rates (Tab. 1, supplementary Table S3, Fig. 2). However, no clear effects of the pruning system could be observed. Total arthropod abundance was 27 % higher under minimal compared to standard sprayings. Likewise predator abundance was 24 % higher. Predation rates were 19 % higher under reduced sprayings. Further, effects of trellis system on predation rates were highest in 2015 (34 % increase in trellis system; Tab. 1), but with no clear temporal trend (Fig. 2 e).

Abundances of spiders and ants were 26 and 35 % higher, respectively, under fungicide reduction, while earwig and cicadellid leafhopper abundances were not affected (Tab. 1, supplementary Table S3, Fig. 3). In contrast, earwig and cicadellid leafhopper abundances were 59 % and 37 % higher in trellis system, respectively (Tab. 1, supplementary Table S3, Fig. 3). Nevertheless, the effects of trellis system on leafhopper abundances varied significantly over time with strongest effects of trellis system in 2015 (90 % increase; Tab. 1, Fig. 3 g).

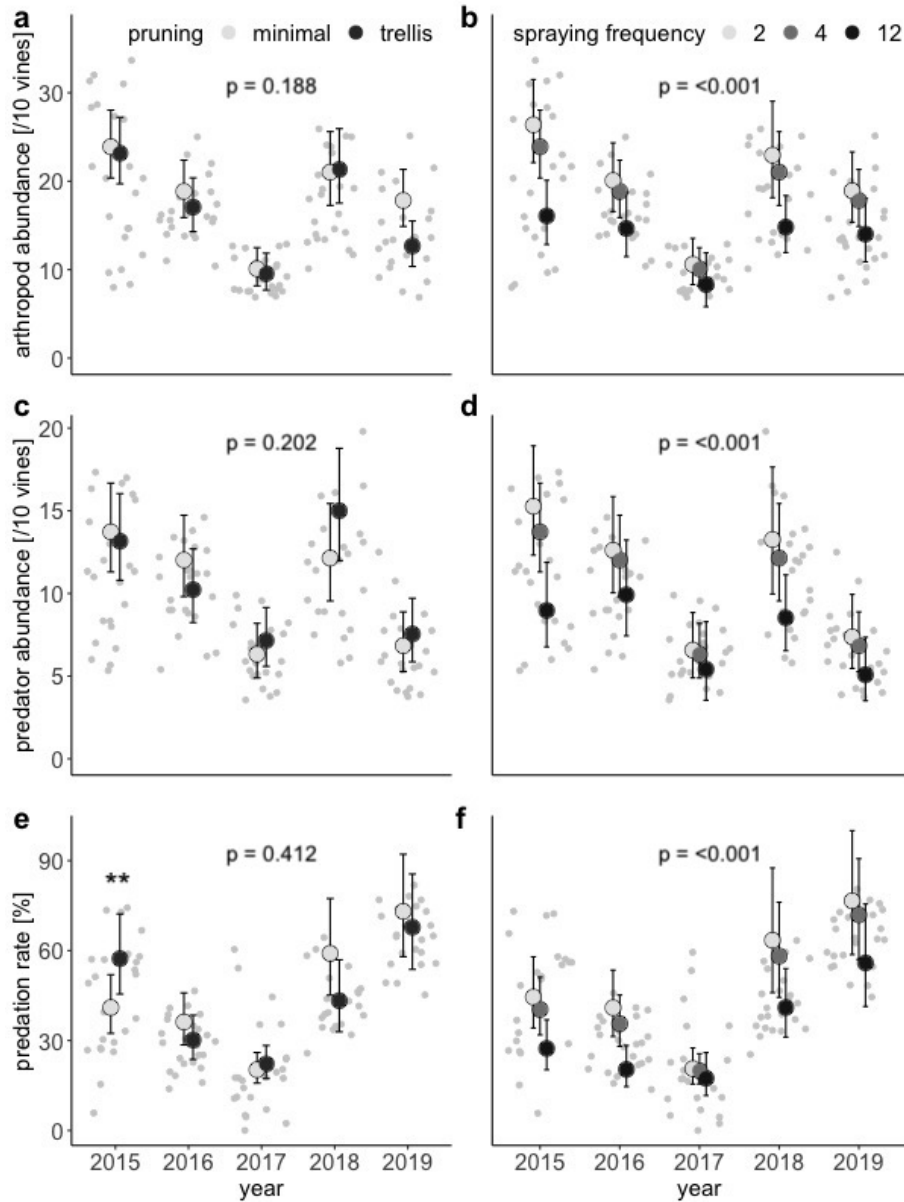


Figure 2 Arthropod abundance (a, b), predator abundances (c, d) and predation rates of *L. botrana* eggs (e, f) in five consecutive years with respect to pruning system (a, c, e) and spraying frequency of fungicides (b, d, f). Larger dots show model predicted means with respective error bars (95 % confidence interval), while smaller grey dots represent individual plots of the experimental vineyard. *P*-values for the impact of pruning and spraying frequency are indicated in the upper middle of the panels, respectively. Differences between the pruning systems were indicated with asterisks ($p < 0.01$ “**”) for the respective year when overall interactive effects between pruning system and year occurred. The significance of the differences between spraying frequencies are not displayed since no interactive effects between spraying frequency and year occurred.

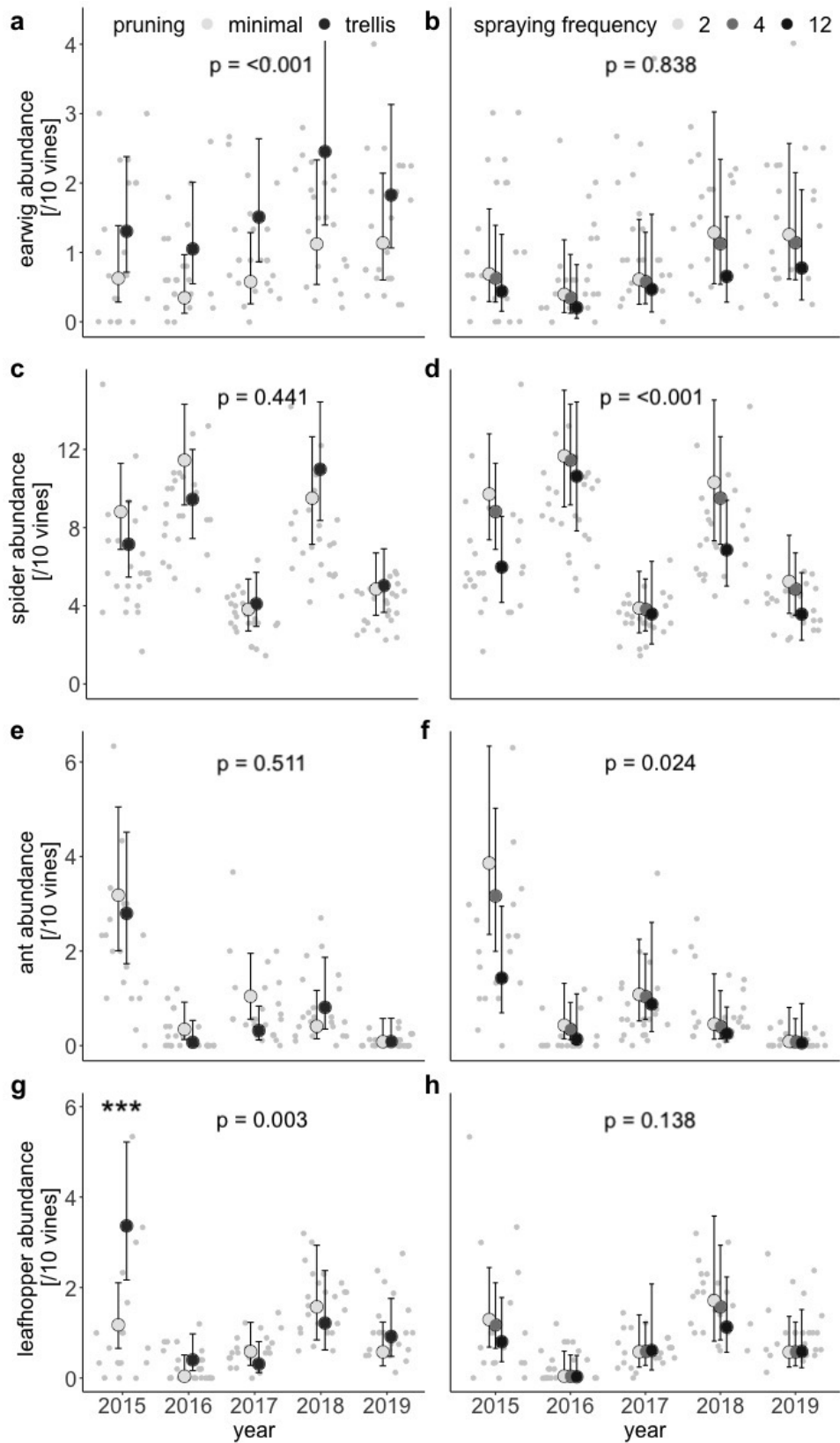


Figure 3 Abundances of spiders (a, b), earwigs (c, d), ants (e, f) and cicadellid leafhoppers (g, h) in five consecutive years with respect to pruning system (a, c, e, g) and spraying frequency of fungicides (b, d, f, h). Larger dots show model predicted means with respective error bars (95 % confidence interval), while smaller grey dots represent individual plots of the experimental vineyard. P-values for the impact of pruning and spraying frequency are indicated in the upper middle of the panels, respectively. Differences between the pruning systems were indicated with asterisks ($p < 0.001$ “***”) for the respective year when overall interactive effects between pruning system and year occurred. The significance of the differences between spraying frequencies are not displayed since no interactive effects between spraying frequency and year occurred.

4 DISCUSSION

4.1 Effects of reduced fungicide applications

In agreement with our hypothesis, we found strong effects of reduced fungicide applications on most of the studied arthropods every year. Significant variation of the fungicide effect over time was found for only one taxon, the Phytoseiidae. We conclude that the impacts of fungicide sprayings are consistent even under strong variation



of environmental conditions. In spite of the high number of applications, fungicide use was restricted to three months per year. Non-target effects of pesticides are strongest shortly after spraying (Schindler et al., 2022). Thus, we assume that arthropod populations levelled out between our plots over the non-sprayed period of the year due to population recovery and movement between plots, making cumulative effects of fungicides unlikely to appear.

Beneficial mites as well as pest mites benefitted from reduced sprayings. Both

Phytoseiidae and Tydeidae are susceptible to numerous fungicides and strongly affected by frequent sprayings (Gadino et al., 2011; Möth et al., 2021; Peverieri et al., 2009; Pozzebon et al., 2010; Reiff et al., 2021a). Further, sulphur is used to control pest mites (Duso et al., 2012). Thus, adverse effects of sulfur-based fungicides on eriophyid mites were expected. We further found strong effects of reduced fungicide treatments on total arthropod abundances as well as on predators and predation rates. Spiders are the most abundant predators in vineyards (Costello and Daane, 2005). Unlike previous studies on canopy dwelling spiders in vineyards (Nash et al., 2010; Pennington et al., 2019) we found clear benefits of reduced fungicide sprayings on spider abundance. Ants are susceptible to insecticides but less so to other pesticides and particularly sulphur (Chong et al., 2007; Masoni et al., 2017; Olotu et al., 2013). However, we found small but consistent effects of reduced fungicide applications on ants, which might be attributed to the copper content of the sprayings (Diehl et al., 2004; Migula and Głowacka, 1996). Since most ants live in colonies in the soil, the catches in the grapevine canopy are, however, not representative of ant densities (Schlick-Steiner et al., 2006). By contrast, densities of *Empoasca* sp. and thrips, as well as the abundance of earwigs were not affected by fungicide intensities. James et al. (2002) already reported a certain tolerance of thrips towards fungicides. Although earwigs are susceptible to insecticides, fungicides appear to have no or low effects on them (Huth et al., 2011; Malagnoux et al., 2015; Orpet et al., 2019). The experimental vineyard was not treated with insecticides, which could thus explain why earwigs were not affected by reduced sprayings. Similar results were also observed in vineyards of self-marketing wineries in the same study region (Reiff et al., 2023).

4.2 Effects of minimal pruning

In contrast to the consistent effects of fungicides, effects of minimal pruning were less strong, and restricted to the leaf mesofauna, earwigs, and leafhoppers. Contrarily, total arthropod abundance and, particularly, predator abundance were not affected by minimal pruning. This contrasts findings of Langellotto and Denno (2004) highlighting that increased architectural complexity of plants promotes natural enemies. However, the effects of the different pruning systems were strongly modulated by the studied years and presumably affected by weather conditions. Beneficial mites as well as *Co. vitis* densities were higher in minimal pruning. Both pest and beneficial mites overwinter on wooded parts of the grapevine, e.g. in bark fissures and under grape bud scales (Duso and de Lillo, 1996; Kinn and Douth, 1972). The higher amounts of wood and increased abundance of buds in minimal pruning might thus have already increased overwintering populations. Further, Duso and de Lillo (1996) describe a favourable development of *Co. vitis* inside leaf patches with high relative humidity. Similarly, high humidity and leaf moisture favours phytoseiid development (Nakai et al., 2021). In agreement with this, the densities of *Co. vitis* and Phytoseiidae were higher in minimal pruning with increased humidity in the grapevine canopy (Kraus et al., 2018). By contrast, thrips densities were higher in trellis system despite their development being also favoured by humidity (Omkar, 2021). This indicates increased natural pest control in minimal pruning. However, the abundance of omnivorous earwigs was higher in trellis system. Huth (2011) found more earwigs in tight compared to loose grape clusters. Since minimal pruned vines have less compact grape clusters than vines in trellis system (Intrieri et al., 2011) we assume that earwigs find more shelter in trellis systems despite the higher wood proportion in minimal pruning. Despite possible differential effects of altered canopy architecture and resulting microclimatic variation on some spider families (Entling et al., 2007; Herrmann et al., 2010), overall spider abundance remained unaffected by minimal pruning. Pennington et al. (2019) describe opposing effects of minimal pruning for some spider families, but detected no overall effect on spider abundance either.

4.2 Implications for pest control

L. botrana is consumed by a wide range of predators, including spiders, earwigs, and ants (Marchesini and Dalla Montà, 1994; Reiff et al., 2021b). Both predator abundance and predation rates on *L. botrana* eggs increased in reduced fungicide sprayings. These findings are in line with studies in vineyards of self-marketing wineries in Austria and Germany (Reiff et al., 2023, 2021b). Further, reduced pesticide input fostered predator abundances and pest control also in other viticultural regions (Caprio et al., 2015; Gaigher and Samways, 2010; Muneret et al., 2019a, 2019b), but it remains unclear to which extent this effect results from the reduction of fungicides, herbicides and/or insecticides. While predator abundance decreased in 2019, predation rates were still high. On the one hand, predators could have been more effective. For instance, a single individual of *Tettigonia viridissima* (Orthoptera:Tettigoniidae) predated five pupae of *L. botrana* in one night of camera-surveyed sentinel card exposition (Reiff et al., 2021b). On the other hand, predator communities with high biomass species (like earwigs) may have higher intra-guild predation and, thus, reduced effects on pest populations (Ostandie et al., 2021). In the study region, Typhlocibynae such as *Empoasca* sp. were the most abundant leafhoppers in beat-sheet samples (Reiff et al., 2023). Despite being susceptible to organic spraying regimes with copper and sulphur (Pavan, 1994) we found no effects of reduced sprayings on leafhopper abundance. Nevertheless, regarding the

overall low number of leafhoppers we assume that generally high numbers of predators kept leafhopper densities below economic relevance.

All four pest taxa of the leaf mesofauna occurred in relatively low densities. For instance, economic thresholds 280 mites/leaf of *Cal. vitis* (Hluchý and Pospíšil, 1992) were undercut by almost factor ten in our study. Similarly, even the highest thrips densities in our study undercut the economic threshold by factor eight (James et al., 2002). Infestations with *Empoasca sp.* in vineyards can cause severe damage to quality and yield (Bosco et al., 1997; Olivier et al., 2012). However, even in 2018 their density undercut the economic threshold by almost factor three (Popa and Roşca, 2011). Furthermore, it is assumed that the infestation with *Co. vitis* does not cause severe damages (Duso and de Lillo, 1996). Both eriophyid mites responded negatively to increased densities of Tydeidae, and *Empoasca sp.* appeared to be negatively affected by increasing densities of Phytoseiidae. Both Phytoseiidae and Tydeidae can feed on several pests such as eriophyid mites and thrips (Schruff, 1972; Engel and Ohnesorge, 1994). We thus assume that natural pest control was effective throughout the study period, particularly in the treatments with reduced fungicide applications.

4.4 Limitations and future perspectives

Experimental vineyards allow to investigate effects in a standardized way. However, upscaling to display real-world conditions must be done with caution. Given the small plot size in our studied vineyard and the high mobility of certain taxa, arthropod movement between plots could have dampened the results. Further, grape varieties affected several taxa without a clear pattern which fails to fit with morphological characteristics (e.g., leaf hairiness). Despite these limitations, similar impacts of fungicides were found in single-year studies across multiple vineyards of the same study region under production conditions of commercial vineries with multiple grape varieties (Reiff et al., 2023, 2021a). Taken together, the long-term study in the experimental vineyard and the observations in the commercial vineries suggest that most of the observed effects can be generalized in our study region.

Arthropods in general and especially phytoseiid mites are directly affected by weather conditions, such as heat and drought, but also indirectly by plant growth (habitat, food, shelter) and pathogen pressure (Yarwood, 1943; Cerdá et al., 1998; Duso et al., 2005; Pozzebon and Duso, 2008; Gadino and Walton, 2012; Orpet et al., 2019; Fricke et al., 2022; Kaczmarek et al., 2022). However, given the large number of variables likely to affect arthropod abundances, we cannot adequately address inter-annual variances. Hence, it underlines once more the persistent benefits of reduced fungicide sprayings. In the studied varieties disease incidence was low in all years even under the strongest fungicide reduction. We conclude, that fungicide applications can be strongly reduced in fungus-resistant varieties while maintaining healthy grapes.

With generally high numbers of predators (Reiff et al., 2023; Retallack et al., 2019; Sáenz-Romo et al., 2019; Shapira et al., 2018), vineyards are habitats with high potential for natural pest control. Our study revealed that natural pest control can be fostered even more by reducing fungicide sprayings. Despite altered climatic conditions in the five consecutive years of the study and arthropods of different trophic levels being studied, we found consistently strong benefits of reduced fungicide sprayings. However, effects of minimal pruning were less constant over the studied years. We conclude that short-term studies may be sufficient to predict the effect of

strong-impact variables like fungicide sprayings. Nevertheless, long-term studies remain important to display effects of other predictor variables. Moreover, with increasing effects of habitat disruption and climate change, short-term studies may fail to predict the direction of shift. In this sense, the benefits of altered microclimatic conditions in minimal pruned grapevine canopies may become more prominent with climate change.

ACKNOWLEDGEMENTS

We are grateful to Thomas Gramm for managing the experimental vineyard, to Sandra Biancu, Anna Markheiser, Sonja Anslinger, and Argyroula Tsormpatzidou for rearing *L. botrana* for use in our experiments, to Christian Kraus for providing data on infection levels with fungal diseases, and to Anja Hollander, Ken Mauser, Malte Neumann, Verena Pfaff, and again Argyroula Tsormpatzidou for their help with sampling and counting arthropods. We thank the anonymous reviewers and editors who improved an earlier version of the manuscript.

FUNGICIDE REDUCTION FAVORS THE CONTROL OF PHYTOPHAGOUS MITES UNDER BOTH ORGANIC AND CONVENTIONAL VITICULTURE

Jo Marie Reiff ^{a,b}, Marvin Ehringer ^{a,b}, Christoph Hoffmann ^b, Martin H. Entling ^a

*a RPTU Kaiserslautern-Landau, iES Landau, Institute for Environmental Sciences,
Fortstraße 7, D-76829, Landau in der Pfalz, Germany*

*b Julius Kühn-Institute, Federal Research Institute for Cultivated Plants,
Institute for Plant Protection in Fruit Crops and Viticulture,
Geilweilerhof, D-76833 Siebeldingen, Germany*

ABSTRACT

Pesticides can have detrimental effects on non-target biodiversity, especially in intensively managed agroecosystems such as vineyards. However, new fungus-resistant grape varieties can greatly reduce the need and use of fungicides. Fungicides can have direct and indirect effects on economically important predatory mites (mainly Phytoseiidae) and on phytophagous mites (Tetranychidae, Eriophyidae) on which they prey. We investigated the impact of fungicide treatments on beneficial and phytophagous mite densities in 32 vineyards of organic and conventional wineries planted with susceptible and fungus-resistant grape varieties in the Palatinate region, Germany. Organic vineyards were sprayed with different formulations of sulfur, copper and potassium bicarbonate, while conventional vineyards received mostly synthetic fungicides. Fungicide applications were reduced by 47-80 % in fungus-resistant varieties, with stronger reductions under organic than under conventional management. Regardless of organic or conventional management, predatory mites (Phytoseiidae and Tydeidae) were significantly enhanced in vineyards planted with fungus-resistant varieties. Contrastingly, phytophagous mites (Eriophyidae) were enhanced in vineyards with fungus-susceptible varieties and in those under organic management. Densities of further predatory mite families increased under organic farming (Anystidae) or showed an interactive response to farming system and grape variety (Trombidiidae). Reduced fungicide applications through cultivation of fungus-resistant varieties enhance predatory mite densities and thus contribute to higher natural pest control potential. Thus, the cultivation of fungus-resistant grape varieties is an effective approach towards more environmentally friendly viticulture.

KEYWORDS

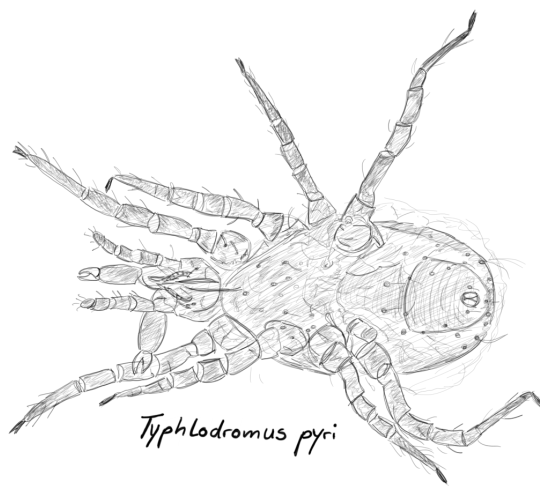
fungus-resistant crops, pest control, non-target effects, Phytoseiidae, predatory mites, Eriophyidae

I INTRODUCTION

Agricultural intensification is leading to global declines of arthropods (Hallmann et al., 2017; Sánchez-Bayo and Wyckhuys, 2019; Seibold et al., 2019). The use of pesticides and fertilizers is considered to be among the main drivers (Sánchez-Bayo and Wyckhuys, 2019). Pesticides can have a detrimental effect on arthropod biodiversity in agricultural landscapes (Benton et al., 2002; Ewald et al., 2015; Geiger et al., 2010) and thus impacts ecosystem services such as natural pest control (Bianchi et al., 2006; Gurr et al., 2003). Therefore, reducing the use of pesticides and creating a stronger reliance on alternative pest management strategies would be a promising approach for a more sustainable agriculture (Brühl and Zaller, 2019, Zehnder et al., 2007).

Due to their susceptibility to numerous pests and diseases, vineyards receive multiple plant protection treatments per year, in particular fungicides (Gary et al., 2010; Gregoire et al., 2010; Mezière et al., 2009; Pertot et al., 2017). While in conventional viticulture mainly synthetic fungicides are sprayed (Cabras and Conte, 2001; Katayama et al., 2019; Pozzebon et al., 2002), organic winegrowers are using non-synthetic fungicides such as copper and sulfur (Provost and Pedneault, 2016). Both synthetic and non-synthetic fungicides are reported to affect non-target organisms (Brühl et al., 2013; Desneux et al., 2007; Nicòtina and Capone, 2007; Pozzebon et al., 2010; Yasmin and D'Souza, 2010). A promising approach towards more sustainable viticulture is the cultivation of new fungus-resistant varieties (Töpfer et al., 2011). Fungicide treatments can be reduced by 80 % in some multi-resistant cultivars (Pedneault and Provost, 2016). Although this fungicide reduction could greatly benefit non-target organisms, we are aware of only a single study that evaluated its effects in commercial vineyards (Pennington et al., 2019).

Despite the high use of agrochemicals, vineyards are providing habitat for a variety of animals. Among arthropods the interactions between predatory mites (Phytoseiidae) and phytophagous mites (Eriophyidae and Tetranychidae) are among the most studied (Ahmad et al., 2015; Duso and Vettorazzo, 1999; Engel and Ohnesorge, 1994; James and Whitney, 1993; Pennington et al., 2017; Prischmann et al., 2006). While infestations of phytophagous mites such as spider mites (Tetranychidae) and Eriophyidae can be economically damaging in viticulture (Duso et al., 2012), several beneficial mite species occur in vineyards being able to suppress pest mite outbreaks. Phytoseiidae are important predators of phytophagous mites (Duso and Vettorazzo, 1999; Walton et al., 2012). They are mostly generalists that can sustain stable populations without prey by feeding on alternative sources such as pollen and fungi (Ahmad et al., 2015; Duso et al., 2012; Engel and Ohnesorge, 1994; McMurty and Croft, 1997; Walton et al., 2012). Tydeid mites are another group of important predatory mites feeding on Eriophyidae, but also feed on fungi and plant tissue (Duso et al., 2005; Khederi and Khanjani, 2014; Perring and McMurtry, 1996; Schruft, 1972). Furthermore, mite families such as Bdellidae, Cunaxidae, Anystidae and Trombidiidae play a role in eriophyid and tetranychid mite predation (Castagnoli, 1989; Gerson, 1992; Khederi and Khanjani, 2014; Schruft, 1969; Walton et al., 2012; Zhang, 1992). Additional taxa such as Oribatida occur mainly on the trunk of vines,



without having clear management relevance for natural pest control (Castagnoli, 1989; Johann et al., 2014). For an overview of the roles of the different mite families, see Table S1. While some pesticides, such as acaricides and sulfur, are used against phytophagous mites (Duso et al., 2012) they can also have adverse effects on predatory mites. Several synthetic fungicides as well as copper, sulfur and plant strengthening agents used in organic farming can impact amongst others fecundity of phytoseiid mites such as *Typhlodromus pyri* (Fischer-Trimborn et al., 2000; Gadino et al., 2011; Morgan et al., 1958; Pozzebon et al., 2010, 2002; Walton et al., 2012). Also, some tydeid mites such as *Tydeus* sp. and *Homeopronematus anconai* are known to be affected by certain fungicides (Ball, 1982; Knop and Hoy, 1983; Schwartz, 1993). However, little is known about the impacts of fungicides on anystid, trombidid, cunaxid, and bdellid mites (Childers and Enns, 1975; James and Prischmann, 2010, 2010; Jubb et al., 1985; Kishimoto, 2002).

The objective of this study was to investigate the single and combined effects on mites of reduced spraying regimes through the cultivation of fungus-resistant grape varieties and organic versus conventional management. We expect higher densities of predatory mites in fungus-resistant varieties and organic management compared to classical varieties and conventional management. While phytophagous mites may also benefit from fungicide reduction, they should be suppressed by higher densities of predatory mites. Correspondingly, we expect higher densities of phytophagous mites in intensively sprayed susceptible varieties.

2 MATERIALS AND METHODS

2.1 Study sites

We investigated mites in 32 vineyards with contrasting spraying regime in the Palatinate region between Weyher and Klingenstein, Germany (supplementary Fig. S3). Vineyards were provided for the experiment by 16 winegrowers. Nine winegrowers managed their vineyards by organic standards, including an organic spraying regime. Seven winegrowers treated their vineyards with conventional plant protection products. Each winegrower provided two vineyards, one planted with susceptible cultivars and one with fungus-resistant varieties, resulting in 16 vineyard pairs with different fungicide intensity but otherwise similar management. Information on the spraying regimes was provided by the winegrowers (Table S4).



2.2 Grapevine leaf fauna

Mites were sampled monthly during the vegetation period between the end of May and mid-October in 2018. Leaf collection was done at 5 sampling dates, beat-sheet sampling at 6 dates, respectively.

2.2.1 Leaf collection

To assess the mite fauna on grapevine leaves, we followed Pennington et al. (2017). Twenty-five randomly selected leaves from different vines in each of the 32 vineyards were collected and washed onto a filter paper. After the mites were washed off, the leaf area was determined using a leaf area meter (Li-COR, Modell 3100 area meter, Lincoln, NE, USA). Leaf area was used to calculate mite densities per square meter of leaf area, which was necessary due to the different varieties studied differing in leaf size. Mites were counted and identified using a stereomicroscope (Stemi 2000, Zeiss, Jena, Germany). We directly identified phytophagous mites *Colomerus vitis* Pagenstecher, *Calepitrimerus vitis* Nalepa (Eriophyidae) and *Panonychus ulmi* Koch (Tetranychidae) and counted individuals of beneficial mites (Tydeidae and Phytoseiidae) at the family level. We randomly selected a subsample of 841 adult beneficial mites (Tydeidae and Phytoseiidae) from the filter paper for species determination using the preparation method described by Krantz (1978). Determination was done using a microscope with phase contrast (Leica DM 4000 B, Leica Microsystems, Wetzlar, Germany).

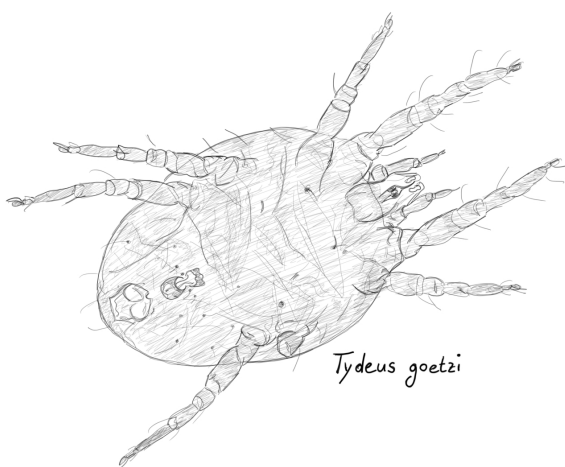
2.2.2 Beat-sheet sampling

To assess the abundance of further mite families, we took samples of the whole grapevine canopy using a beat-sheet with a diameter of 72 cm (beat-sheet by Dynort, bioform Dr. J. Schmidl e.K., Nürnberg, Germany). The sheet was placed under the vines while they were shaken vigorously. All arthropods falling on the sheet were collected and stored in 70 % ethanol for further identification. We repeated the shaking on 30 vines per vineyard. Mites were separated from the samples, counted and identified using a stereomicroscope (Stemi 2000, Zeiss, Jena, Germany).

2.3 Data analysis

Densities of Phytoseiidae, Tydeidae and Eriophyidae per leaf area were averaged, and numbers of Anystidae and Trombiidae from the beat sheet sampling summed over all sampling dates, resulting in one observation for each vineyard (for dataset see supplementary Table S5). The densities of both eriophyid species were summed to obtain

a “eriophyid mite density” dataset. Data were analyzed in R version 3.4.2 (R Core Team, 2015) using the package lme4 (Bates et al., 2015). Model distribution was chosen according to the distribution of response variables and was checked visually using ‘qqp’. Number of sprayings and phytoseiid mite densities were analyzed with linear mixed-effect models, fitted with the function ‘lmer’. Eriophyid and tydeid mite densities, and trombidiid and anystid mite abundance were analyzed with negative binomial generalized linear mixed-effect models, fitted with the function ‘glmer.nb’ (see Table S2).



In a first step, response variables were tested against “management” (organic/conventional) and “grape variety” (resistant/susceptible) with their interactions as fixed factor and “site” as random factor. In case fungus-resistance

showed significant effects on mite densities or abundances, these response variables were fitted with “site” as random factor and “number of sprayings” as fixed factor. “Number of sprayings” was not included as fixed factor in the first model to avoid collinearity of variables. A correlation test was conducted with eriophyid mite densities and phytoseiid or tydeid mite densities, respectively, using the function ‘cor.test’. Cook’s Distance was used to check for outliers, and did not exceed 0.5. Assumptions were checked for all models using graphical validation procedures (Zuur, 2009).

3 RESULTS

3.1 Plant protection

Organic and conventional spraying regimes differed considerably in number of treatments and type of applied compounds (Table 1). Organic spraying regimes included variable combinations of sulfur, copper, potassium bicarbonate and plant strengthening agents. Conventional spraying regimes included the products used by organic farmers plus a broad spectrum of synthetic fungicides. Out of 29 applied synthetic fungicides, 8 were classified moderately harmful towards predatory mites (3 specifically towards *T. pyri*; BVL, 2018).

The number of fungicide applications differed significantly between susceptible and fungus-resistant varieties (but see Table 2 for statistics; Fig. 1). Susceptible varieties in organic management were sprayed the most (9-15 times), whereas fungus-resistant varieties in organic management were sprayed the least (0-4 times). In conventional vineyards, fungus-resistant varieties were sprayed more often (3-7 times) and susceptible varieties less often (6-10 times) than in organic vineyards. As a result, the mean number of fungicide applications did not differ between organic and conventional viticulture.

Table 1 Mean number of total sprayings and applications per compound with respective standard deviations by vineyard type.

	organic		conventional	
	resistant	susceptible	resistant	susceptible
number of sprayings	2.2 ± 1.2	10.8 ± 1.9	4.3 ± 1.6	8.1 ± 1.6
copper ^{ab*}	1.8 ± 1.5	8.3 ± 4.8	0.3 ± 0.8	0.7 ± 1.5
sulfur ^a	2.0 ± 1.0	8.7 ± 1.7	1.7 ± 1.1	2.7 ± 0.1
with potassium bicarbonate ^b	0.6 ± 0.7	5.0 ± 1.2	–	0.3 ± 0.8
synthetic fungicides ^a	–	–	2.3 ± 1.1	5.4 ± 3.3
synthetic fungicides ^b	–	–	3.1 ± 3.2	4.9 ± 2.4

a products are classified as harmless towards predatory mites; **b** products are classified as harmful towards predatory mites (BVL, 2018); * Two different copper formulations sprayed (see Table S4, for a complete list).

Table 2 Model outputs for six tested response and four explanatory variables. Significant *P*-values are displayed in bold. Model estimates and standard errors are displayed as difference between first and second level of the respective variable. See Table S2 for model types and families.

	management (conventional/organic)				grape variety (resistant/susceptible)				interaction (management x grape variety)				number of sprayings			
	Est.	SE	X ²	P	Est.	SE	X ²	P	Est.	SE	X ²	P	Est.	SE	X ²	P
number of sprayings	-2.35	0.87	<0.01	0.724	3.86	0.68	209.94	<0.001	4.70	0.90	26.99	<0.001	-	-	-	-
Phytoseiid mite density	81.93	57.66	0.11	0.737	-46.08	47.85	14.40	<0.001	-131.58	63.80	4.25	0.039	-19.35	4.07	22.62	<0.001
Tydeid mite density	-0.04	0.55	0.92	0.339	-0.26	0.31	12.53	<0.001	-0.89	0.42	4.42	0.035	-0.11	0.03	10.80	<0.001
Eriophyid mite density	0.47	0.21	3.30	0.069	0.41	0.15	7.27	0.007	-0.26	0.20	1.79	0.181	0.03	0.01	5.72	0.017
Anystid mite abundance	0.79	0.46	4.12	0.042	0.38	0.39	2.32	0.128	-0.06	0.48	0.01	0.908	-	-	-	-
Trombidiid mite abundance	0.08	0.48	1.18	0.277	0.34	0.33	0.97	0.326	-1.11	0.46	5.84	0.016	-	-	-	-

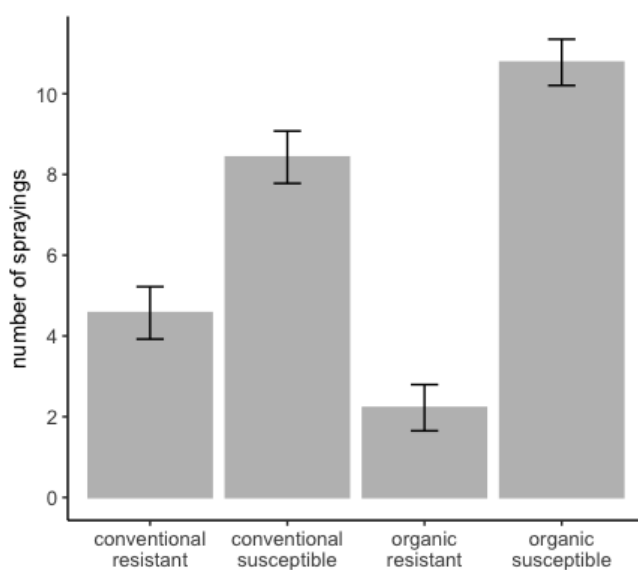


Figure 1 Relationship between management (organic/conventional), grape variety (susceptible/resistant) and number of fungicide treatments in N = 32 vineyards (model predicted means ± standard errors).

3.2 Leaf mesofauna

Beneficial mites were dominated by *Typhlodromus pyri* Scheuten (91 % of Phytoseiidae) and *Tydeus goetzi* Schruft (100 % of Tydeidae; see Table S6 for a complete list). Phytoseiidae had 35 % higher densities in vineyards with fungus-resistant compared to susceptible varieties, whereas organic versus conventional management resulted in similar densities. In organic vineyards, phytoseiid mite densities were two times higher in fungus-resistant compared to susceptible varieties, while in conventional vineyards the increase was only 20 % (Table 2; Fig. 2A). Tydeidae had almost two times higher densities in vineyards with fungus-resistant compared to susceptible varieties. In organic vineyards tydeid mite densities were three times as high in fungus-resistant compared to susceptible varieties, while in conventional vineyards the increase was only 20 % (Table 2; Fig. 2A).

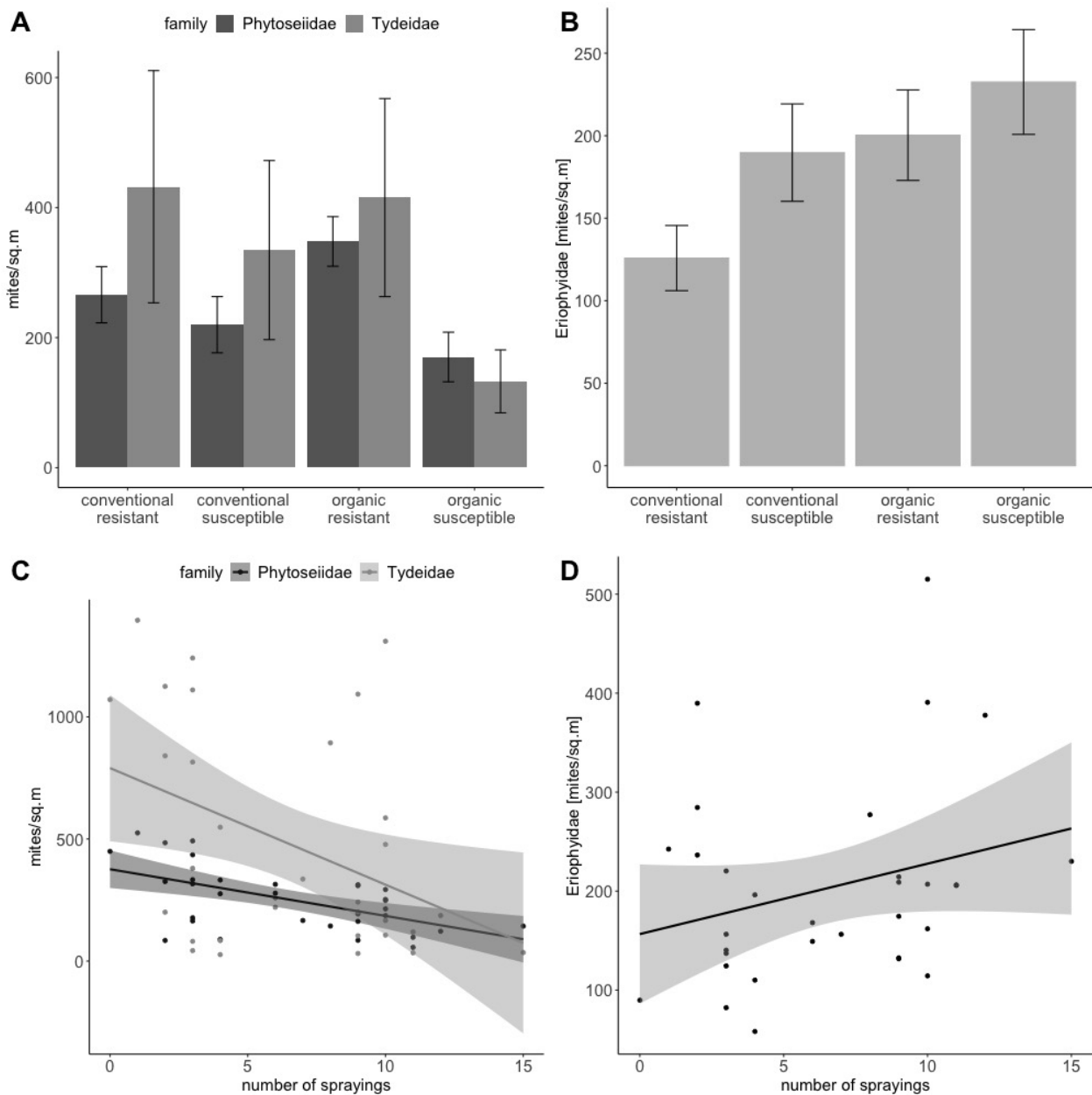


Figure 2 Relationships between management (organic/conventional), grape variety (susceptible/resistant) and **A**) beneficial mite densities (Phytoseiidae and Tydeidae) and **B**) phytophagous mite densities (Eriophytidae) in $N = 32$ vineyards (model predicted means \pm standard errors). Relationships between the number of fungicide treatments and **C**) beneficial mite densities (Phytoseiidae and Tydeidae), and **D**) phytophagous mite densities (Eriophytidae) in $N = 32$ vineyards (black dots = mite densities per vineyard; line = model-predicted densities; grey area = 95%-confidence-interval).

Contrary to beneficial mites, eriophyid mite densities were increased by 20 % in vineyards with susceptible compared to fungus-resistant varieties. Additionally, densities were 30 % higher in organic compared to conventional vineyards (Table 2; Fig. 2B). Densities of Eriophytidae were neither correlated with densities of Phytoseiidae ($r = -0.038$, $P = 0.835$) nor with densities of Tydeidae ($r = 0.276$, $P = 0.127$). Occurring in only 12 out of 32 studied vineyards, spider mites (*Panonychus ulmi*) were not frequent enough for analysis. The highest densities of spider mites were observed in two vineyards with resistant varieties, of which one was organic (694 mites/sq.m) and one conventional (289 mites/sq.m). Increasing numbers of fungicide applications decreased both,

densities of phytoseiid and tydeid mites, with stronger decrease of Tydeidae (Table 2; Fig. 2C). Contrastingly, increasing numbers of fungicide applications increased eriophyid mite densities (Table 2; Fig. 2D).

3.3 Beat-sheet samples

The most numerous mites in the beat-sheet samples were trombidiid mites with 741 individuals followed by the anystid mites with 189 individuals. Additionally, we identified 18 individuals of the family of Bdellidae and 4 individuals of the order of Oribatida. The abundance of Trombidiidae was not significantly affected by either the farming management nor the grape variety. However, the interaction of both did affect trombidiid mite abundance (Table 2; Fig. 3A). In vineyards with susceptible varieties, Trombidiidae occurred 2.5 times more often under conventional management compared to organic management. The abundance of Anystidae was more than two times higher in organic compared to conventional vineyards, whereas the abundance was not significantly increased in susceptible compared to fungus-resistant varieties (Table 2; Fig. 3B).

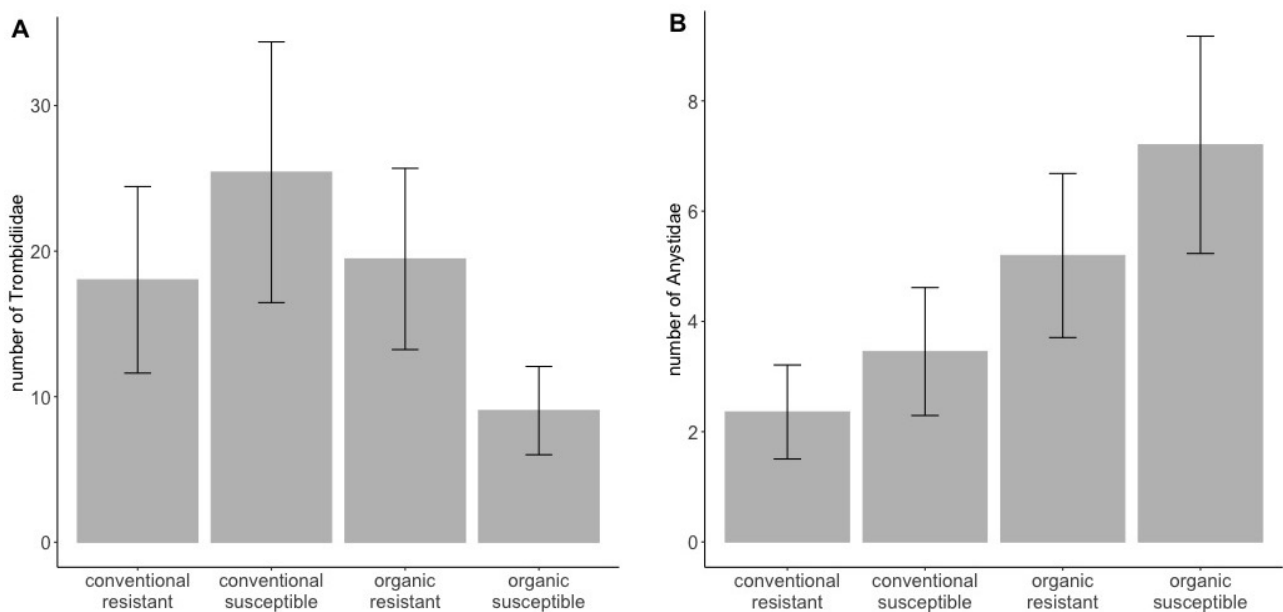


Figure 3 Relationships between management (organic/conventional), grape variety (susceptible/ resistant) and abundances of **A)** Trombidiidae and **B)** Anystidae in N = 32 vineyards (model predicted means \pm standard errors).

4 DISCUSSION

As expected, beneficial mites (Phytoseiidae, Tydeidae) showed strong benefits from fungicide reduction in both management systems. Oppositely, phytophagous mites had higher abundance in intensively sprayed varieties, and in organic farming. Higher predatory mite density was also found in untreated or less sprayed vineyards in Italy and Germany (Bigot, 2000; Pennington et al., 2017; Peverieri et al., 2009). Although higher numbers of fungicide application strongly affected phytoseiid and tydeid mite densities, sufficient mites were found in all cases to

ensure pest regulation (3.5 mites/leaf; Mohr, 2005). In contrast to our study, phytoseiid mites were reduced in conventional compared to organic vineyards in Italy (Bigot, 2000; Peverieri et al., 2009). This may be due to the application of Mancozeb, a conventional fungicide which is highly toxic to phytoseiid mites (Gadino et al., 2011) and which was not sprayed in our investigated conventional vineyards. Contrastingly, phytoseiid mites were harmed by frequent use of fungicides and plant protection agents in organic vineyards in Switzerland (Linder et al., 2006). We speculate that if highly harmful fungicides are avoided, the type of management (organic/conventional) is less important than the number of fungicide treatments per season. Further aspects of organic management, such as implementation of cover crop mixtures, might enhance predatory mite abundance (Hoffmann et al., 2017; McGourty, 2004; Vogelweith and Thiéry, 2017) and mediate fungicide impacts by alternative food supply (Pozzebon et al., 2014).

Eriophyid mite densities were significantly higher in organic vineyards, the reasons for which are unclear. Contrastingly, Muneret et al. (2018b) observed higher densities of gall mites (Eriophyidae) in conventional compared to organic vineyards in landscapes with low complexity. Eriophyid mite densities were higher in susceptible varieties with their intense spraying regimes than in fungus-resistant varieties. This is surprising because pest mites can also be negatively affected by fungicides, with some substances such as sulfur even being used as acaricides (Duso et al., 2012). Opposite to the expected direct effect, phytophagous mites showed increased densities under higher numbers of fungicide applications in our study. This is consistent with the results of Pennington et al. (2017) in a field experiment that varied fungicide intensity within standardized grape varieties. As direct effects of fungicides on pest mites would be negative, we suggest that their higher densities in susceptible varieties are indirect. Most likely, the reduced densities of predatory mites in intensely sprayed vineyards favored high densities of pest mites. However, as the direct correlation of phytophagous and beneficial mite densities was non-significant, this mechanism requires further study. As a cautionary note, other properties of grape varieties than fungicide intensity can influence mite densities. For example, the leaf hairiness can promote several mite species to different degrees (Peverieri et al., 2009; Roda et al., 2003). However, due to the high number of grape varieties involved (Fig. S3), we cannot distinguish direct effects of grape variety from the effects of the spraying regime. Still, as Pennington et al. (2017) observed similar effects of reduced fungicide application on mites in a field experiment with standardized grape varieties, we suggest that the effects observed here are most likely due to the spraying regime rather than due to other properties of fungus-resistant versus traditional grape varieties. Overall, the density of pest mites was very low in all investigated vineyards, and more than 100 times below thresholds of economic damage (Hluchý, 1993). In Europe, both eriophyid mites (*Co. vitis*, *Ca. vitis*) rarely damage grapes due to population regulation by phytoseiid mites (Duso et al., 2012). Although Phytoseiidae are mainly held responsible for the natural pest control of Eriophyidae, we also investigated Tydeidae in the group of beneficial mites due to their pest control potential (Duffner, 1999; Perring and McMurtry, 1996).

Anystid mites benefitted from organic management. They seem to be less susceptible to fungicides than phytoseiids (Cuthbertson and Murchie, 2003; Laurin and Bostanian, 2007). The occurrence in organic vineyards can be explained by higher alternative prey incidence. Anystidae can feed on a broad spectrum of prey, including phytophagous mites, leafhoppers, thrips and springtails (Cuthbertson and Murchie, 2004; Khederi and Khanjani, 2014; Sorensen et al., 1976), which could be more present in organic vineyards due to the implementation of

cover crop mixtures (Katayama et al., 2019). We did not detect a clear effect of management or variety on trombidid mites. Similar to anystid mites, the prey spectrum of adult trombidids is broad, including spider mites, moth eggs and aphids (Zhang, 1999, 1992). Both Anystidae and Trombidiidae are highly mobile and oviposit on the ground (Cuthbertson and Murchie, 2004; Sorensen et al., 1976; Zhang, 1999). Thus, they may be less affected by the fungicide applications that are focused on the canopy.

The implications of our results for other wine growing regions or other crop types need to account for differences in pesticide regimes. Pesticide treatments in vineyards strongly depend on the growing region. In Italy, pesticides were sprayed on average 12 times per season (ISTAT, 2011), whereas in France, 16 pesticide applications per year are common (Rusch et al., 2017). Pertot et al. (2017) stated even up to 25-30 fungicide treatments under unfavorable conditions per year. By comparison, on average 11 pesticide (10 fungicide) applications per season have been reported for German vineyards (Roßberg and Ipach, 2015). This corresponds to the average spraying number of susceptible varieties under organic management in this study. Thus, most of the investigated vineyards are generally treated less often than the European average. Positive effects of fungus-resistant varieties could therefore be even greater in other wine-growing regions. Another peculiarity of the study region is the higher number of fungicide treatments in organic vineyards compared to conventional ones. Similar frequencies of fungicide treatments were found elsewhere in Germany (15.3 in organic versus 11.2 in conventional; Uzman et al., 2019) and in Switzerland (13.6 in organic and 11.6 in conventional; Linder et al., 2006). This contrasts for example with higher treatment frequencies in conventional viticulture in France (9 in organic vs. approx. 18 in conventional; Muneret et al., 2018b). Vineyards in our study region rarely receive insecticides, and herbicides are restricted to conventional viticulture and to the zone directly below the grape plants. Thus, overall pesticide intensity between conventional and organic vineyards is quite similar. This contrasts with annual cropping systems, where agrochemicals are used in much higher frequency under conventional compared to organic management (Mäder, 2002; Schneider et al., 2014). This can explain why we did not find the commonly observed benefits of organic farming on predatory arthropods (Bengtsson et al., 2005; Muneret et al., 2018a).

Apart from the fungicide regime, other differences between organic and conventional viticulture can influence mites. In the majority of the here studied organic vineyards, diverse cover crop mixtures were sown, whereas conventional vineyards were mainly managed with short grass cover. Pollen is an important food source for predatory mites (Duso et al., 2012) and could be more present in flowering cover crops. However, Hoffmann et al. (2017) found no influence of cover crops on predatory mite abundance compared to spontaneous vegetation in a field experiment. Since cover crop management was not the scope of this study, the management was not reported. Thus, we cannot exclude that differences in cover crop management have contributed to the different mite abundances between organic and conventional vineyards in addition to the differing fungicide applications.

5 CONCLUSION

As expected, fungicide reduction in fungus-resistant varieties enhanced beneficial mites, along with reduced phytophagous mite densities. Phytophagous mite densities were higher in organic compared to conventional viticulture. Also, predatory Anystidae had higher densities in organic vineyards, but densities of predatory

Phytoseiidae and Tydeidae showed no significant difference. Thus, organic farming had no clear benefit on mites in viticulture, which may be due to the low use of particularly harmful fungicides (such as Mancozeb) by conventional winegrowers in our region. Overall, fungus-resistant varieties had a dominant positive effect on beneficial mites and phytophagous mite suppression and should be promoted to improve the sustainability of viticulture.

ACKNOWLEDGEMENTS

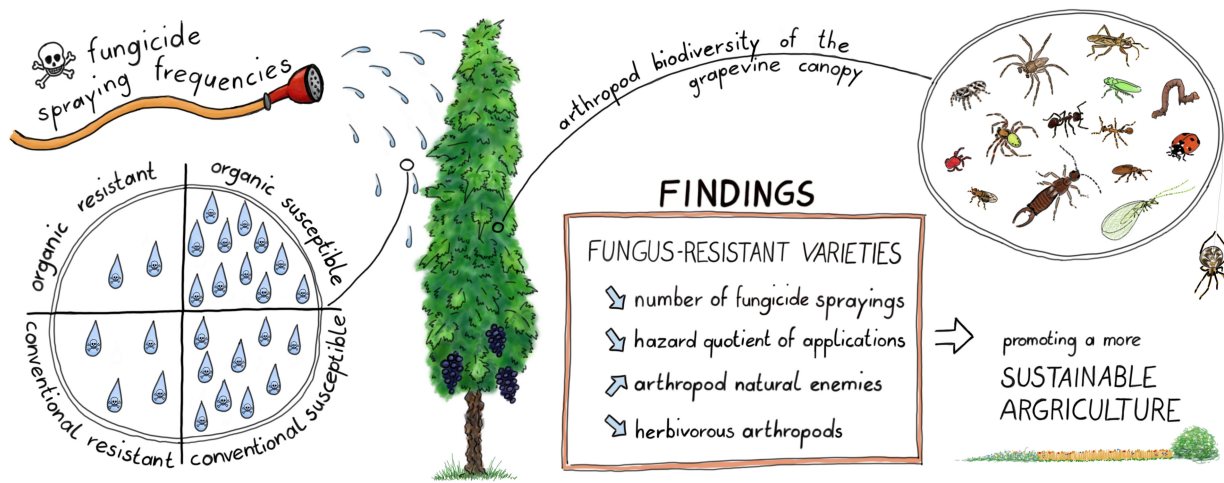
We are grateful to all collaborating winegrowers, to Anja Hollander, Paul Mason and Rosalie Shrestha for their help with sampling and counting mites and again to Paul Mason for proofreading the manuscript.

ARTHROPODS ON GRAPES BENEFIT MORE FROM FUNGICIDE REDUCTION THAN FROM ORGANIC FARMING

Jo Marie Reiff ^{a,b}, Keerthi Sudarsan ^{a,b}, Christoph Hoffmann ^b, Martin H. Entling ^a

*a RPTU Kaiserslautern-Landau, iES Landau, Institute for Environmental Sciences,
Fortstraße 7, D-76829, Landau in der Pfalz, Germany*

*b Julius Kühn-Institute, Federal Research Institute for Cultivated Plants,
Institute for Plant Protection in Fruit Crops and Viticulture,
Geilweilerhof, D-76833 Siebeldingen, Germany*



Graphical Abstract The reduction of fungicides in vineyards through the cultivation of fungus-resistant grape varieties, under both organic and conventional management, enhances the abundance of natural enemies, particularly theridiid and philodromid spiders.

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 to reduce pesticide applications and their impacts on non-target organisms and the environment. We investigated the effects of organic vs. conventional management and fungus-resistant vs. 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.

KEYWORDS

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

I INTRODUCTION

Agricultural intensification counts as one of the main drivers of global declines in arthropods (Hallmann et al., 2017; Sánchez-Bayo and Wyckhuys, 2019; Seibold et al., 2019), reducing food availability to subsequent trophic levels such as birds (Bowler et al., 2019) and further decreasing the provision of ecosystem services notably natural pest control (Bianchi et al., 2006; Gurr et al., 2003). Organic farming can enhance abundance and richness of natural enemies of pest species and, consequently, their effectiveness in pest control (Bengtsson et al., 2005; Muneret et al., 2018a). 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 (Geldenhuys et al., 2021; Kolb et al., 2020; Kratschmer et al., 2019; Puig-Montserrat et al., 2017). 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 (Gutierrez et al., 2012; Martínez-Bracero et al., 2020; Reineke and Thiéry, 2016). 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 (Masoni et al., 2017; Nash et al., 2010) or where regulations on fungicide specificity are lax. Organic viticulture can have positive effects on biodiversity and arthropod abundance (Gaigher and Samways, 2010; Katayama et al., 2019; Meissner, 2015; Paiola et al., 2020). In particular, the abundance of predatory arthropods such as spiders, ants and coccinellid beetles has been enhanced by organic viticulture (Caprio et al., 2015; Fleury and Fleury, 2016; Froidevaux et al., 2017; Gaigher and Samways, 2010; Masoni et al., 2017). 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 (Gaigher and Samways, 2010; Katayama et al., 2019; Muneret et al., 2018b). Conversely, pesticide applications can be more frequent in organic than in conventional vineyards in some regions with high disease pressure (Kolb et al., 2020). Furthermore, fungicides such as copper and sulphur which are applied in organic viticulture can also have detrimental effects on beneficial arthropods (Daniel et al., 2001; Komárek et al., 2010; Thomson et al., 2000). In addition, plant protection products are rapidly changing and pesticide regulations in many countries are imposing increasingly strict requirements on environmental safety (Ansari et al., 2021; Islam et al., 2017; Nishimoto, 2019; Singh et al., 2020). 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 disease and thus are strongly depending on fungicide applications, which account for 70-100 % of all pesticide input (Pertot, 2016). Thus, a vast potential to reduce pesticide inputs can be achieved by the cultivation of fungus-resistant grape varieties (Thiollet-Scholtus et al., 2021). Field experiments suggest strong benefits of reduced plant protection in fungus-resistant varieties on arthropod biodiversity and natural pest control (Pennington et al., 2018, 2017). 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* (Marchesini and Dalla Montà, 1994; Pennington et al., 2018; Reiff et al., 2021b). Furthermore, numerous parasitic hymenopterans attack different stages of *L. botrana* (Bagnoli and Lucchi, 2006; Hoffmann and Michl, 2003; Xuéreb and Thiéry, 2006). 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 (Güven and Göven, 2003; Nash et al., 2010; Thomson et al., 2000;

Thomson and Hoffmann, 2006). Consequently, Muneret et al. (2019b) 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 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 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 (LD₅₀; Campbell et al., 2000) 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 LD₅₀ values for honeybees were obtained through the Pesticide Properties DataBase (Lewis et al., 2016). 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 LD₅₀ 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. (2018). Following Pennington et al. (2018), 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 one-year-old branches and exposing them for 72 hours. 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, Jena, Germany). We stored the eggs that remained on the baits in a climate chamber at 70 % R.H. and 21 °C for four 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 (The R Development Core Team, 2015). 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; Fox and Weisberg, 2019). Accordingly, HQ, spraying frequency, abundances of individuals, families, predators, and herbivore arthropods, Araneidae, Theridiidae, Salticidae, Cicadellidae, and predation rate were analyzed with Gaussian distribution using linear mixed-effect models fitted with the function 'lmer' (R package lme4; Bates et al., 2015). Abundances of other arthropods, Forficulidae, Latridiidae, Formicidae, and Philodromidae were analyzed with negative binomial distribution using generalized linear mixed-effect models fitted with the function 'glmer.nb' (R package lme4; Bates et al., 2015). 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 in 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 analyzed using the R package vegan (Oksanen et al., 2018). Partial distance-based redundancy analysis (dbRDA) using Bray-Curtis distance as a dissimilarity measure was used with the function ,capscale' (Oksanen et al., 2018). 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 $\log_{10}(x + 1)$ transformed. Cook's Distance was used to check for outliers. Assumptions were checked for all models using graphical validation procedures (Zuur et al., 2009).



3 RESULTS

In total, we identified 17715 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 (Tab. 1, 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. 1A; Tab. 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. 1B; Tab. 2). Similar to the spraying frequency, the reduction of hazard quotients in resistant varieties was higher under organic management.

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, 2) hazard quotient of applications. Negative and positive correlations of hazard quotient and response variables are highlighted with +/- . Significant *p*-values are displayed in bold, respective Chisq-values are given in brackets.

	Model 1 (Df = 26)		Model 2 (Df = 28)	
	grape variety (resistant / susceptible)	management (organic / conventional)	management x 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)

*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). Displayed are model-predicted means \pm standard errors (N=32 vineyards).

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

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.

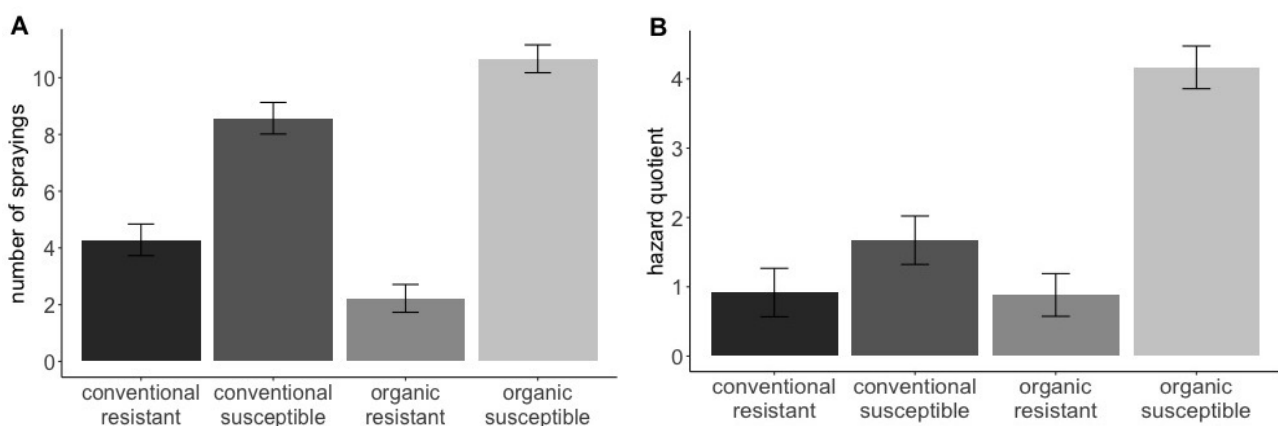


Figure 1 Differences in (A) spraying frequency and (B) hazard quotient of applications between management types (organic/conventional) and grape varieties (susceptible/resistant) in N = 32 vineyards (model predicted means \pm standard errors).

By contrast, resistant varieties had fewer herbivores (-23 %) mostly in conventional vineyards (Tab. 1, 2; Fig. 2B). Total abundance of arthropods, the abundance of other arthropods, and predation rates did not differ significantly between grape varieties (Tab. 1, 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 (Tab. 1, 2; Fig. 2). Further, the abundance of carnivores correlated negatively with hazard quotients of applied pesticides (Tab. 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.

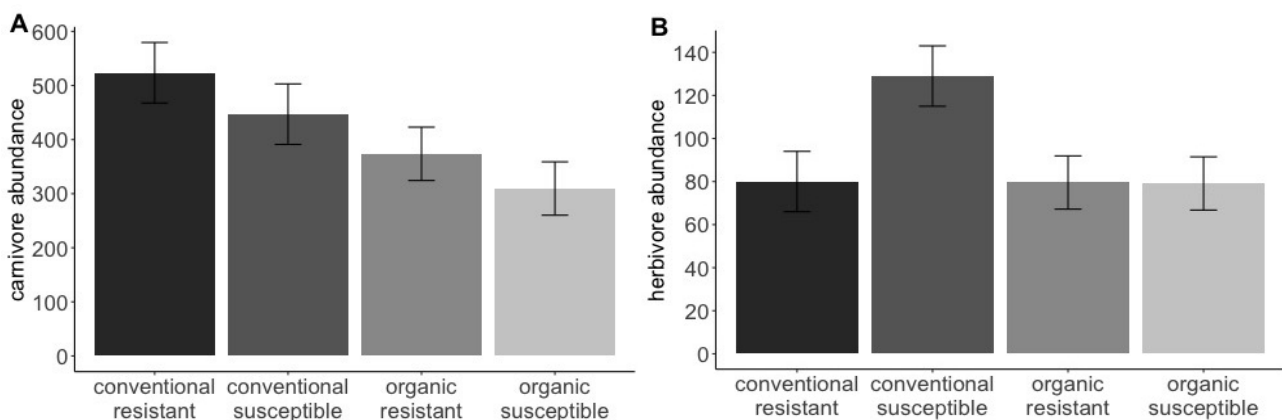


Figure 2 Differences in (A) carnivore abundance and (B) herbivore abundance between management types (organic/conventional) and grape varieties (susceptible/resistant) in N = 32 vineyards (model predicted means \pm standard errors).

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 (Tab. 1, 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) (Tab. 1, 2; 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 (Tab. 1, 2; Fig. 4). Abundances of Theridiidae, Philodromidae, and Latridiidae, were negatively correlated to hazard quotients (Tab. 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).

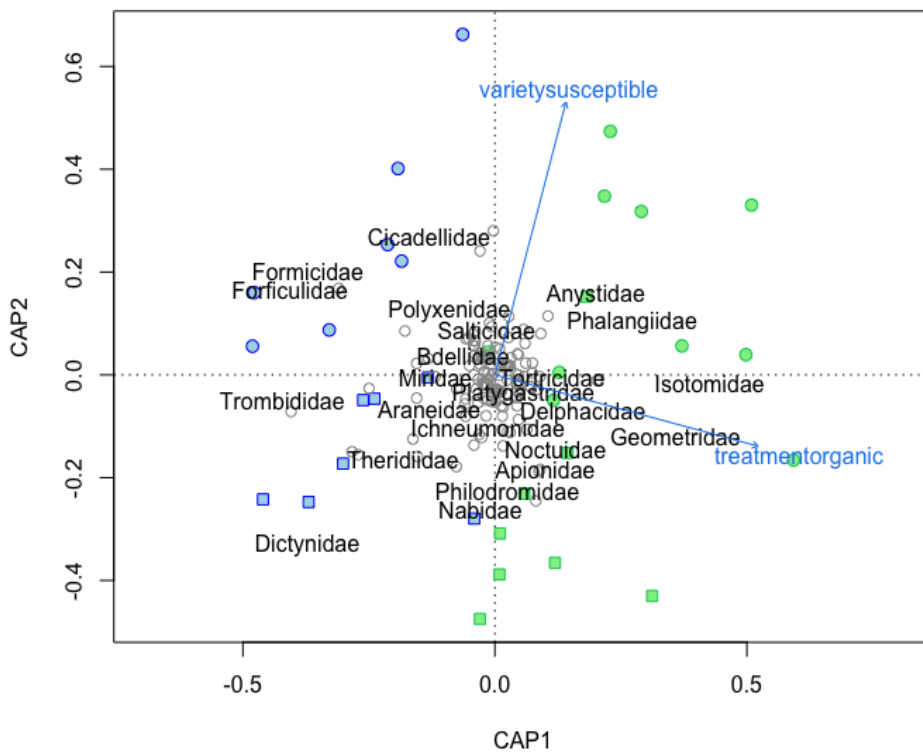


Figure 3 Relationship of arthropod families with vineyard management (organic/conventional) and grape variety (susceptible/ resistant) analysed using dbRDA with Bray-Curtis distance as dissimilarity measure. Blue symbols represent conventional and green symbols organic vineyards, while circles represent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

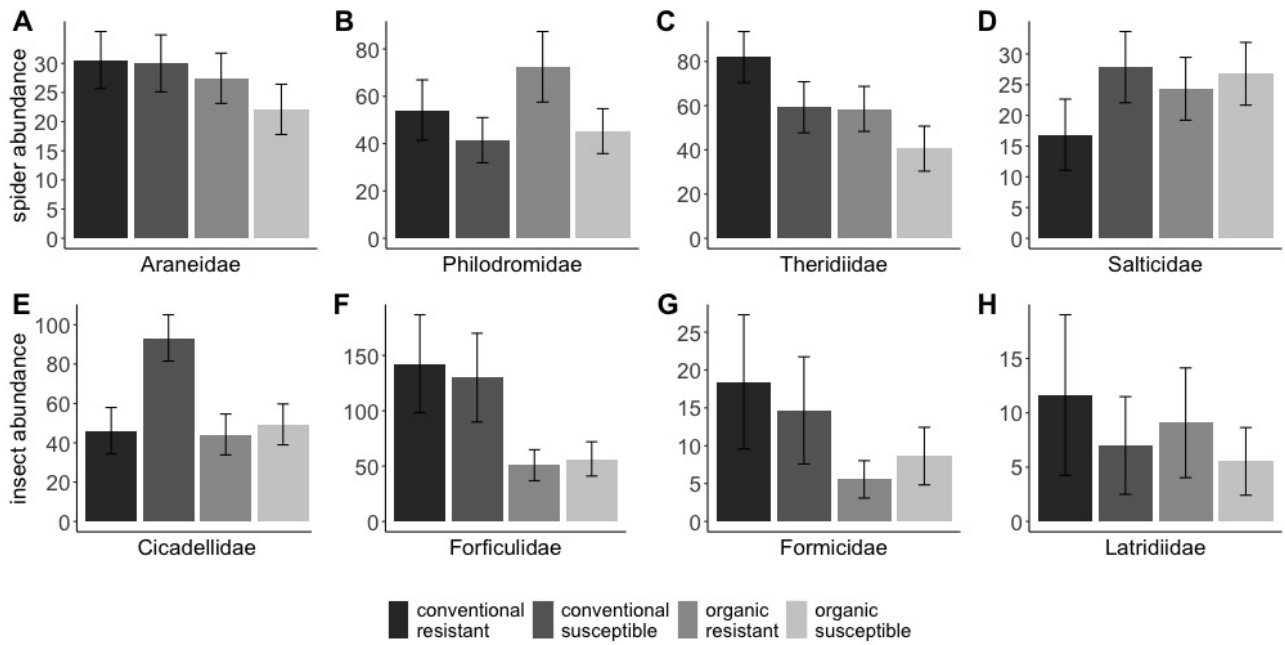


Figure 4 Abundance of the most abundant spider and insect families with respect to grape varieties (resistant/susceptible) and management types (organic/conventional) in N = 32 vineyards (model predicted means \pm standard errors): A) Araneidae, B) Philodromidae, C) Theridiidae, D) Salticidae, E) Cicadellidae,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

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 (Caprio et al., 2015; Gaigher and Samways, 2010; Isaia et al., 2006; Muneret et al., 2019a; Ostandie et al., 2021). Nevertheless, lethal effects of single fungicides on non-target organisms, particularly beneficial arthropods, are well documented (Fiedler and Sosnowska, 2014; Lewis et al., 2016; Miles and Green, 2004; Pekár, 2002). Further, sublethal effects of fungicides on predatory arthropods were observed e.g. by reduced fecundity (Gadino et al., 2011), reduced prey consumption (Beers and Schmidt, 2014) or population decrease due to altered prey availability (Pekár, 2012). Consequently, higher pesticide toxicity affected predatory arthropods in Australia (Thomson and Hoffmann, 2006). 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. (2018) in resistant grape varieties. In other viticultural areas, reduced pesticide use enhanced natural pest control of *L. botrana* regardless of organic or conventional vineyards (Muneret et al., 2019b; Reiff et al., 2021b; Rusch et al., 2015). 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 (Bosco et al., 1997; Olivier et al., 2012; Sáenz-Romo et al., 2019). 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* (Reineke and Thiéry, 2016; Santos et al., 2020). 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 (Markó et al., 2010). 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 detritivores 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. (2019) 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 (Herrmann et al., 2010; Hogg and Daane, 2010) 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 (Gobin et al., 2008; Orpet et al., 2019; Schlick-Steiner et al., 2006). Both ants and earwigs play a crucial role in vineyard pest control (Blaise et al., 2021; Frank et al., 2007; Pennington et al., 2019; Reiff et al., 2021b) and tend to be susceptible to pesticides, particularly insecticide applications, in vineyards and orchards (Le Navenant et al., 2021; Malagnoux et al., 2015; Masoni et al., 2017; Nash et al., 2010; Pennington et al., 2018). Nonetheless, neither ants nor earwigs were affected by reduced fungicide sprayings in our study.

The negative effect 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 (Caprio et al., 2015; Froidevaux et al., 2017; Isaia et al., 2006; Muneret et al., 2019a; Ostandie et al., 2021). However, it is unclear to what extent the benefit of organic farming in these studies resulted from non-crop 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, Bruggisser et al., 2010; Germany, Kolb et al., 2020). 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, solely 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 (Huth et al., 2011; Kehrlí et al., 2012).

The abundance and richness of arthropods that we sampled in the vine canopy were similar to other viticultural regions worldwide (Nobre et al., 2000; Ostandie et al., 2021; Retallack et al., 2019; Sáenz-Romo et al., 2019; Wilson et al., 2015). 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 (Retallack et al., 2019; Sáenz-Romo et al., 2019). Spiders were observed to be the most abundant group of predators elsewhere (Costello and Daane, 2005; Ostandie et al., 2021; Shapira et al., 2018). 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 (Buchanan et al., 2018; González et al., 2017). Under similar conditions, total arthropod abundance and family richness were even considerably lower in

cotton fields, highlighting the dominance of herbivore guilds (Thomazoni et al., 2013). Vineyards, thus, seem to have a higher potential for natural pest control compared to other crops. This was confirmed by a meta-analysis of spider's effects on pest control and yield, where vineyards were the crops with the second-strongest top-down effects from spiders worldwide (Michalko et al., 2019). Further, most of the sampled herbivore arthropods do not feed on vines but on non-crop vegetation in vineyards (Gonçalves et al., 2018), and thus offer 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 (Chen et al., 2022). 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. Non-selective compounds such as copper and sulphur applied in organic viticulture resulted in high levels of toxicity towards non-target organisms (Lewis et al., 2016). Further, according to Schulz et al. (2021) 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 highly increases the adverse effects. Given this, every single spray application further contains combinations of different pesticide products with different active ingredients and adjuvants (Mullin et al., 2015; Nash et al., 2010; Thomson, 2012). Such mixes may be more harmful to non-target organisms than the single products (Chen and Stark, 2010). 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 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 fostering functional biodiversity and natural pest control. Fungus-resistant cultivars offer a higher potential to minimise adverse effects of intensive agriculture on ecosystems, and should therefore be more widely cultivated to enhance the sustainability of agriculture.

ACKNOWLEDGEMENTS

We are grateful to all collaborating winegrowers and to Alexandra Dreyer, Anja Hollander, Paul Mason, Ken Mauser and Rosalie Shrestha for their help with sampling and identifying arthropods. Three reviewers provided valuable comments on an earlier version of the manuscript.

DOMINANT EFFECTS OF FUNGICIDE SPRAYINGS ON SPIDERS IN THE VINEYARD CANOPY

Jo Marie Reiff ^{a,b}, Christoph Hoffmann ^b, Martin H. Entling ^a

*a RPTU Kaiserslautern-Landau, iES Landau, Institute for Environmental Sciences,
Fortstraße 7, D-76829, Landau in der Pfalz, Germany*

*b Julius Kühn-Institute, Federal Research Institute for Cultivated Plants,
Institute for Plant Protection in Fruit Crops and Viticulture,
Geilweilerhof, D-76833 Siebeldingen, Germany*

ABSTRACT

Spiders are the most abundant predators in vineyards and play a crucial role in natural pest control. However, vineyards receive high numbers of particularly fungicide sprayings which can in turn harm spider communities. Fungus-resistant grape varieties can drastically reduce this fungicide input. We studied how spiders in the vineyard canopy are affected by the intensity of fungicide applications in 32 vineyards with different landscape composition in Southwestern Germany. Vineyards received between 0 and 14 fungicide sprayings with varying toxicity of products (cumulated hazard quotients up to 6). The majority of spiders benefited from reduced fungicide sprayings, particularly Dictynidae, Philodromidae, Theridiidae and Thomisidae. Overall, space web weavers, orb web weavers, and ambush hunters were most strongly affected by the frequency and toxicity of fungicide applications. Spider responses to landscape composition were highly variable and included both positive and negative effects of the cover of woody habitats. In conclusion, reducing cumulated hazard effects of fungicides by reducing the number of fungicide applications is a key element to fostering spiders in vineyards.

KEYWORDS

fungus-resistant varieties, hunting strategy, agroecology, taxonomic resolution, pesticide toxicity

I INTRODUCTION

Spiders are highly abundant predators in agroecosystems and constitute a crucial component for natural pest control (Cahenzli et al., 2017). Although most spiders are generalists, their hunting strategies differ greatly (Cardoso et al., 2011). For instance, ambush hunters have the greatest share of Hymenoptera amongst their prey while orb web weavers catch particularly Diptera (Michalko and Pekár, 2016). And even within the same family of web-building spiders, prey preference varies between the different spider species (Birkhofer et al., 2017). This suggests, that the potential for natural pest control of different pest species and life stages is promoted with high spider biodiversity.

However, agroecosystems are characterized by frequent disturbances such as tillage and pesticide treatments (Landis et al., 2000). Particularly pesticides can have detrimental effects on spiders. Some insecticides, acaricides and fungicides showed lethal effects on single spider species in laboratory experiments (Mansour and Nentwig, 1988; Pekár, 2002). Additionally, web building behaviour such as web size, frequency of web renewal and accuracy of the web construction can be affected by pesticides (Samu and Vollrath, 1992). In the field, mostly insecticides but also some fungicides affected spider abundances in orchards, vineyards and cereal fields (Bostanian et al., 1984; Holland et al., 2005; Markó et al., 2010; Marliac et al., 2016; Thomson and Hoffmann, 2006; Wisniewska and Prokopy, 1997). Although the majority of fungicides appears to be harmless to spiders, at least under field conditions (Pekár, 2012), there is evidence that frequent applications of fungicides can have detrimental effects on arthropod communities including spiders (Nash et al., 2010). Vineyards are among the most pesticide depending crops worldwide. Grapes are highly susceptible to several fungal diseases which can result in 12-15 fungicide sprayings per year (Pertot et al., 2017). A frequent use of fungicides is further related to increased accumulated toxicity and thus exposes greater hazard to non-target organisms (Möth et al., 2023). Fungus-resistant grape varieties can reduce this fungicide input on average by 80 % (Thiollet-Scholtus et al., 2021) and consequently foster natural enemies (Pennington et al., 2017, 2018; Reiff et al., 2021a, 2023).

In addition to local factors, spiders are known to be greatly influenced by the composition of agricultural landscapes (Chaplin-Kramer et al., 2011; Schmidt et al., 2008). Usually natural habitats harbour a greater arthropod richness and abundance, and particularly of predators, than intensive agriculture (Attwood et al., 2008; Mestre et al., 2018). Accordingly, natural pest control is promoted in complex landscapes (Bianchi et al., 2006; Veres et al., 2013). However, effects of landscape composition on arthropods in vineyards are highly variable, and may be less strong than in annual crops (González et al., 2017; Judt et al., 2019; Kaczmarek et al., 2023; Möth et al., 2021; Papura et al., 2020; Thomson et al., 2010; Wilson et al., 2015). However, previous studies on landscape effects on spiders in vineyards focused on ground-dwelling species (Kolb et al., 2020). Thus, there is a lack of research on how spiders in the vineyard canopy respond to the landscape context.

Here, we studied how spiders in the vineyard canopy are affected by the intensity of fungicide applications and the composition of the landscape in 32 vineyards in Southwestern Germany. Within this setting negative effects of frequent fungicide application were already described for two of the four analysed dominant spider families (Reiff et al., 2023). In the current manuscript, we use the same samples as in Reiff et al. (2023), but expand the taxonomic coverage to all spiders, examine trait composition and spider diversity at different taxonomic level, and add analyses of landscape effects. We hypothesize that the frequency of fungicide treatments and the overall

toxicity of applications have a dominant negative effect on spiders. Secondly, we expect higher spider diversity in landscapes with high cover of seminatural habitats.

2 MATERIALS AND METHODS

2.1 Study sites

We investigated 32 vineyards in the Palatinate region, Germany. Vineyards were on the one hand either managed conventionally or by organic standards and on the other hand either planted with fungus-resistant or susceptible grape varieties. These four combinations resulted in a highly variable plant protection regime, including different frequencies of fungicide treatments and hazard quotients of applied products. No insecticides were applied in the studied vineyards, with the exception of one application each in two conventionally managed vineyards. Hazard quotients were calculated by summing up the quotient between application rates and contact acute LD50 values for honeybees across all applied fungicides and insecticides (Reiff et al., 2023). We did not consider half-lives of pesticides, as we assumed direct effects in the canopy where spraying and spider sampling took place, and as persistent pesticides such as copper would influence disproportionately the calculated hazard quotient (e.g. dislocation to soils after rain events). Further, we analysed coverage of woody semi-natural habitats (mainly hedgerows, woodlands, and forest) in a 500 m radius around the vineyards using QGIS (QGIS Development Team, 2016) and satellite images obtained from Landesamt für Vermessung und Geobasisinformation Rheinland-Pfalz, Koblenz, 2014.

2.2 Spider sampling

Spiders were sampled from the grapevine canopy where the impact of fungicide applications is expected to be highest. Sampling took place during the vegetation period from the end of May to mid-October 2018, resulting in overall six sampling dates. Each time we sampled 30 randomly selected vines per vineyard by placing a beat-sheet of diameter 72 cm (Dynort, bioform Dr. J. Schmidl e.K., Nürnberg, Germany) underneath the canopy and then shaking the vines vigorously for approximately 5 seconds. Spiders falling on the sheet were collected and stored in 70 % ethanol. Adult spiders were identified to species level, whilst juvenile spiders were identified to family level. Several juveniles were further identified to genus level when habitus was unique.

2.3 Data analyses

To account for the study design and to reduce seasonal effects, we summed spider abundances over all sampling dates, resulting in one observation per vineyard. All statistical analyses were done in R version 3.6.3 (The R Development Core Team, 2015). Individuals were classified into guilds according to their hunting strategy described in (Cardoso et al., 2011).

We checked for distribution of response and predictor variables visually using ‘qqp’ (R package car)(Fox and Weisberg, 2019) and used either Gaussian or negative binomial distribution, accordingly (see Table 1). We used

(generalized) linear mixed-effect models containing “site” as a random factor fitted with the functions ‘lmer’ or ‘glmer.nb’ (R package lme4)(Bates et al., 2015). We further ran a separate lmer with “spraying frequency” as explanatory and “hazard quotient” as response variable to test for correlation (see Fig. 1). To calculate the R²-value for this correlation we used the function ‘rsquare’ (R package modelr)(Wickham, 2023) (see Fig. 1). Due to strong dependency of the two explanatory variables “spraying frequency” and “hazard quotient” we calculated two models for all variables. Both models contained “% woody semi-natural habitat” as explanatory variable, model 1 further contained “spraying frequency” while model 2 further contained “hazard quotient” (see Table 1). Effects on the composition of families, genera, species, and guilds were analyzed using the R package vegan (Oksanen et al., 2018). Partial distance-based redundancy analysis (dbRDA) using Bray-Curtis distance as a dissimilarity measure was used with the function ‘capscale’ (Oksanen et al., 2018). 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, genera, and guilds, community data were log₁₀(x + 1) transformed. Again, we conducted two analyses for all variables. Both dbRDAs were fitted with “% woody semi-natural habitat” whereas either “spraying frequency” or “hazard quotient” was further added. Cook’s Distance was used to check for outliers. Assumptions were checked for all models using graphical validation procedures (Zuur et al., 2009).

3 RESULTS

The number of fungicide sprayings and their toxicity were strongly correlated and 57% lower in fungus-resistant than in susceptible varieties (Fig. 1). Fungicide savings in fungus-resistant varieties were stronger under organic management, but overall hazard quotients of sprayings were lower under conventional management.

We identified a total of 6867 spiders of which 5 % were adult. Among the 349 adult individuals, *Synageles venator* was the most abundant species (17 %), followed by *Heliophanus auratus* (14 %), *Tenuiphantes tenuis* (13 %), and *Philodromus cespitum* (12 %). The dominant spider guilds were other hunters (38.91 %), space web weavers (32.52 %), and orb web weavers (13.89 %). With 27 % Theridiidae and Philodromidae were the most abundant families, followed by Araneidae (13 %) and Salticidae (11 %; Tab. 1). The genus *Philodromus* dominated with almost 24 % amongst different genera. Spider communities included 21 families, 63 genera, 34 species, and 8 different guilds of hunting strategies (Tab. 1). Family, genus, and guild composition were clearly affected by fungicide spraying frequency and hazard quotient, but did not respond to altered proportions of woody semi-natural habitats (Fig. 2, Tab. 2). Although species composition was similar, species richness decreased by 31 % with an increase of sprayings from 0 to 14 and by 43 % with an increased hazard quotient from 0 to 6 (Tab. 2, 3). Neither family richness nor genus richness were significantly affected by pesticide sprayings. An increased proportion of woody semi-natural habitats from 0 % to 45 % increased genus richness by 28 % (Tab. 3). Neither family richness nor species richness responded to landscape composition.

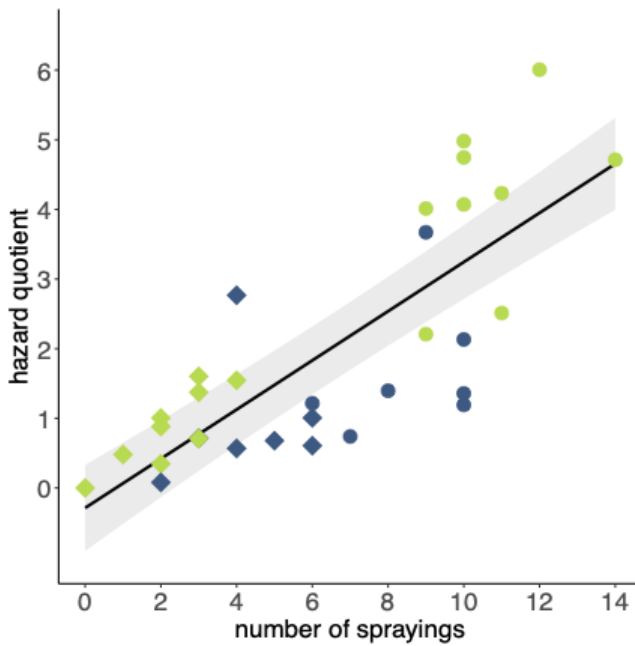


Figure 1 Correlation of hazard quotients of applied pesticides with the actual number of applications in 32 vineyards: $P = <0.001$ ($X^2 = 137.54$; $df = 1$); $R^2 = 0.924$. Displayed are organic (green) and conventional (blue) management as well as fungus-resistant (diamonds) and susceptible (circle) grape varieties.

The reduction of spraying frequencies from 14 to 0 increased the total abundance of spiders by 41 %. The same range of spraying reduction promoted the abundance of the families Philodromidae (52 %), Theridiidae (49 %), and Thomisidae (59 %), the abundance of the genus *Misumena* (69 %), and the abundance of the guilds space web weavers (56 %) and ambush hunters (59 %; Tab. 3). In 29 of 33 investigated groups spider abundances decreased with increasing fungicide sprayings, however, in some cases without statistical significance (Tab. 3). Total spider abundances were increased by 49 % in reduced hazard quotients (0 compared to 6; Tab. 3, Fig. 3A). Reduced hazard quotients further increased the abundance of the families Dictynidae (84 %), Philodromidae (54 %), Theridiidae (53 %), and Thomisidae (58 %), the abundance of the genus *Araniella* (69 %) and *Dictyna* (77 %), and the abundance of the guilds other hunters (44 %), orb web weavers (41 %), space web weavers (61 %) and ambush hunters (54 %, Tab. 3, Fig. 3A, B). In 31 of 33 investigated groups spider abundances decreased with increasing hazard quotients albeit some groups showed no significant effects (Tab. 3). In landscapes with higher proportions of woody semi-natural habitats (45 % compared to 0 %) abundances of the genera *Philodromus* and *Misumena* were increased (67 %, 90 %) but abundances of Dictynidae were decreased by 98 %, as well as those of the genera *Dictyna* (99 %), *Marpissa* (98 %), and *Salticus* (72 %, Tab. 3, Fig. 3C). Spider abundances increased with higher proportions of woody semi-natural habitats in 14 of 33 investigated groups (Tab. 3).

Table 1 Abundances of spider species and their relative proportions ordered by family.

taxon	number of individuals	proportion [%]	guild
Agelenidae	1	0.01	sheet web weaver
Amaurobiidae	1	0.01	sheet web weaver
<i>Amaurobius</i> sp. Koch	1	0.01	
Anyphaenidae	30	0.44	other hunter
<i>Anyphaena</i> sp. Sundevall	30	0.44	
Araneidae	870	12.67	orb web weaver
<i>Aculepeira</i> sp. Chamberlin & Ivie	20	0.29	
<i>Araneus</i> sp. Clerck	87	1.27	
<i>Araniella</i> sp. Chamberlin & Ivie	239	3.48	
<i>Araniella opistographa</i> Kulczynski	2	0.03	
<i>Cyclosa</i> sp. Menge	4	0.06	
<i>Gibbaranea</i> sp. Archer	2	0.03	
<i>Lariniodes</i> sp. Caporiacco	4	0.06	
<i>Mangora</i> sp. O.P.-Cambridge	466	6.79	
<i>Mangora acalypha</i> Walckenaer	3	0.04	
<i>Metellina</i> sp. Chamberlin & Ivie	1	0.01	
<i>Nuctenea</i> sp. Simon	28	0.41	
<i>Nuctenea umbratica</i> Clerck	2	0.03	
<i>Zygiella</i> sp. Pickard-Cambridge	3	0.04	
<i>Zygiella x-notata</i> Clerck	1	0.01	
Cheiracanthiidae	13	0.19	other hunter
<i>Cheiracanthium</i> sp. C.L. Koch	13	0.19	
Clubionidae	23	0.33	other hunter
<i>Clubiona</i> sp. Latreille	18	0.26	
Dictynidae	380	5.53	
<i>Dictyna</i> sp. Sundevall	334	4.86	space web weaver
<i>Dictyna uncinata</i> Thorell	12	0.17	space web weaver
<i>Lathys</i> sp. Simon	14	0.20	ground hunter
<i>Nigma</i> sp. Lehtinen	4	0.06	space web weaver
<i>Nigma puella</i> Simon	1	0.01	space web weaver
Gnaphosidae	12	0.17	ground hunter
<i>Drassodes</i> sp. Westring	2	0.03	
<i>Scotophaeus</i> sp. Simon	2	0.03	
Linyphiidae	397	5.78	
<i>Agyneta fuscipalpa</i> C.L. Koch	3	0.04	sheet web weaver
<i>Agyneta rurestris</i> Koch	24	0.35	sheet web weaver
<i>Araeoncus humilis</i> Blackwall	1	0.01	other hunter
<i>Erigone atra</i> Blackwall	2	0.03	other hunter
<i>Erigone dentipalpis</i> Wider	1	0.01	other hunter
<i>Frontinellina</i> sp. Cambridge	1	0.01	sheet web weaver
<i>Linyphia</i> sp. Latreille	1	0.01	sheet web weaver
<i>Mermessus trilobatus</i> Emerton	1	0.01	sheet web weaver
<i>Microlyniphia</i> sp. Gerhardt	2	0.03	sheet web weaver
<i>Neriene</i> sp. Blackwall	7	0.10	sheet web weaver
<i>Porrhomma microphthalmum</i> O.P.-Cambridge	1	0.01	sheet web weaver
<i>Tenuiphantes</i> sp. Saaristo & Tanasevitch	240	3.49	sheet web weaver
<i>Tenuiphantes tenuis</i> Blackwall	47	0.68	sheet web weaver
Lycosidae	11	0.16	ground hunter
Mimetidae	6	0.09	specialist
<i>Ero aphana</i> Walckenaer	1	0.01	
Philodromidae	1821	26.52	other hunter
<i>Philodromus</i> sp. Walckenaer	1623	23.63	
<i>Philodromus cespitum</i> Walckenaer	41	0.60	
<i>Tibellus</i> sp. Simon	13	0.19	
<i>Tibellus oblongus</i> Walckenaer	1	0.01	
Pholcidae	1	0.01	space web weaver
<i>Pholcus opilionoides</i> Schrank	1	0.01	

Pisauridae	3	0.04	sheet web weaver
<i>Pisaura</i> sp. Simon	3	0.04	
Salticidae	773	11.26	other hunter
<i>Ballus</i> sp. C.L. Koch	3	0.04	
<i>Euophrys</i> sp. Koch	4	0.06	
<i>Evarcha</i> sp. Simon	3	0.04	
<i>Evarcha arcuata</i> Clerck	1	0.01	
<i>Heliophanus</i> sp. Koch	190	2.77	
<i>Heliophanus auratus</i> Koch	49	0.71	
<i>Leptorchestes beroliensis</i> C.L. Koch	1	0.01	
<i>Marpissa</i> sp. C.L. Koch	162	2.36	
<i>Marpissa muscosa</i> Clerck	29	0.42	
<i>Salticus</i> sp. Latreille	158	2.30	
<i>Salticus scenicus</i> Clerck	24	0.35	
<i>Synageles</i> sp. Simon	77	1.12	
<i>Synageles venator</i> Lucas	58	0.84	
Segestriidae	2	0.03	sensing web weaver
<i>Segestria</i> sp. Latreille	2	0.03	
Sparassidae	3	0.04	other hunter
<i>Micrommata</i> sp. Latreille	1	0.01	
Tetragnathidae	83	1.21	orb web weaver
<i>Meta</i> sp. C.L. Koch	2	0.03	
<i>Tetragnatha</i> sp. Latreille	81	1.18	
Theridiidae	1881	27.39	space web weaver
<i>Anelosimus</i> sp. Simon	3	0.04	
<i>Dipoena</i> sp. Thorell	18	0.26	
<i>Enoplognatha</i> sp. Pavesi	2	0.03	
<i>Enoplognatha latimana</i> Hippa & Oksala	8	0.12	
<i>Neottiura</i> sp. Menge	322	4.69	
<i>Neottiura bimaculata</i> Linneaus	5	0.07	
<i>Paidiscura</i> sp. Archer	8	0.12	
<i>Paidiscura pallens</i> Blackwall	5	0.07	
<i>Phylloneta</i> sp. Archer	367	5.34	
<i>Phylloneta impressa</i> Koch	9	0.13	
<i>Platnickina</i> sp. Koçak & Kemal	5	0.07	
<i>Platnickina tincta</i> Walckenaer	1	0.01	
<i>Rugathodes</i> sp. Archer	1	0.01	
<i>Simitidion</i> sp. Wunderlich	1	0.01	
<i>Theridion</i> sp. Walckenaer	599	8.72	
<i>Theridion boesenbergii</i> Strand	2	0.03	
<i>Theridion mystaceum</i> L. Koch	1	0.01	
<i>Theridion varians</i> Hahn	1	0.01	
Thomisidae	501	7.30	ambush hunter
<i>Diaea</i> sp. Thorell	2	0.03	
<i>Misumena</i> sp. Latreille	45	0.66	
<i>Misumena vatia</i> Clerck	9	0.13	
<i>Ozyptila praticola</i> C.L.Koch	1	0.01	
<i>Runcinia</i> sp. Simon	2	0.03	
<i>Synema</i> sp. Simon	7	0.10	
<i>Tmarus</i> sp. Simon	2	0.03	
<i>Xysticus</i> sp. C.L.Koch	427	6.22	
Uloboridae	1	0.01	orb web weaver
unidentified spiderlings	54	0.79	
total	6867	100	

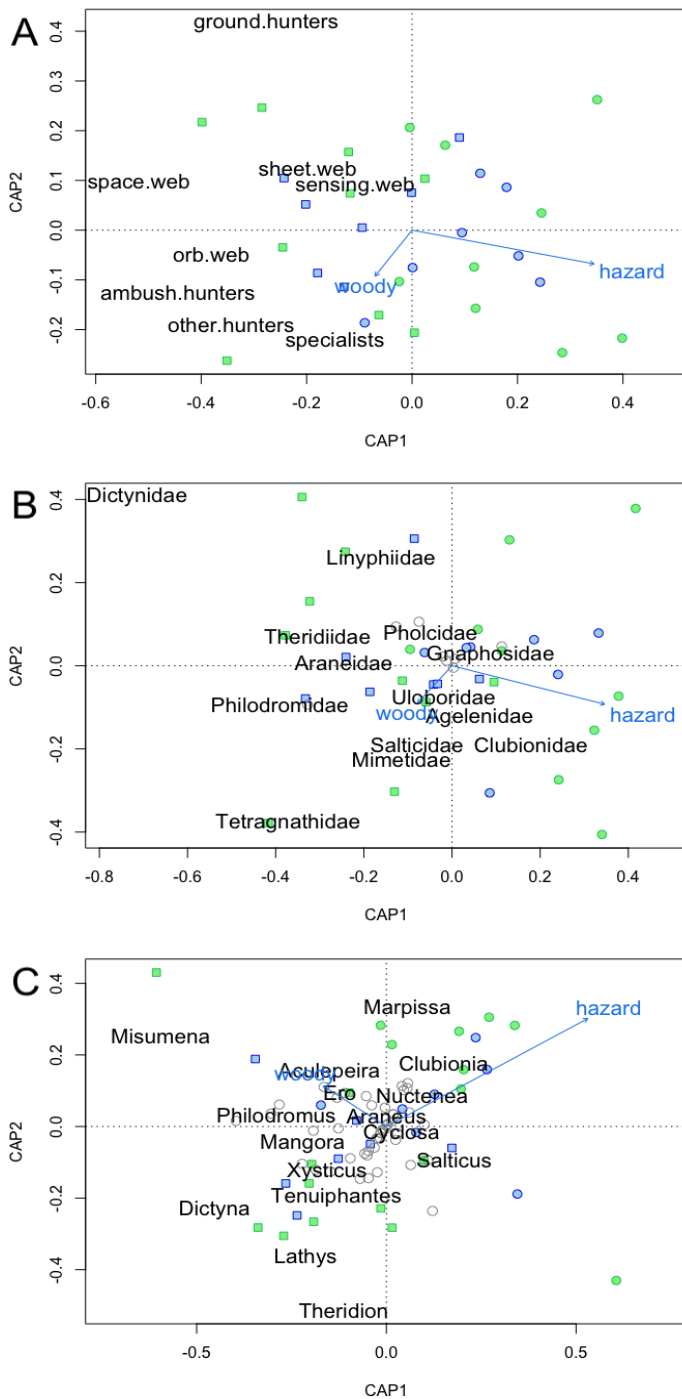


Figure 2 Relationship of spiders with hazard quotients of applied pesticides and landscape complexity in 500 m radius analysed using dbRDA with Bray-Curtis distance as dissimilarity measure. Spiders are grouped by A) different hunting strategies, and communities at B) family level and C) genus level. 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 were displayed as text and less common species as small grey surrounded dots.

Table 2 Model output of redundancy analyses for two models and 33 tested response variables. Significant P-values are highlighted in bold.

	model 1				model 2			
	spraying frequency		% woody SNH		hazard quotient		% woody SNH	
	F	P	F	P	F	P	F	P
family composition	3.145	0.008	0.997	0.860	3.457	0.014	1.025	0.806
genus composition	1.969	0.009	1.472	0.540	1.905	0.013	1.340	0.653
species composition	1.097	0.526	0.659	0.660	0.783	0.542	0.919	0.730
guild composition	3.210	0.007	0.692	0.904	3.675	0.009	0.599	0.919

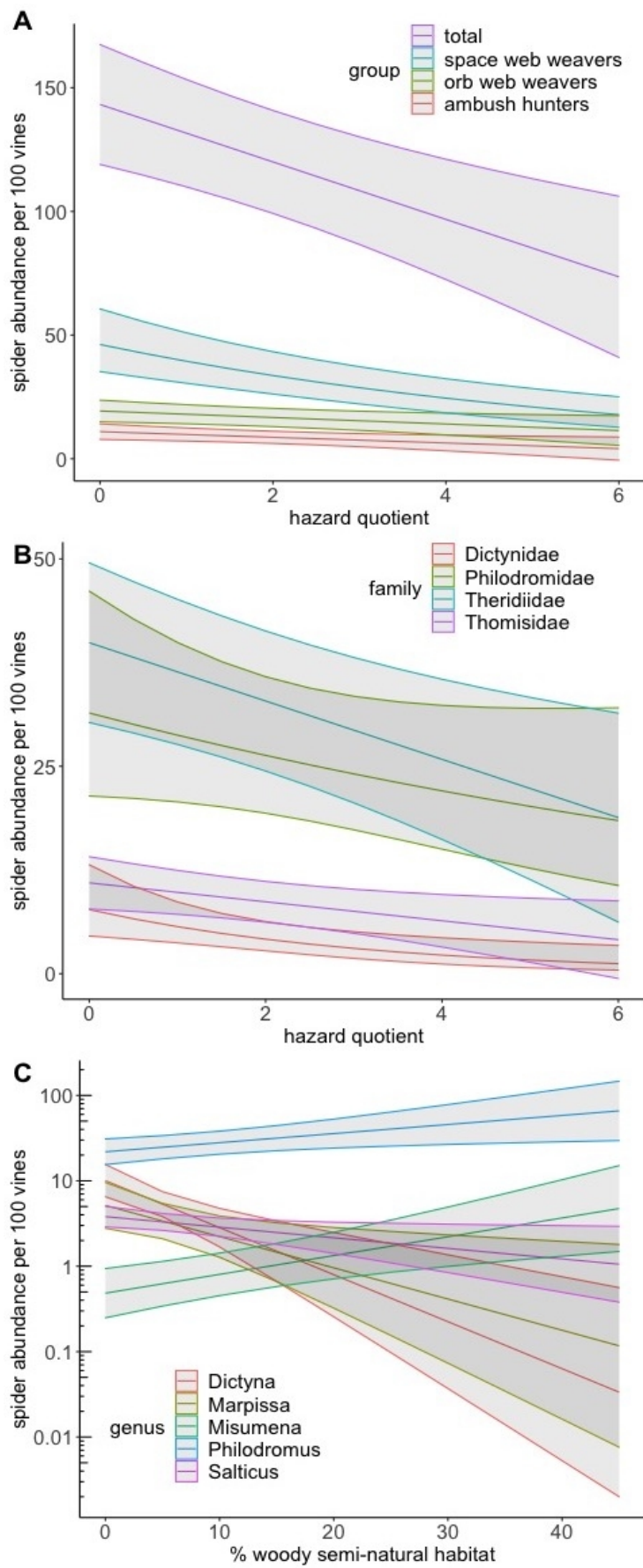


Figure 3 Effects of increasing hazard quotients of applied pesticides on the abundances of A) all spiders and three different hunting strategies and B) four families, and C) effects of landscape composition in 500 m radius on five genera. Displayed are model-predicted abundances and corresponding 95 %-confidence-intervals.

Table 3 Family distribution and model output for two models and 33 tested response variables. Model predicted effect sizes for the number of sprayings (from 0 to 14), hazard quotients (from 0 to 6), and proportion of semi-natural habitats (from 0 to 45 %) are given as percentage increase or decrease. Significant P-values ($\alpha = 0.05$) are highlighted in bold.

		model 1						model 2					
		spraying frequency			% woody SNH			hazard quotient			% woody SNH		
	family distribution	X ²	P	%	X ²	P	%	X ²	P	%	X ²	P	%
spider abundance	Gaussian	12.176	<0.001	-41.42	0.021	0.885	+4.75	13.263	<0.001	-48.65	0.020	0.888	+4.67
family richness	Gaussian	0.452	0.501	-4.84	1.760	0.185	+16.53	0.295	0.530	-4.78	1.846	0.174	+16.99
genus richness	Gaussian	0.438	0.508	-5.31	6.279	0.012	+28.59	2.082	0.149	-11.23	6.318	0.012	+28.32
species richness	Gaussian	3.999	0.046	-31.30	0.075	0.785	+7.29	7.761	0.005	-42.73	0.084	0.772	+7.38
ambush hunters	Gaussian	7.419	0.006	-62.72	0.005	0.946	-3.56	5.112	0.024	-62.61	0.009	0.924	+5.53
orb web weavers	Gaussian	2.553	0.110	-29.11	0.445	0.505	-27.11	4.758	0.029	-40.89	0.428	0.513	-26.66
other hunters	Gaussian	2.949	0.086	-35.54	1.593	0.207	+53.65	3.833	0.050	-42.93	1.708	0.191	+55.93
sheet web weavers	negative binomial	0.001	0.994	+1.19	0.073	0.788	+23.05	0.266	0.606	-20.74	0.015	0.902	+8.21
space web weavers	negative binomial	70.063	<0.001	-55.80	0.161	0.688	-12.78	31.910	<0.001	-61.35	0.715	0.398	-29.79
Araneidae	Gaussian	1.839	0.175	-25.83	0.689	0.407	-31.97	3.671	0.055	-37.21	0.651	0.420	-31.36
<i>Araneus sp.</i>	negative binomial	0.023	0.880	-8.97	0.101	0.750	+28.78	0.009	0.923	+6.70	0.114	0.736	+30.88
<i>Araniella sp.</i>	negative binomial	1.777	0.183	-41.73	0.001	0.976	-1.53	5.324	0.021	-59.98	0.008	0.928	-4.28
<i>Mangora sp.</i>	Gaussian	0.660	0.417	-24.44	3.656	0.056	-69.48	0.562	0.453	-26.56	3.473	0.062	-68.72
Dictynidae	negative binomial	3.777	0.052	-74.30	12.771	<0.001	-97.72	7.818	0.005	-84.41	12.103	<0.001	-97.56
<i>Dictyna sp.</i>	negative binomial	2.169	0.141	-62.26	13.523	<0.001	-99.63	4.668	0.031	-77.14	13.149	<0.001	-99.67
Linyphiidae	negative binomial	0.075	0.784	-10.00	0.018	0.894	+11.38	0.429	0.513	-24.86	0.001	0.982	+1.92
<i>Tenuiphantes sp.</i>	negative binomial	0.076	0.783	+30.28	0.096	0.757	-26.38	0.757	0.384	-50.23	0.493	0.483	-42.92
Philodromidae	negative binomial	4.361	0.037	-51.17	2.715	0.099	+118.11	4.461	0.035	-52.57	2.979	0.084	+122.49
<i>Philodromus sp.</i>	negative binomial	2.867	0.090	-44.20	5.892	0.015	+203.53	2.302	0.129	-41.26	5.779	0.016	+201.05
Salticidae	Gaussian	0.435	0.510	+21.77	1.517	0.218	-60.41	0.020	0.889	-4.53	1.942	0.163	-66.47
<i>Heliophanus sp.</i>	negative binomial	0.477	0.490	-36.02	0.591	0.442	-41.88	2.302	0.129	-62.45	0.566	0.452	-40.33
<i>Marpissa sp.</i>	negative binomial	0.008	0.929	-7.91	5.855	0.016	-97.99	0.141	0.707	+37.44	5.782	0.016	-97.72
<i>Salticus sp.</i>	negative binomial	0.299	0.584	+25.56	4.407	0.036	-71.00	0.022	0.881	-6.25	4.739	0.029	-72.35
<i>Synageles sp.</i>	negative binomial	0.042	0.838	-11.87	0.001	0.982	+1.88	0.567	0.452	-38.07	0.007	0.934	-7.43
Tetragnathidae	negative binomial	3.237	0.072	-58.16	0.011	0.918	-9.64	3.561	0.059	-65.43	0.022	0.881	-13.40
<i>Tetragnatha sp.</i>	negative binomial	1.395	0.238	-54.24	0.001	0.978	+2.59	2.180	0.140	-66.78	0.042	0.837	-18.05
Theridiidae	Gaussian	12.033	<0.001	-49.26	0.379	0.538	+73.48	8.731	0.003	-52.86	0.353	0.552	+73.20
<i>Phylloneta sp.</i>	negative binomial	1.222	0.269	-33.43	0.065	0.799	-10.62	2.481	0.115	-45.98	0.139	0.709	-15.58
<i>Neottiura sp.</i>	negative binomial	0.331	0.565	-22.96	0.416	0.519	-33.60	1.842	0.175	-45.42	0.443	0.506	-33.20
<i>Theridion sp.</i>	negative binomial	3.676	0.055	-67.56	0.004	0.950	-5.38	2.373	0.123	-61.46	0.026	0.873	-13.44
Thomisidae	Gaussian	7.419	0.006	-62.72	0.005	0.946	-3.56	5.112	0.024	-62.61	0.009	0.924	+5.53
<i>Misumena sp.</i>	negative binomial	4.153	0.042	-69.27	10.287	0.001	+811.11	3.814	0.051	-70.68	11.060	<0.001	+883.72
<i>Xysticus sp.</i>	negative binomial	3.141	0.076	-47.37	0.059	0.808	-11.51	0.921	0.337	-30.37	0.033	0.856	-9.05

4 DISCUSSION

Overall spider abundance was affected by both the frequency and the hazard of applied fungicides. Given that the most dominant families Philodromidae and Theridiidae as well as the abundant Thomisidae responded significantly to fungicide applications, it becomes obvious that they shaped overall patterns. However, the equally abundant families Salticidae and Araneidae were not significantly affected by fungicide applications. (Pekár, 2012) proposes that some pesticides have guild-specific effects. Hunting spiders appear to be more impacted by pesticide treatments than web building spiders (Bostanian et al., 1984; Pekár and Haddad, 2005). However, it is discussed whether webs protect spiders from contact with pesticides or even accumulate them to lethal levels (Pekár, 1999; Samu et al., 1992). We observed that families in both groups, hunters and web builders, were affected by fungicide applications to variable extent.

Although the effects were significant only for some groups, almost all spiders responded negatively to the frequency of fungicide applications and their hazard quotient. For instance, abundances of *Heliophanus*, *Philodromus*, *Tetragnatha*, and *Theridion* decreased strongly albeit not significantly. For some taxa a certain vulnerability towards fungicides is already documented. For instance, Theridiidae benefited from reduced fungicide applications in previous studies (Pennington et al., 2019; Wisniewska and Prokopy, 1997). Likewise, *Phylloneta* was reported being susceptible towards one fungicide (Pekár, 2002). Further, *Araniella* was decreased by sulphur applications in a previous study (Clymans et al., 2015). Contrastingly, *Philodromus* was described to be relatively unsusceptible towards fungicides by (Mansour and Nentwig, 1988). Further, Philodromidae were not affected by reduced fungicide applications in previous studies (Pennington et al., 2019; Wisniewska and Prokopy, 1997). Here, we found strong effects of fungicide applications on both, Philodromidae and *Philodromus*. In brief, we can conclude that the majority of spiders were harmed by fungicides. However, Salticidae and particularly *Salticus* and *Marpissa* appear relatively unaffected. Nevertheless, the decreased abundances of *Heliophanus* and *Synageles* with regard to fungicide applications, albeit not significant, suggest that the responses were specific to the taxonomic resolution of the data. This inconsistent pattern suggests that the revealed effects on spiders can be more likely explained by phylogenetic sensitivity to fungicides (Duque, under review) rather than by exposition to them (e.g., foraging behaviour). Some spider responses to fungicides were revealed in the same intensity for both frequency and hazard quotients of applications. Nevertheless, in some cases the shifts in abundance were better explained by either hazard quotients (e.g. orb web weavers, Dictynidae, *Araniella*, *Dictyna*) or frequency (*Misumena*). We thus assume that several proxies are necessary to adequately display the impacts of fungicides. Nevertheless, as the strong correlation of hazard quotients with the spraying frequency highlights, one of the spraying variables can be used if complete information on spraying schemes is lacking. The calculated gradients for the frequency of sprayings and the hazard quotients of applications clearly illustrate the differences between organic and conventional spraying regimes in fungus-resistant and susceptible grape varieties. Organic farming is often said to use less pesticides with lower toxicity which in turn promotes arthropod biodiversity and natural pest control (Bengtsson et al., 2005; Muneret et al., 2018a). However, pesticide use of viticulture is similar or even higher under organic management (Beaumelle et al., 2023b; Kaczmarek et al., 2023; Reiff et al., 2021b). Thus, benefits of organic management in the studied viticultural region prevail solely in fungus-resistant varieties.

Landscape complexity had contrasting effects which were revealed particularly at genus level. However, neither overall abundance nor spider guilds were affected by increased proportions of semi-natural habitats. Similarly, spiders were not affected by the surrounding landscapes or even promoted by increased proportions of agricultural surfaces in other viticultural regions (Caprio et al., 2015; Judt et al., 2019; Kolb et al., 2020). Nevertheless, ambush hunters such as *Misumena* and also *Philodromus* strongly benefited from higher proportions or the proximity of woody habitat (Isaia et al., 2006; Picchi et al., 2020). Shrubs and trees are the preferred habitat of *Philodromus* (Nentwig et al., 2023) which makes vineyards suitable habitats. Contrastingly, negative correlations of abundances of *Dictyna* and *Salticus* with woody habitats in the landscape were already described by (Herrmann et al., 2010). As open-habitat species (Nentwig et al., 2023), *Salticus* prefers less complex structures even within vineyards (Pennington et al., 2019). Spider guilds in the canopy of our studied vineyards were shaped by communities similar to those that have been found on trees, comprising orb web weavers (mainly Araneidae), space web weavers (mainly Theridiidae) and hunters such as Philodromidae, Thomisidae, and Salticidae (Herrmann et al., 2010; Pekár, 2012). Although these taxa are observed ballooning, their aeronautic dispersal is less frequent than that of many species occurring in annual crops (Blandenier, 2009; Bonte et al., 2003; Entling et al., 2011). This suggests that vineyard recolonisation by these spiders from surrounding semi-natural habitats is presumably less important than in annual crops. Since landscape composition had contrasting effects on genus level, we conclude that local management effects such as pesticide input are of clearly higher importance for spider abundance and diversity than the effects of the surrounding landscape.

Spiders are the most abundant predators in vine canopies (Costello and Daane, 1999; Reiff et al., 2023) which makes them key species for natural pest control. For instance, spiders are observed attacking larvae and pupae of lepidopteran grapevine pests (Frank et al., 2007; Marchesini and Dalla Montà, 1994; Reiff et al., 2021b). Furthermore, web building spiders play an important role in capturing flying adult vineyard pests (Michalko et al., 2019). Preserving a diverse spider community comprising different hunting strategies may thus be crucial to suppress vineyard pests in different life stages.

Effects of fungicide applications on spiders in vineyard canopies prevail over effects of landscape complexity. Here, we demonstrate that these effects are depending on the considered taxonomic level. Dominant effects of fungicide applications were already visible on total spider abundance and appeared in all taxonomic levels (family, genus, species) as well as amongst different hunting strategies but not in all groups to the same extent. However, effects of landscape complexity appeared only on some genera. Particularly in samples with high numbers of juveniles it might be worth to identify morphologically to genus level. In conclusion, reducing cumulated hazard effects of fungicides by reducing the number of fungicide applications is a key element to fostering spiders in vineyards. Up to date a relevant reduction can only be achieved by the cultivation of fungus-resistant grapevine cultivars in both organic and conventional viticulture.

ACKNOWLEDGEMENTS

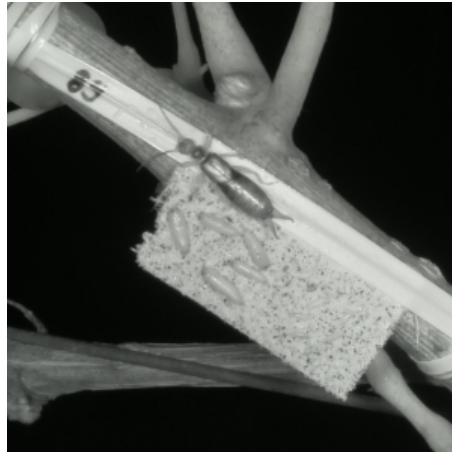
We are grateful to all collaborating winegrowers and to Alexandra Dreyer, Anja Hollander, Paul Mason, Ken Mauser, Rosalie Shrestha and Keerthi Sudarsan for their help with sampling, counting and identifying arthropods. Special thanks to Sebastian Kolb for verifying some questionable species.

ARTHROPODS IN THE SPOTLIGHT – IDENTIFYING PREDATORS OF VINEYARD PEST INSECTS WITH INFRARED PHOTOGRAPHY

Jo Marie Reiff ^{a,b}, Konrad Theiss ^{a,b}, Christoph Hoffmann ^b, Martin H. Entling ^a

*a RPTU Kaiserslautern-Landau, iES Landau, Institute for Environmental Sciences,
Fortstraße 7, D-76829, Landau in der Pfalz, Germany*

*b Julius Kühn-Institute, Federal Research Institute for Cultivated Plants,
Institute for Plant Protection in Fruit Crops and Viticulture,
Geilweilerhof, D-76833 Siebeldingen, Germany*



Surveying predatory arthropods in vineyards

ABSTRACT

Grape berry moths (particularly *Lobesia botrana*, Denis & Schiffermüller [Lepidoptera: Tortricidae]) and vinegar flies (*Drosophila melanogaster*, Meigen, *Drosophila suzukii*, Matsumura [Diptera: Drosophilidae]) are important vineyard pests, causing severe quality loss of grapes. Several arthropod taxa may be involved in natural pest control. However, the comparative efficacy of arthropod predators in vineyards remains unclear. We investigated 32 vineyards in the Palatinate region, Germany, under organic and conventional management receiving full and reduced fungicide applications, respectively. Predation of exposed *L. botrana* eggs and pupae and *D. melanogaster* pupae was observed with infra-red cameras. In total, nine different predators could be identified. The most dominant predator was the European earwig (*Forficula auricularia*) with 90 % of all predation events. We conclude that *F. auricularia* is likely a key predator of vineyard pests, and that special attention should be paid to maintain it at high population densities.

KEYWORDS

natural pest control, *Lobesia botrana*, *Drosophila* sp., camera observation, *Forficula auricularia*

I INTRODUCTION

Vineyards must produce both yield and high most quality. To ensure this, high quantities of plant protection products are frequently applied. This may affect non-target organisms and can therefore impact natural pest control (Bianchi et al., 2006; Geiger et al., 2010; Gurr et al., 2003). However, if natural enemies of pests are protected, this can also lead to increased resilience and reduce reliance of insecticide applications (Cahenzli et al., 2017).

The European grapevine moth *Lobesia botrana*, Denis & Schiffermüller (Lepidoptera: Tortricidae), is one of the major grapevine pests in Europe and beyond. Larvae feed on inflorescences and grape berries. However, the main damage arises in quality loss due to subsequent infections with bunch rot (*Botrytis cinerea*) and sour rot. The latter disease complex induces the development of volatile acidity causing sensorial interference in wine (Lemperle, 2007).

Vinegar flies such as *Drosophila melanogaster*, Meigen, and *Drosophila suzukii*, Matsumura (Diptera: Drosophilidae), can severely impact most quality by infecting grapes with sour rot (Entling and Hoffmann, 2020). Unlike *D. melanogaster*, which is able to oviposit only in overripe or damaged berries, *D. suzukii* can actively oviposit in healthy berries (Atallah et al., 2014). Both vinegar flies act as vector for yeasts and bacteria associated with sour rot but also trigger the development of the disease directly by larval development inside the grape berries (Barata et al., 2012; Hall et al., 2018).

Several species of mites, spiders, and bush crickets as well as harvestmen, earwigs, ants, and lacewings are known to predate on *L. botrana* (Marchesini and Dalla Montà, 1994; Papura et al., 2020; Pennington et al., 2018; Reiff et al., 2021b). *Drosophila* sp. and particularly *D. suzukii* are predated by earwigs, ants, bugs, harvestmen, spiders, rove beetles and centipedes (Wolf et al., 2018; Woltz and Lee, 2017). However, the efficacy of this wide range of arthropod predators in vineyards remains poorly investigated (Thiéry et al., 2018). The aim of this study was to identify predators of *L. botrana* and *Drosophila* sp. and their natural pest control capacity in the Palatinate region.

2 MATERIALS AND METHODS

2.1 Study sites

We investigated 32 vineyards in a 10 km radius around Landau in the Palatinate region, Germany (compare Reiff et al., 2023, for detailed information). Of these vineyards, 18 were managed by organic standards, including an organic spraying regime. The other 14 vineyards were treated with conventional plant protection products (mostly synthetic fungicides). In both management type, half of the vineyards were planted with susceptible cultivars (e.g. Riesling, Pinot blanc), and the other half with fungus-resistant varieties (e.g. Cabernet blanc, Regent).

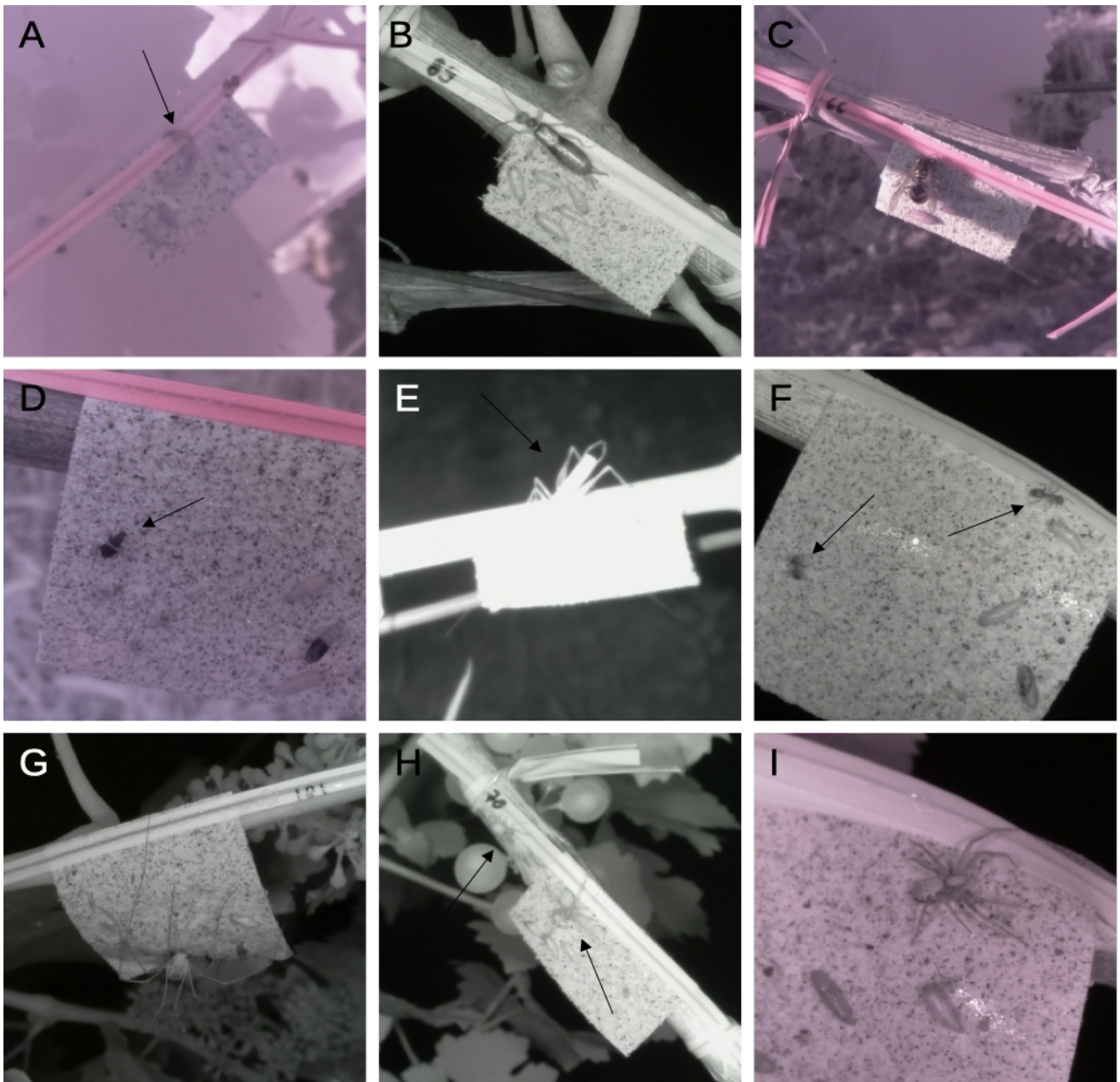


Figure 1 Identified predators of *Lobesia botrana* and *Drosophila melanogaster*: A) Chrysopidae larvae, B) *Forficula auricularia*, C) *Vespula* sp., D) Blattoptera nymph, E) *Meconema meridionale* male, F) Formicidae, G) Opiliones, H) *Cheiracanthium* sp., I) *Philodromus* sp. on camera surveilled sentinel cards.

2.2 Camera surveillance of sentinel cards

Sentinel cards combined *L. botrana* eggs and pupae of both *L. botrana* and *D. melanogaster*. We chose *D. melanogaster* rather than *D. suzukii* because of its easier cultivation. For rearing of *L. botrana* we followed Markheiser et al. (2018) and for rearing of *D. melanogaster* Entling and Hoffmann (2020). Egg-laden polyethylene strips were harvested after 24 hours from *L. botrana* rearing containers. Pupae of both insect species were harvested twice per week and stored at 4 °C until field exposure. Five pupae of *L. botrana* and *D. melanogaster* were attached to the adhesive surface of approximately 20 by 40 mm cutting duct tape, respectively (HEB19L10GC, TOOLCRAFT, Conrad Electronic SE, Hirschau, Germany). The remaining adhesive

surface was covered with sand to prevent predators from sticking. Sentinel cards were stored at 4 °C until exposure. Sentinel cards were randomly attached to selected one-year-old branches of grape plants and exposed for 24 hours. The number of eggs and pupae was counted before and after exposure. Predation was monitored with two cameras in each vineyard. Monitoring was repeated four times between May and August of 2018, resulting in 256 days of camera observations. We used the camera system described in Pennington et al. (2018) consisting of a raspberry pi computer (Raspberry Pi Foundation, UK) and a camera module with two infrared light-emitting diodes (IR-LEDs; Electreeks, Dresden, Germany). The cameras were programmed to take a picture every 10 second for 24 hours.

2.3 Data analysis

Due to low numbers of predation events, statistical analysis was only possible for predation by earwigs. Data were summed over all sampling dates, resulting in one observation per vineyard. All statistical analyses were executed in R version 3.6.3 (The R Development Core Team, 2015). Taking zero counts into account, we used generalized linear mixed-effect models fitted with the function ‘glmmTMB’ (R package glmmTMB; Brooks et al., 2017). Models contained “site” as a random factor and “grape variety” plus “management” as the explanatory variables, including their interaction. Model distribution was checked graphically using the function ‘simulateResiduals’ (R package DHARMA; Hartig and Lohse, 2022) and family distribution was chosen accordingly (Table S1).

Table 1 Number of predated eggs and pupae and respective identified predators. Sum of initially exposed eggs and pupae is displayed in the bottom row.

	<i>Lobesia botrana</i> eggs				<i>Lobesia botrana</i> pupae				<i>Drosophila melanogaster</i> pupae			
	organic		conventional		organic		conventional		organic		conventional	
	resistant	susceptible	resistant	susceptible	resistant	susceptible	resistant	susceptible	resistant	susceptible	resistant	susceptible
<i>Forficula auricularia</i>	242	346	717	439	54	61	41	16	75	94	84	60
Formicidae	33	-	-	33	1	-	-	1	12	-	6	3
Chrysopidae larvae	-	-	4	-	-	-	1	-	-	-	-	-
<i>Vespula</i> sp.	-	-	-	-	-	-	1	-	-	2	-	-
<i>Meconema meridionale</i>	-	-	-	-	3	-	-	-	-	-	-	-
Blattoptera	-	-	-	-	-	-	-	-	2	-	-	-
Opiliones	-	-	-	-	5	5	1	1	5	2	2	1
<i>Cheiracantium</i> sp.	-	40	-	-	-	-	2	-	-	-	-	-
<i>Philodromus</i> sp.	-	13	-	-	-	-	-	-	-	-	-	2
exposed	3051	3144	2705	2640	360	359	279	280	360	360	280	280

3 RESULTS

We observed nine different taxa preying on the sentinel cards (Table 1, Figure 1). The European earwig *Forficula auricularia*, Linnaeus (Dermaptera: Forficulidae), accounted for 93 % of *L. botrana* egg predation, for 90 % of

L. botrana pupae predation, and for 89 % of *D. melanogaster* predation. Predation rates did not differ significantly between organic vs. conventional management and resistant vs. susceptible grape varieties. However, we found a trend that *L. botrana* eggs were predated more frequently resistant grapes under conventional compared to organic management. In addition *L. botrana* pupae were predated more frequently in susceptible grapes under organic than under conventional management (Table S1). Overall predation rates of *L. botrana* eggs were highest in May (28.8 %) whilst those of *L. botrana* and *D. melanogaster* pupae were highest in June (22.8 % and 42.8 %, respectively; Supplementary Table S2). Highest predator diversity on sentinel cards was found in May and July with 6 different predatory taxa observed (Supplementary Table S2).

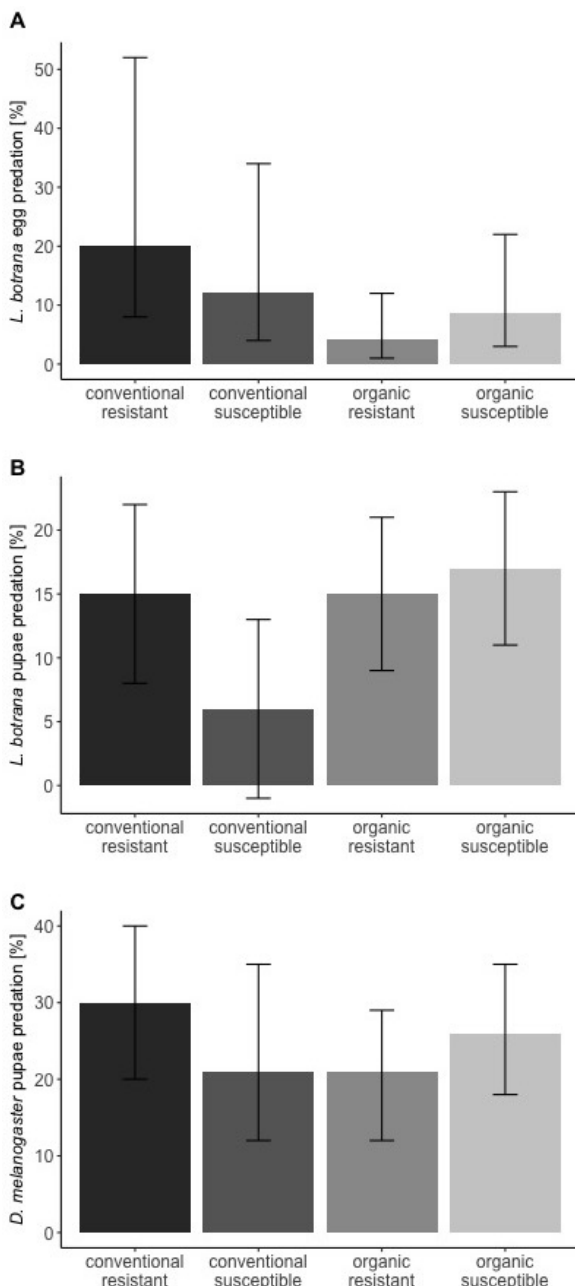


Figure 2 Observed predation rates of *Forficula auricularia* on A) *Lobesia botrana* eggs, B) *Lobesia botrana* pupae and C) *Drosophila melanogaster* pupae in 32 vineyards under organic vs. conventional management planted with resistant vs. susceptible varieties. Displayed are model predicted means and the corresponding 95 % confidence interval.predators

4 DISCUSSION

Earwigs were by far the most dominant predators in all studied vineyards the sole taxon that was observed in all vineyards and at all sampling dates. Likewise, Frank et al. (2007) detected highest predation activities of earwigs in New Zealand vineyards. Despite being sometimes considered pest in viticulture (Huth et al., 2011; Kehrli et al., 2012) earwigs can greatly contribute to pest control (Englert and Herz, 2019; Pennington et al., 2018; Reiff et al., 2021b). However, earwig abundances strongly vary between viticultural regions and pest control potential by earwigs may vary accordingly. For instance, harvestmen abundances were considerably higher than earwig abundances in southern France (Muneret et al., 2019a). Increased proportions of high biomass generalist predators (like harvestmen and earwigs) may on the other hand promote intra-guild predation (Ostandie et al., 2021). Further, shifts in predator communities towards single dominant generalist predators can weaken resilience for biological control (Tschardt et al., 2008).

Eight other taxa were identified to be involved in predation incidents. To our knowledge, we recorded for the first time predation on *L. botrana* and *Drosophila* sp. by Blattoptera and *Vespula* sp. in vineyards. We assume that the range of natural enemies of important vineyard pests may be even broader than currently assumed. For example, bush crickets are important predators of *L. botrana* in Austrian vineyards (Reiff et al., 2021b). By contrast, our observations in the Palatinate region revealed just one predation event of the bush cricket *Meconema meridionale*. However, bush crickets may become more prominent predators in Palatinate vineyards with climate change (Buse and Griebeler, 2011).

Overall, 17 % of *L. botrana* eggs, 15 % of *L. botrana* pupae and 27 % of *D. melanogaster* pupae were predated in only 24 h. Under real conditions, both pest species are exposed to potential predators for longer periods. *L. botrana* develops in approximately five weeks from egg to pupation with an additional pupation time of more than a week (Thiéry and Moreau, 2005). Development time of *D. suzukii* varies between 10-30 days depending on temperature (Winkler et al., 2020). Accordingly, increased predation rates were expected with longer exposure time. For instance, predation rates of *L. botrana* eggs were 2-5 fold higher than in our study when sentinel cards were exposed for 72 h in the same study region (Reiff et al., 2023; Pennington et al., 2018). Further, adult stages of *L. botrana* and *Drosophila* sp. which were not observed in this study are more easily regulated by e.g. spiders than by earwigs (Englert and Herz, 2019; Michalko et al., 2019). In conclusion, the overall potential for natural pest control in vineyards is expected to be even higher than observed by our sentinel card snapshots. Earwigs were the dominant predators during our study, but the prevalence of different enemies can vary between study regions.

ACKNOWLEDGEMENTS

We are grateful to all collaborating winegrowers, to Sonja Anslinger for rearing *L. botrana* and *D. melanogaster* and to Anja Hollander for her help with preparing sentinel cards.

CHAPTER VII

SELECTED POSTER PUBLICATIONS

Fungicide reduction enhances beneficial arthropods in grapevine



Jo Marie Reiff ^{1,2}, Sebastian Kolb ¹, Christoph Hoffmann ², Martin H. Entling ¹

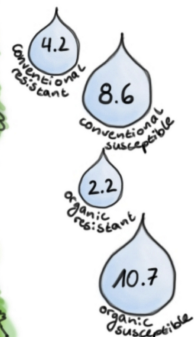
¹ IES, Institute for Environmental Sciences, University Koblenz-Landau ² Julius Kühn-Institut, Institute for Plant Protection in Fruit Crops and Viticulture, Siebeldingen

Recent declines of arthropods in agricultural landscapes are alarming, and pesticides are among the most likely causes of such declines. Grapevine is one of the most pesticide depending crops, typically receiving more than ten fungicide sprays in three months of growing season in Central Europe. Spraying contains several plant protection products of varying toxicity towards non-target organisms in both organic and conventional viticulture. Novel fungus-resistant grape varieties offer a promising approach to a more environmentally friendly viticulture, because they allow a considerable reduction of fungicide treatments while maintaining health, productivity and quality of grapes.

We studied effects of organic vs. conventional viticulture under full (susceptible grapes) and reduced (fungus-resistant grapes) fungicide sprays on non-target arthropods in the grapevine foliage in 32 vineyards of self-marketing wineries in the Palatinate region, Germany.

Fungicide spraying frequencies were significantly higher in susceptible vs. resistant grape varieties but did not differ between organic vs. conventional management.

Number of fungicide sprays:



Arthropods were sampled from the grapevine foliage at six dates between end of May and end of September 2018. Sampling was done by vigorously shaking the vines while placing a beat-sheet under the foliage.



Arthropod abundances in organic vs. conventional management and resistant vs. susceptible varieties. Different orders are depicted in bars. Most prominent families within these orders are highlighted by shifted blocks. Predatory arthropods (including omnivores and parasitoids) are colored in shades of red. Herbivorous arthropods are colored in shades of green. Fungivorous and detritivorous arthropods are colored in shades of brown and beige. Orders containing arthropods with multiple diet forms are colored in shades of blue.

Effects of organic vs. conventional management and fungus-resistant vs. susceptible grape varieties on arthropod abundances. Directions and significances of effects are highlighted with +/- and asterisks.

	fungus-resistant	organic	variety * management
individuals	n.s.	- *	n.s.
Dermoptera	n.s.	- *	n.s.
Araneae	+ ***	n.s.	n.s.
Araneidae	n.s.	n.s.	n.s.
Phidromidae	+ **	n.s.	n.s.
Salticidae	n.s.	n.s.	n.s.
Therididae	+ ***	n.s.	n.s.
Thomisidae	+ *	n.s.	n.s.
Dictynidae	+ *	n.s.	n.s.
Linyphiidae	n.s.	.	n.s.
Acari	n.s.	n.s.	*
Trombididae	n.s.	n.s.	*
Opliones	n.s.	n.s.	n.s.
Hymenoptera	n.s.	n.s.	n.s.
Formicidae	n.s.	n.s.	n.s.
Neuroptera	n.s.	+ **	n.s.
Coleoptera	n.s.	n.s.	.
Coccinellidae	+ *	n.s.	n.s.
Latrididae	+ *	n.s.	n.s.
Phalacridae	+ *	n.s.	**
Chrysomelidae	n.s.	n.s.	n.s.
Lepidoptera	n.s.	n.s.	n.s.
Hemiptera	n.s.	+ *	n.s.
Cicadellidae	- **	.	*
Miridae	n.s.	n.s.	n.s.
Diptera	+ **	+ **	n.s.
Psocoptera	n.s.	n.s.	*

In total, we identified 47645 arthropods of 188 different families (20 taxonomic orders). Organic vs. conventional management showed no clear effect across different taxa. Reduced fungicide sprays in fungus-resistant varieties enhanced predatory taxa up to 1.8 fold, particularly spiders. Oppositely, herbivorous Cicadellidae were reduced by almost 40 % in fungus-resistant varieties. This shift in arthropod communities of fungus-resistant grapes should enhance their resilience to arthropod pest attack.

In addition to reducing production cost and pesticide pollution, reduced sprays in fungus-resistant grape varieties, under both organic and conventional management, proves to be a pivotal component to foster functional biodiversity and natural pest suppression.¹²

PROMOTING SUSTAINABLE VITICULTURE
by **CULTIVATING FUNGUS-RESISTANT VARIETIES** and **REDUCING FUNGICIDE SPRAYINGS**

¹ Pennington, T., Kolb, S., Waizer, J., Hoffmann, C., Entling, M.H. 2019. Does minimal pruning and reduced fungicide use impact spiders in the grapevine canopy? *J. Arachnol.* 47, 364.
² Pennington, T., Reiff, J.M., Theiss, K., Entling, M.H., Hoffmann, C., 2018. Reduced fungicide applications improve insect pest control in grapevine. *BioControl* 63, 657-675.

We thank all participating wineries for the provision of vineyards and data. Many thanks to Keerthi Sudarshan, Paul Mason, Rosalie Shreebhe, Anja Hollander, Alexandra Dreyer, Kim Meuser and Gerli Pfeil for their help during field season and arthropod identification.



Reduced Pesticide Application promotes Natural Pest Mite Control in Vineyards

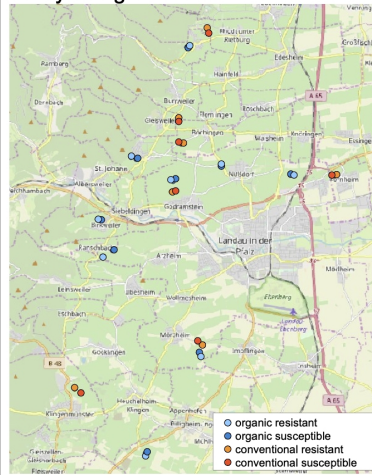
Jo Marie Reiff^{1,2}, Marvin Ehringer¹, Martin H. Entling¹, Christoph Hoffmann²

¹ University of Koblenz – Landau, Institute for Environmental Sciences, Landau
² Julius Kühn-Institut, Institute for Plant Protection in Fruit Crops and Viticulture, Siebeldingen

Agricultural intensification is a major driver of biodiversity decline including arthropods. This may also affect important ecosystem services such as natural pest regulation. With more than ten fungicide applications per season, grapevine is one of the most intensively sprayed crops in Central Europe, limiting ecological and economic sustainability in viticulture. One promising approach to a more environmentally friendly viticulture is growing fungus resistant cultivars which can allow fungicide applications to be reduced by up to 90 %.



Study design



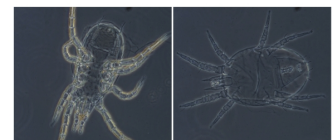
We investigated phytophagous mites (Eriophyidae, Tetranychidae) and their natural enemies (Phytoseiidae, Tydeidae) in the Palatinate region (Germany) in 2018. The study was carried out in **32 vineyards of organic and conventional wineries**, half of which were planted with **fungus resistant cultivars** and treated with reduced plant protection regimes. Leaves were collected five times between May and September and mite fauna on the leaf surface was washed onto coloured filter papers. We counted Phytoseiidae and *Tydeus goetzi* as predatory mites. *Co. vitis* and *Cal. vitis* (Eriophyidae) were counted as pest mites.

	organic		conventional	
	resistant	susceptible	resistant	susceptible
total number of sprayings	2.2 ± 1.2	10.8 ± 1.9	4.3 ± 1.6	8.1 ± 1.6
copper	1.8 ± 1.5	8.3 ± 4.8	0.3 ± 0.8	0.7 ± 1.5
sulfur	2.0 ± 1.0	8.7 ± 1.7	1.7 ± 1.1	2.7 ± 1.1
baking soda (NaHCO ₃)	0.6 ± 0.7	5.0 ± 1.2	–	0.3 ± 0.8
harmless conventional	–	–	2.3 ± 1.1	5.4 ± 3.3
harmful conventional	–	–	3.1 ± 3.2	4.9 ± 2.4

Average number of fungicide sprayings and treatments per compound in the four management systems and the respective standard deviation.



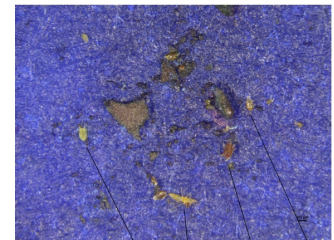
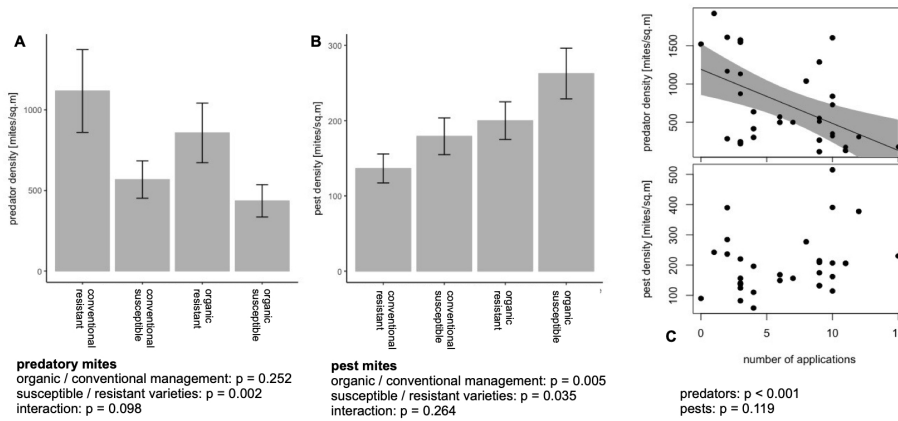
Colomerus vitis (Eriophyidae) infestation on grapevine.



Typhlodromus pyri (Phytoseiidae) and *Tydeus goetzi* (Tydeidae).

Results

Organic spraying regimes and higher plant protection intensities promoted phytophagous mites significantly. Highest densities of pest mites were observed on susceptible grape varieties under organic management (Fig. B). Predatory mites were not significantly affected by organic or conventional management but benefited from cultivation of fungus resistant varieties (Fig. A). Predatory mite densities decreased by almost 90 % with increasing number of fungicide applications (Fig. C).



Colorful leaf fauna: *T. goetzi*, Thysanoptera, *P. ulmi* and *T. pyri*.



We thank all participating wineries for the provision of vineyards and data: Peter Argus, Marcel Barbey, Franz Braun, Bernhard Bentz, Ottmar Graf, Michael Kern, Stefan Kuntz, Emil Linz, Martin Löhr, Ingo Mathis, Andreas Müller, Heinz Pfaffmann, Klaus Rummel, Thomas Schaurer, Hermann Schneider, Heiner Sauer, Ludwig Seiler. Many thanks to Paul Mason, Rosalie Shrestha, Anja Hollander and Gerti Michl for their help during field season.

Conclusion

In an experimental system, reduced plant protection in fungus-resistant grapes favoured pest mites and the biological control of grape berry moth (Pennington et al. 2017, 2018). Here, we show that natural pest suppression benefits from fungicide reduction also in commercial vineyards, whereas organic farming alone did not show any positive effects. We conclude that in addition to other advantages, the cultivation of fungus resistant grape varieties under reduced spraying intensity can improve the natural control of pest mites in viticulture.

Pennington, T., Kraus, C., Alakina, E., Entling, M.H., Hoffmann, C., 2017. Minimal Pruning and Reduced Plant Protection Promote Predatory Mites in Grapevine. Insects 8, 86.
 Pennington, T., Reiff, J.M., Theiss, K., Entling, M.H., Hoffmann, C., 2018. Reduced fungicide applications improve insect pest control in grapevine. BioControl 63, 687–695.

CHAPTER VIII

CONCLUSION AND OUTLOOK

Jo Marie Reiff

Summed up in a nutshell, reduced fungicide applications promoted arthropods in vineyards. Benefits of fungicide reduction prevailed over other variables such as minimal pruning (Chapter II), organic management (Chapters III and IV), and landscape complexity (Chapter V). Further, the effects were consistent over five years of study in the experimental vineyard (Chapter II) and were confirmed in commercially managed vineyards of the same study region (Chapters III-V). At a glance, the effects of reduced fungicide applications are presented in Figure 1 for the experimental vineyard (Chapter II) and in Figure 2 for the commercially managed vineyards (Chapters III-VI).

In the experimental vineyard (Chapter II) the majority of arthropods was significantly promoted by reduced fungicide sprayings (Fig. 1). Most affected by fungicide applications was the beneficial mite family Tydeidae with 313 % increase under reduced fungicide sprayings. Foliar arthropods such as mites are directly exposed to fungicide sprays, so strong effects on the leaf mesofauna were to be expected. However, ants, which also live both in and on the soil, also strongly benefited from reduced fungicide sprayings (198 % increase). Only four taxa were not significantly affected, three of them potential vineyard pests. Accordingly, the increased predation rate and the higher predator abundance under reduced sprayings make vineyards with lower treatment intensity more resilient in the long term. Thus, under largely standardised experimental conditions, viticulture appears to be consistently more sustainable under reduced fungicide sprays. However, it is important that this can also be implemented in actual practice under commercial conditions.

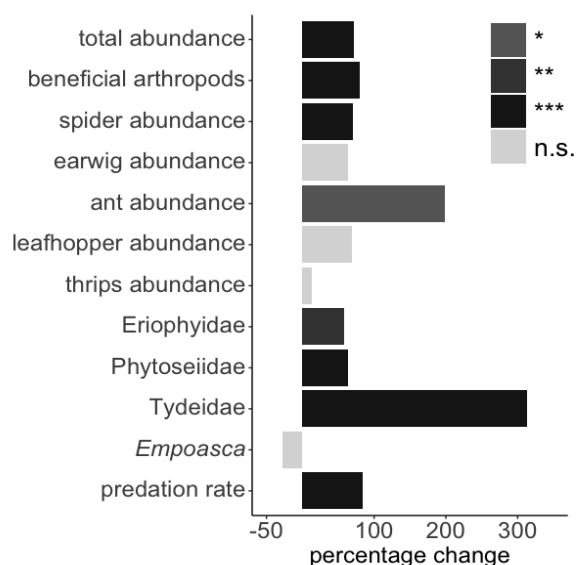


Figure 1 Percentage changes of different arthropod taxa, functional groups and predation rates by reduction in fungicide sprayings from 13 to 2 per season in one experimental vineyard. Levels of significance are highlighted in different shades of grey (*' p < 0.05; ***' p < 0.01; ****' p < 0.001).

Chapters III-VI focus on actual viticultural practices in 32 commercially managed vineyards. A visual summary of the results is provided in Figure 2. The majority of investigated taxa and functional groups responded positively to fungus-resistant varieties which allow for reduced fungicide applications and thus lower cumulative hazard quotients. Of particular interest for sustainable agroecosystems are arthropods providing ecosystem services. Fungus-resistant varieties, and thus reduced fungicide applications and lower hazard quotients enhanced abundances of natural enemies (here beneficial arthropods) and particularly spiders and predatory mites. Further, pollinators as well as fungivorous and detritivorous arthropods (here other arthropods) benefited from reduced fungicide sprayings and lower hazard quotients. Consequently, ecosystem services apart from pest control such as

pollination and nutrient cycling which were not covered in this study should be promoted with increased arthropod abundance and diversity (Kremen and Miles, 2012; Oliver et al., 2015). Even though arthropod diversity was not affected at the family level, the species richness of spiders increased under fungicide reduction. This suggests that species-level diversity could be higher in other groups as well, although the resolution of the data was unable to reveal this. Particularly dictynid spiders (329 % and 627 % increase, respectively), tydeid mites (433 % and 559 % increase, respectively), and the thomisid spider genus *Misumena* (417 % and 340 % increase, respectively) benefited from reduced fungicide sprayings and lower hazard quotients (Fig. 2A, B). The thomisid spider genus *Xysticus* was the most affected taxon in fungus-resistant varieties (90 % increase; Fig. 2C). Significantly negative effects of reduced fungicide applications occurred in solely two groups, the pest mite family Eriophyidae and in the camera surveyed predation experiment. Similarly, fungus-resistant varieties had lower abundances of herbivores in general and of two phytophagous families in detail, the Cicadellidae and the Eriophyidae. The decline of pest species under reduced fungicide applications in resistant varieties highlights their potential for natural pest regulation. In conclusion, fungicide reduction had either positive or no effect on non-pest arthropods.

Although there was a great potential for fungicide reduction in fungus-resistant varieties (one vineyard received no sprayings at all) the variance in between both types of varieties (fungus-resistant vs. susceptible) was high. As displayed in Figure 1 of Chapter V, organic rather than conventional winegrowers exploited the fungicide reduction potential in resistant varieties. However, the susceptible varieties in organic vineyards were sprayed considerably more frequent than the conventional ones. Consequently, in sum, there was no clear benefit of organic viticulture. This contradicts the common assumption that organic farming avoids pesticide sprayings (Bengtsson et al., 2005; Hole et al., 2005). In arable farming, pesticides are truly renounced under organic management (Lechenet et al., 2014). Although pesticide use is usually lower under organic management, organic perennial crops are sprayed frequently nonetheless (Muneret et al., 2018a). Viticulture is a special case in this respect, as wine is promoted as a luxury good. According to Rosenheim et al. (2020) pesticides are applied more frequently with increasing monetary value of the crops. A notably reduction of fungicide applications can only be archived in fungus-resistant varieties while maintaining healthy grapes of high quality in both organic and conventional management.

Another aspect arising from different spraying regimes in organic and conventional vineyards (Figure 1, Chapter V) is the variable hazard quotient of the applied products. The fungicides applied in the organic vineyards tended to reveal higher acute toxicity towards honeybees than the conventional products.⁵ Copper and sulfur, both frequently applied in organic viticulture, are of environmental concern. As multisite fungicides they are characterised by a non-specific toxicity towards a broad spectrum of target (and non-target) organisms (Hermann and Stenzel, 2019). Wettable sulfur can strongly evaporate at temperatures above 30 °C as hydrogen sulfide which is highly toxic to humans and animals (Flanders, 1943; Guidotty, 2010). In this context, it is alarming, for instance, that the hazard classification of sulfur (not harmful to beneficial insects, predatory mites, and spiders) contradicts the declared mode of action (fungicide and acaricide) in its safety data sheet (BVL, 2023). Copper

5 Contrastingly, a comparison of all authorized pesticide active ingredients in the EU revealed that pesticides used in conventional agriculture were significantly more hazardous to human (e.g. acute toxicity if swallowed or inhaled, reproduction toxicity, skin and eye damage, specific organ damage) compared to pesticides certified for organic farming (Burtscher-Schaden et al., 2022).

accumulations in soils can be phytotoxic to roots, affect microbial activity, harm macro-organisms such as earthworms, and subsequently reduce soil fertility (Lamichhane et al., 2018).⁶ Despite ongoing research to identify potent substitutes copper is the sole fungicide to efficiently control downy mildew in organic viticulture (Gessler et al., 2011). Thus, fungus-resistant grape varieties are the best opportunity to reconcile sustainability and plant protection, especially in organic viticulture.

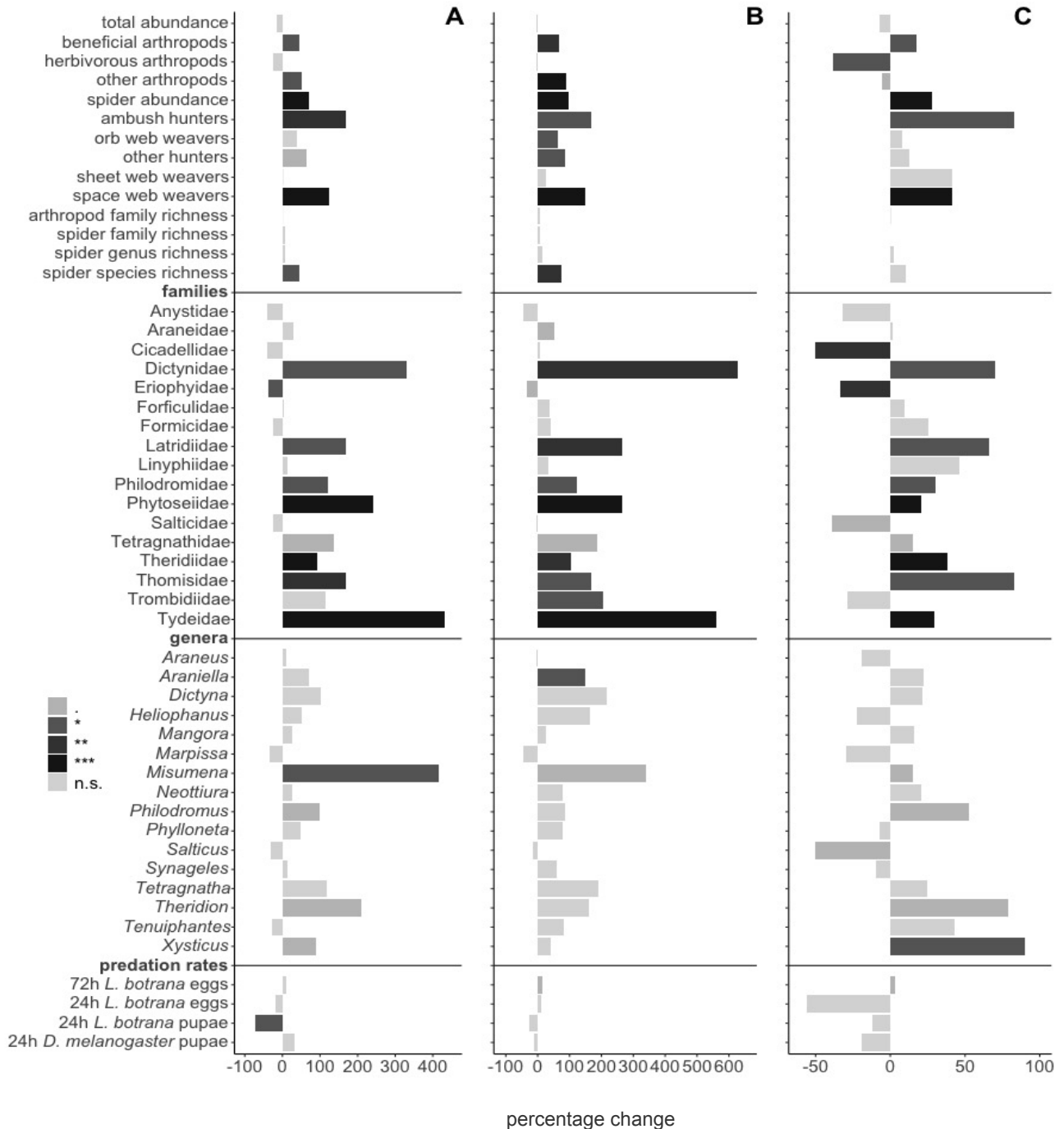


Figure 2 Effects of A) a reduction in fungicide sprays from 14 to 0 per season, B) a decrease in cumulated hazard quotients of applied fungicides from 6 to 0 per season, and C) the cultivation of fungus-resistant compared to susceptible grape varieties. Percentage changes of different arthropod taxa, functional groups and predation rates are displayed for 32 commercially managed vineyards. Levels of significance are highlighted in different shades of grey (‘.’ $p < 0.1$; ‘*’ $p < 0.05$; ‘**’ $p < 0.01$; ‘***’ $p < 0.001$).

⁶ Copper sulfate was the first fungicide described by Isaac-Bénédict Prévost in 1807 (Klittich, 2008). 200 years of copper applications may now have accumulated in agricultural soils.

Irrespective of these two fungicides, the calculated quotients may in general underestimate the actual hazard for arthropods. Despite newer pesticides being postulated to be more selective, they negatively affect non-target organisms of even phylogenetically distant groups (Schmidt-Jeffris, 2023; Wan et al., 2023). There is increasing evidence that current risk assessments fail to adequately address the complexity of environmental interactions highlighting the need for new realistic approaches for pesticide authorization to substantially protect the environment (Brühl and Zaller, 2019; Zaller and Brühl, 2019; Schäfer et al., 2019). For instance, Franklin and Raine (2019) criticize the use of only one test organism in risk assessments (e.g. honeybee) to protect the vast group of pollinators. More phylogenetically distant organisms are thus even less in scope of protective measures. Further, transformation products of pesticides may be even more harmful than the parent pesticide but are disregarded in risk assessments (Ji et al., 2020). Albeit fungus-resistant varieties being not inevitably sprayed less, they are currently the best solution to reduce fungicide sprayings in viticulture. As a consequence, (i) fungicide reduction by cultivation of fungus-resistant varieties should be pursued in politics, (ii) research should focus on breeding other resistant crops and their possible benefit for the environment, and (iii) fungus-resistant grape varieties should be promoted and commercialised more effectively.

As primarily stated, arthropods benefit from reduced fungicide applications. But what about humans? Multiple health disorders such as Parkinson's disease, Alzheimer's disease, reproductive disorders, and respiratory disorders, as well as several cancers are associated with pesticide exposure (Sabarwal et al., 2018). This also has social implications. For instance, the annual health costs associated with organophosphate pesticide use in the United States are estimated to be as high as \$ 44.7 billion (Attina et al., 2016). The interaction of multiple stressors (e.g. cumulative exposure) can further increase the health risk of pesticides (Knudsen, 2017). Obviously, people frequently getting in direct contact with pesticides bear the greatest risk of poisoning. It is estimated that 44 % of farmers are globally intoxicated by pesticides every year resulting in approximately 11 000 fatalities (Boedecker et al., 2020). However, pesticide drift poses a high health risk to all humans living in agricultural areas (Zaller et al., 2022). Further, there is evidence for poisoning by unintentional pesticide uptake by consumption of pesticide contaminated fruits and ground water (Aktar et al., 2009). Accordingly, pesticide residues were also detected on grapes as well as in must and wine (Cabras et al., 2000).⁷ Besides possible effects on human health these residues can also affect microbial activity and subsequently inhibit a successful fermentation (Russo et al., 2019). Thus, there are many self-serving reasons for winegrowers to reduce the use of pesticides. Therefore, fungus-resistant varieties are also the most promising approach to reduce pesticide impact on human health in addition to evident environmental benefits. However, up to date fungus-resistant varieties account for only 2.62 % of the German viticultural area (Richter and Hanf, 2022). With increasing environmental awareness, consumer interest in sustainably produced wines is also growing, and with it the acceptance of new and lesser-known fungus-resistant grape varieties (Nesselhauf et al., 2020; Vecchio et al., 2022). Time to act.

⁷ Although we were not able to detect clear benefits of organic viticulture on arthropods, 72 % less pesticides and 97 % lower pesticide residues were detected in organic compared to conventional wines (González et al., 2022). The consumption of organic wine might therefore be less harmful (assuming that alcohol consumption is considered not to be a problem itself).

REFERENCES

A

- Ahmad, S., Pozzebon, A., Duso, C., 2015. Predation on heterospecific larvae by adult females of *Kampimodromus aberrans*, *Amblyseius andersoni*, *Typhlodromus pyri* and *Phytoseius finitimus* (Acari: Phytoseiidae). *Exp. Appl. Acarol.* 67, 1–20. <https://doi.org/10.1007/s10493-015-9940-1>.
- Aktar, M.W., Sengupta, D., Chowdhury, A., 2009. Impact of pesticides use in agriculture: their benefits and hazards. *Interdiscip Toxicol* 2, 1-12. <https://doi.org/10.2478/v10102-009-0001-7>.
- Ansari, I., El-Kady, M.M., Arora, C., Sundararajan, M., Maiti, D., Khan, A., 2021. A review on the fatal impact of pesticide toxicity on environment and human health. In: Singh, S., Singh, P., Rangabhashiyam, S., Srivastava, K.K. (eds.), *Global Climate Change*. Elsevier, Amsterdam, Netherlands, pp. 361–391.
- Atallah, J., Teixeira, L., Salazar, R., Zaragoza, G., Kopp, A., 2014. The making of a pest: the evolution of a fruit-penetrating ovipositor in *Drosophila suzukii* and related species. *Proc. R. Soc. B Biol. Sci.* 281, 20132840. <https://doi.org/10.1098/rspb.2013.2840>.
- Attina, T.M.; Hauser, R.; Sathyanarayana, S.; Hunt, P.A.; Bourguignon, J.-P.; Myers, J.P.; Trasande, L., 2016. Exposure to endocrine-disrupting chemicals in the USA: A population-based disease burden and cost analysis. *Lancet Diabetes Endocrinol.* 4, 996–1003.
- Attwood, S.J., Maron, M., House, A.P.N., Zammit, C., 2008. Do arthropod assemblages display globally consistent responses to intensified agricultural land use and management? – *Glob. Ecol. Biogeogr.* 17, 585–599. <https://doi.org/10.1111/j.1466-8238.2008.00399.x>.

B

- Bagnoli, B., Lucchi, A., 2006. Parasitoids of *Lobesia botrana* (Den. & Schiff.) in Tuscany. *IOBCWPRS Bull* 29, 139–142.
- Bakker, F.M., Aldershof, S.A., Šmilauer, P., 2022. Not all insects decline: 30-years of comprehensive sampling show increasing and decreasing arthropod population trends in EU-farmland. *SSRN Electron. J.* 4011758.
- Barata, A., Santos, S.C., Malfeito-Ferreira, M., Loureiro, V., 2012. New Insights into the Ecological Interaction Between Grape Berry Microorganisms and *Drosophila* Flies During the Development of Sour Rot. *Microb. Ecol.* 64, 416–430. <https://doi.org/10.1007/s00248-012-0041-y>.
- Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting Linear Mixed-Effects Models Using **lme4**. *J. Stat. Softw.* 67. <https://doi.org/10.18637/jss.v067.i01>.
- Beaumelle, L., Tison, L., Eisenhauer, N., Hines J., Malladi, S., Pelosi, C., Thouvenot, L., Phillips, H.R.P., 2023a. Pesticide effects on soil fauna communities—A meta-analysis. *J Appl Ecol*, 1–15. <https://doi.org/10.1111/1365-2664.14437>
- Beaumelle, L., Giffard, B., Tolle, P., Winter, S., Entling, M.H., Benítez, E., Zaller, J.G., Auriol, A., Bonnard, O., Charbonnier, Y., Fabreguettes, O., Joubard, B., Kolb, S., Ostandie, N., Reiff, J.M., Richart-Cervera, S., Rusch, A., 2023b. Biodiversity conservation, ecosystem services and organic viticulture: A glass half-full. – *Agric. Ecosyst. Environ.* 351, 108474. <https://doi.org/10.1016/j.agee.2023.108474>.
- Beers, E.H., Schmidt, R.A., 2014. Impacts of orchard pesticides on *Galendromus occidentalis*: Lethal and sublethal effects. *Crop Prot.* 56, 16–24. <https://doi.org/10.1016/j.cropro.2013.10.010>.

- Benelli, G., Lucchi, A., Anfora, G., Bagnoli, B., Botton, M., Campos-Herrera, R., Carlos, C., Daugherty, M.P., Gemeno, C., Harari, A.R., Hoffmann, C., Ioriatti, C., López Plantey, R.J., Reineke, A., Ricciardi, R., Roditakis, E., Simmons, G.S., Tay, W.T., Torres-Vila, L.M., Vontas, J., Thiéry, D., 2023. European grapevine moth, *Lobesia botrana*, Part I: Biology and ecology. *Entomol. Gen.* 43: 261-280.
- Bengtsson, J., Ahnström, J., Weibull, A.-C., 2005. The effects of organic agriculture on biodiversity and abundance: a meta-analysis: Organic agriculture, biodiversity and abundance. *J. Appl. Ecol.* 42, 261–269. <https://doi.org/10.1111/j.1365-2664.2005.01005.x>.
- Bianchi, F.J.J.A., Booij, C.J.H., Tscharntke, T., 2006. Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. *Proc. R. Soc. B Biol. Sci.* 273, 1715–1727. <https://doi.org/10.1098/rspb.2006.3530>.
- Biedermann, R., Niedringhaus, R., 2011. Die Zikaden Deutschlands. Bestimmungstabellen für alle Arten. Fründ, Scheeßel.
- Biondi, A., Mommaerts, V., Smagghe, G., Viñuela, E., Zappalà, L., Desneux, N., 2012. The non-target impact of spinosyns on beneficial arthropods. *Pest. Manag. Sci.* 68, 1523-1536. <https://doi.org/10.1002/ps.3396>.
- Birkhofer, K., Diehl, E., Wolters, V., Smith, H.G., 2017. Global Metawebs of Spider Predation Highlight Consequences of Land-Use Change for Terrestrial Predator–Prey Networks. In: Moore, J.C., De Ruiter, P.C., McCann, K.S., Wolters, V. (eds.), *Adaptive Food Webs*. Cambridge University Press, pp. 193–213. <https://doi.org/10.1017/9781316871867.015>.
- Blaise, C., Mazzia, C., Bischoff, A., Millon, A., Ponel, P., Blight, O., 2021. The key role of inter-row vegetation and ants on predation in Mediterranean organic vineyards. *Agric. Ecosyst. Environ.* 311, 107327. <https://doi.org/10.1016/j.agee.2021.107327>.
- Blandenier, G., 2009. Ballooning of spiders (Araneae) in Switzerland: General Results from an Eleven-Year Survey. *Arachnology* 14, 308–316. <https://doi.org/10.13156/ arac.2009.14.7.308>.
- Boedeker, W., Watts, M., Clausing, P., Marquez, E. (2020). The global distribution of acute unintentional pesticide poisoning: estimations based on a systematic review. *BMC Public Health* 20, 1875. <https://doi.org/10.1186/s12889-020-09939-0>.
- Bömer, J., Zabawa, L., Sieren, P., Kicherer, A., Klingbeil, L., Rascher, U., Müller, O., Kuhlmann, H., Roscher, R., 2020. Automatic Differentiation of Damaged and Unharmed Grapes Using RGB Images and Convolutional Neural Networks. In: Bartoli, A., Fusiello, A. (eds) *Computer Vision – ECCV 2020 Workshops*. ECCV 2020. Lecture Notes in Computer Science, vol 12540. Springer, Cham. https://doi.org/10.1007/978-3-030-65414-6_24.
- Bonte, D., Vandenbroecke, N., Lens, L., Maelfait, J.-P., 2003. Low propensity for aerial dispersal in specialist spiders from fragmented landscapes. *Proc. R. Soc. Lond. B Biol. Sci.* 270, 1601–1607. <https://doi.org/10.1098/rspb.2003.2432>.
- Borrello, M., Cembalo, L., Vecchio, R., 2021. Consumers' acceptance of fungus resistant grapes: Future scenarios in sustainable winemaking. *J. Clean. Prod.* 307: 127318.
- Bosco, D., Alma, A., Arzone, A., 1997. Studies on population dynamics and spatial distribution of leafhoppers in vineyards (Homoptera: Cicadellidae). *Ann. Appl. Biol.* 130, 1–11. <https://doi.org/10.1111/j.1744-7348.1997.tb05778.x>.
- Bostanian, N.J., Dondale, C.D., Binns, M.R., Pitre, D., 1984. Effects of Pesticide use on Spiders (Araneae) in Quebec Apple Orchards. *Can. Entomol.* 116, 663–675. <https://doi.org/10.4039/Ent116663-5>.
- Boudon-Padieu, É., Maixner, M., 2007. Potential effects of climate change on distribution and activity of insect vectors of grapevine pathogens. *Colloque international et pluridisciplinaire sous l'égide de la chaire UNESCO Vin et Culture*, Dijon. 23.
- Bower, L.F., Snetsinger, R., 1985. Tree bark as an overwintering niche for spiders (Araneae) in oak-maple forest edge. *Melsheimer Entomological Series* 35: 1–5.

- Bowler, D.E., Heldbjerg, H., Fox, A.D., de Jong, M., Böhning-Gaese, K., 2019. Long-term declines of European insectivorous bird populations and potential causes. *Conserv. Biol.* 33, 1120–1130. <https://doi.org/10.1111/cobi.13307>.
- Brooks, M.E., Kristensen, K., van Benthem, K.J., Magnusson, A., Berg, C.W., Nielsen, A., Skaug, H.J., Maechler, M., Bolker, B.M., 2017. glmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized Linear Mixed Modeling. *R J.* 9, 378–400.
- Bruggisser, O.T., Schmidt-Entling, M.H., Bacher, S., 2010. Effects of vineyard management on biodiversity at three trophic levels. *Biol. Conserv.* 143, 1521–1528. <https://doi.org/10.1016/j.biocon.2010.03.034>.
- Brühl, C.A., Schmidt, T., Pieper, S., Alscher, A., 2013. Terrestrial pesticide exposure of amphibians: An underestimated cause of global decline? *Sci. Rep.* 3 <https://doi.org/10.1038/srep01135>.
- Brühl, C.A., Zaller, J.G., 2019. Biodiversity Decline as a Consequence of an Inappropriate Environmental Risk Assessment of Pesticides. *Front. Environ. Sci.* 7, 177. <https://doi.org/10.3389/fenvs.2019.00177>.
- Buchanan, A., Grieshop, M., Szendrei, Z., 2018. Assessing annual and perennial flowering plants for biological control in asparagus. *Biol. Control* 127, 1–8. <https://doi.org/10.1016/j.biocontrol.2018.08.013>.
- Burtscher-Schaden, H., Durstberger, T., Zaller, J.G., 2022. Toxicological Comparison of Pesticide Active Substances Approved for Conventional vs. Organic Agriculture in Europe. *Toxics* 10, 753. <https://doi.org/10.3390/toxics10120753>.
- Buse, J., Griebeler, E.M., 2011. Incorporating classified dispersal assumptions in predictive distribution models – A case study with grasshoppers and bush-crickets. *Ecol. Model.* 222, 2130–2141. <https://doi.org/10.1016/j.ecolmodel.2011.04.010>.
- BVL, Bundesamt für Verbraucherschutz und Lebensmittelsicherheit, 2018. Pflanzenschutzmittel-Verzeichnis 2018 – Teil 3: Weinbau, 66th ed. Bundesamt für Verbraucherschutz und Lebensmittelsicherheit, Braunschweig.
- BVL, Bundesamt für Verbraucherschutz und Lebensmittelsicherheit, 2023. Verzeichnis zugelassener Pflanzenschutzmittel. <https://apps2.bvl.bund.de/psm/jsp/DatenBlatt.jsp?kennr=052273-00> (accessed on 01.08.2023).

C

- Cabras, P., Conte, E., 2001. Pesticide residues in grapes and wine in Italy. *Food Addit. Contam.* 18, 880–885.
- Cahenzli, F., Pfiffner, L., Daniel, C., 2017. Reduced crop damage by self-regulation of aphids in an ecologically enriched, insecticide-free apple orchard. *Agron. Sustain. Dev.* 37, 65. <https://doi.org/10.1007/s13593-017-0476-0>.
- Campbell, P.J., Brown, K.C., Harrison, E.G., Bakker, F., Barrett, K.L., Candolfi, M.P., Canez, V., Dinter, A., Lewis, G., Mead-Briggs, M., Miles, M., Neumann, P., Romijn, K., Schmuck, R., Shires, S., Ufer, A., Waltersdorfer, A., 2000. A hazard quotient approach for assessing the risk to non-target arthropods from. *Anz. Für Schädlingskunde* 73, 117–124. <https://doi.org/10.1007/bf02956443>.
- Caprio, E., Nervo, B., Isaia, M., Allegro, G., Rolando, A., 2015. Organic versus conventional systems in viticulture: Comparative effects on spiders and carabids in vineyards and adjacent forests. *Agric. Syst.* 136, 61–69. <https://doi.org/10.1016/j.agsy.2015.02.009>.
- Cardoso, P., Pekár, S., Jocqué, R., Coddington, J.A., 2011. Global Patterns of Guild Composition and Functional Diversity of Spiders. *PLoS ONE* 6, e21710. <https://doi.org/10.1371/journal.pone.0021710>.
- Caro, T., Rowe, Z., Berger, J., Wholey, P., Dobson, A., 2022. An inconvenient misconception: Climate change is not the principal driver of biodiversity loss. *Conservation Letters*, 15, e12868. <https://doi.org/10.1111/conl.12868>.

- Castagnoli, M., 1989. Recent advances in knowledge of the mite fauna in the biocenosis of grapevine in Italy. Influence of Environmental Factors on the Control of Grape Pests, Diseases and Weeds. Balkema, Rotterdam, NL, pp. 169–180.
- Cerdá, X., Retana, J., Manzaneda, A., 1998. The role of competition by dominants and temperature in the foraging of subordinate species in Mediterranean ant communities. *Oecologia* 117: 404–412.
- Chaplin-Kramer, R., O'Rourke, M.E., Blitzer, E.J., Kremen, C., 2011. A meta-analysis of crop pest and natural enemy response to landscape complexity: Pest and natural enemy response to landscape complexity. *Ecol. Lett.* 14, 922–932. <https://doi.org/10.1111/j.1461-0248.2011.01642.x>.
- Chen, X.D., Stark, J.D., 2010. Individual- and population-level toxicity of the insecticide, spirotetramat and the agricultural adjuvant, Destiny to the Cladoceran, *Ceriodaphnia dubia*. *Ecotoxicology* 19, 1124–1129. <https://doi.org/10.1007/s10646-010-0495-y>.
- Chen, Y., Alcalá Herrera, R., Benitez, E., Hoffman, C., Möth, S., Paredes, D., Plaas, E., Popescu, D., Rascher, S., Rusch, A., Sandor, M., Tolle, P., Willemen, L., Winter, S., Schwarz, N., 2022. Winegrowers' decision-making: A pan-European perspective on pesticide use and inter-row management. *J. Rural Stud.* 94, 37–53.
- Childers, C.C., Enns, W.R., 1975. Predaceous Arthropods Associated with Spider Mites in Missouri Apple Orchards. *J. Kans. Entomol. Soc.* 48, 453–471.
- Chong, C.S., Hoffmann, A.A., Thomson, L.J., 2007. Commercial agrochemical applications in vineyards do not influence ant communities. *Environ. Entomol.* 36: 1374-1383.
- Clymans, R., Vrancken, K., Bylemans, D., Beliën, T., 2015. Side effects on spiders of plant protection products commonly used during spring and autumn in Belgian pear production. *Acta Hort.* 451–456. <https://doi.org/10.17660/ActaHortic.2015.1094.59>.
- Costello, M.J., Daane, K.M., 1999. Abundance of Spiders and Insect Predators on Grapes in Central California. *J. Arachnol.* 27, 531–538.
- Costello, M.J., Daane, K.M., 2005. Day vs. Night Sampling for Spiders in Grape Vineyards. *J. Arachnol.* 33, 25–32. <https://doi.org/10.1636/H02-52>.
- Cuthbertson, A.G.S., Murchie, A.K., 2003. The impact of fungicides to control apple scab (*Venturia inaequalis*) on the predatory mite *Anystis baccarum* and its prey *Aculus schlechtendali* (apple rust mite) in Northern Ireland Bramley orchards. *Crop. Prot.* 22, 1125–1130.
- Cuthbertson, A.G.S., Murchie, A.K., 2004. The phenology, oviposition and feeding rate of *Anystis baccarum*, a predatory mite in Bramley apple orchards in Northern Ireland. *Exp. Appl. Acarol.* 34, 367–373.

D

- Daniel, C., Haesli, A., Weibel, F., 2001. The side effects of lime sulphur on predaceous arthropods, i.e. *Typhlodromus pyri*, and other leaf occupying arthropods. FiBL Homepage. URL <http://www.fibl.net/archiv/pdf/daniel-et-al-2001-lime-sulphur.pdf>.
- De Graaff, M.-A., Hornslein, N., Throop, H.L., Kardo, P., van Diepen, L.T.A., 2019. Chapter One – Effects of agricultural intensification on soil biodiversity and implications for ecosystem functioning: A meta-analysis. *Advances in Agronomy* 155, 1-44. <https://doi.org/10.1016/bs.agron.2019.01.001>.
- Desneux, N., Decourtye, A., Delpuech, J.-M., 2007. The Sublethal Effects of Pesticides on Beneficial Arthropods. *Annu. Rev. Entomol.* 52, 81–106. <https://doi.org/10.1146/annurev.ento.52.110405.091440>.

- Diehl, E., Sanhudo, C.E.D., Diehl-Fleig, E., 2004. Ground-dwelling ant fauna of sites with high levels of copper. *Braz. J Biol* 64: 33–39.
- Dubey, A., Lewis, M.T., Dively, G.P., Hamby, K.A., 2020. Ecological impacts of pesticide seed treatments on arthropod communities in a grain crop rotation. *J Appl Ecol.* 57, 936–951. <https://doi.org/10.1111/1365-2664.13595>.
- Duffner, K., 1999. Untersuchungen zur Biologie, Morphologie und Bekämpfung der Kräuselmilbe *Calepitrimerus vitis* NALEPA 1905 (Acari, Eriophyoidea). Albert-Ludwigs-Universität, Freiburg im Breisgau.
- Duque, T., Chowdhury, S., Scherf, G., Riess, K., Pekár, S., Isaia, M., Schäfer, R.B., Entling, M.H. (under review). Chemical Sensitivity of Spiders from Different Ecosystems: Effects of Phylogeny and Habitat. – *Pest Management Science*. (submitted on 01st June 2023).
- Duso, C., de Lillo, E., 1996. Grape. In: Lindquist, E.E., Sabelis, M.W., Bruin, J. (eds) *Eriophyoid mites – their biology, natural enemies and control*. Elsevier Science B.V., pp 571–582.
- Duso, C., Vettorazzo, E., 1999. Mite Population Dynamics on Different Grape Varieties With or Without Phytoseiids Released (Acari: Phytoseiidae). *Exp. Appl. Acarol.* 23, 741–763.
- Duso, C., Pozzebon, A., Capuzzo, C., Malagnini, V., Otto, S., Borgo, M., 2005. Grape downy mildew spread and mite seasonal abundance in vineyards: effects on *Tydeus caudatus* and its predators. *Biological Control.* 32, 143–154. <https://doi.org/10.1016/j.biocontrol.2004.09.004>.
- Duso, C., Pozzebon, A., Kreiter, S., Tixier, M.-S., Candolfi, M., 2012. Management of Phytophagous Mites in European Vineyards. In: Bostanian, N.J., Vincent, C., Isaacs, R. (eds.), *Arthropod Management in Vineyards*. Springer Netherlands, Dordrecht, pp. 191–217. https://doi.org/10.1007/978-94-007-4032-7_9.

E

- Engel, R., Ohnesorge, B., 1994. Die Rolle von Ersatznahrung und Mikroklima im System *Typhlodromus pyri* Scheuten (Acari, Phytoseiidae)- *Panonychus ulmi* Koch (Acari, Tetranychidae) auf Weinreben I. Untersuchungen im Labor. *J. Appl. Entomol.* 118, 129–150. <https://doi.org/10.1111/j.1439-0418.1994.tb00788.x>.
- Englert, C., Herz, A., 2019. Acceptability of *Drosophila suzukii* as prey for common predators occurring in cherries and berries. *J. Appl. Entomol.* 143, 387–396. <https://doi.org/10.1111/jen.12613>.
- Entling, M.H., Stämpfli, K., Ovaskainen, O., 2011. Increased propensity for aerial dispersal in disturbed habitats due to intraspecific variation and species turnover. *Oikos* 120, 1099–1109. <https://doi.org/10.1111/j.1600-0706.2010.19186.x>.
- Entling, W., Schmidt, M.H., Bacher, S., Brandl, R., Nentwig, W., 2007. Niche properties of Central European spiders: shading, moisture and the evolution of the habitat niche. *Glob. Ecol. Biogeogr.* 16: 440–448.
- Entling, W., Hoffmann, C., 2020. Single and combined effects of *Drosophila suzukii* and *Drosophila melanogaster* on sour rot development in viticulture. *J. Appl. Entomol.* 144, 153–160. <https://doi.org/10.1111/jen.12721>
- Estes, L., Elsen, P.R., Treuer, T., Ahmed, L., Caylor, K., Chang, J., Choi, J.J., Ellis, E.C., 2018. The spatial and temporal domains of modern ecology. *Nat. Ecol. Evol.* 2: 819–826.
- European Commission, 2023. Sustainable use of pesticides. https://food.ec.europa.eu/plants/pesticides/sustainable-use-pesticides_en (accessed on 21.07.23).

Ewald, J.A., Wheatley, C.J., Aebischer, N.J., Moreby, S.J., Duffield, S.J., Crick, H.Q.P., Morecroft, M.B., 2015. Influences of extreme weather, climate and pesticide use on invertebrates in cereal fields over 42 years. *Glob. Change Biol.* 21, 3931–3950. <https://doi.org/10.1111/gcb.13026>.

F

Fiedler, Ž., Sosnowska, D., 2014. Side effects of fungicides and insecticides on predatory mites, in laboratory conditions. *J. Plant Prot. Res.* 54, 349–353. <https://doi.org/10.2478/jppr-2014-0052>.

Fischer-Trimborn, B., Weltzien, H.C., Schruft, G., 2000. Contributions to Environmentally Safe Plant Protection Systems in Grapevine Cultivation. In: Willer, H., Meyer, U. (eds.), *Proceedings / 6th International Congress on Organic Viticulture: 25 to 26 August 2000 Convention Center Basel, SÖL-Sonderausgabe*, p. 166. Stiftung Ökologie und Landbau, Bad Dürkheim.

Flanders, S.E., 1943. The susceptibility of parasitic Hymenoptera to sulfur. *J. Econ. Entomol.* 36, p. 469.

Fleury, D., Fleury, I., 2016. Evaluation des populations de coccinelles asiatiques en viticulture intégrée ou biologique. *Rev. Suisse Vitic Arboric Hortic* 48, 124–129.

Fox, J., Weisberg, S., 2019. *An R Companion to Applied Regression*, 3rd ed. SAGE Publications, Thousand Oaks, CA, USA.

Frank, S.D., Wratten, S.D., Sandhu, H.S., Shrewsbury, P.M., 2007. Video analysis to determine how habitat strata affects predator diversity and predation of *Epiphyas postvittana* (Lepidoptera: Tortricidae) in a vineyard. *Biol. Control* 41, 230–236. <https://doi.org/10.1016/j.biocontrol.2007.01.012>.

Franklin, E.L., Raine, N.E., 2019. Moving beyond honeybee-centric pesticide risk assessments to protect all pollinators. *Nat Ecol Evol* 3, 1373–1375. <https://doi.org/10.1038/s41559-019-0987-y>.

Fricke, U., Steffan-Dewenter, I., Zhang, J., Tobisch, C., Rojas-Botero, S., Benjamin, C.S., Englmeier, J., Ganuza, C., Haensel, M., Riebl, R., Uhler, J., Uphus, L., Ewald, J., Kollmann, J., Redlich, S., 2022. Landscape diversity and local temperature, but not climate, affect arthropod predation among habitat types. *PLoS ONE* 17(4): e0264881.

Froidevaux, J.S.P., Louboutin, B., Jones, G., 2017. Does organic farming enhance biodiversity in Mediterranean vineyards? A case study with bats and arachnids. *Agric. Ecosyst. Environ.* 249, 112–122. <https://doi.org/10.1016/j.agee.2017.08.012>.

Fuller, K.B., Alston, J.M., Sambucci, O.S., 2014. The value of powdery mildew resistance in grapes: Evidence from California. *Wine Economics and Policy* 3, 90-107. <https://doi.org/10.1016/j.wep.2014.09.001>.

G

Gadino, A.N., Walton, V.M., Dreves, A.J., 2011. Impact of Vineyard Pesticides on a Beneficial Arthropod, *Typhlodromus pyri* (Acari: Phytoseiidae), in Laboratory Bioassays. *J. Econ. Entomol.* 104, 970–977. <https://doi.org/10.1603/EC10330>.

Gadino, A.N., Walton, V.M., 2012. Temperature-related development and population parameters for *Typhlodromus pyri* (Acari: Phytoseiidae) found in Oregon vineyards. *Exp. Appl. Acarol.* 58: 1–10.

- Gaigher, R., Samways, M.J., 2010. Surface-active arthropods in organic vineyards, integrated vineyards and natural habitat in the Cape Floristic Region. *J. Insect Conserv.* 14, 595–605. <https://doi.org/10.1007/s10841-010-9286-2>.
- Gary, C., Hoffmann, C., Mugnai, L., Dubois, P.H., Blum, B., Viranyi, F., Fermaud, M., Wiedemann-Merdinoglu, S., Thiéry, D., Barbier, J.M., Lolas, M., Calonnec, A., Valdés, H., Raddi, P., 2010. Pesticide use in viticulture, available data on current practices and innovations, bottlenecks and need for research (No. Deliverable DR1.23), Grapevine Case Study. European Network for Durable Exploitation of crop protection strategies (Endure).
- Geiger, F., Bengtsson, J., Berendse, F., Weisser, W.W., Emmerson, M., Morales, M.B., Ceryngier, P., Liira, J., Tschamntke, T., Winqvist, C., Eggers, S., Bommarco, R., Pärt, T., Bretagnolle, V., Plantegenest, M., Clement, L.W., Dennis, C., Palmer, C., Oñate, J.J., Guerrero, I., Hawro, V., Aavik, T., Thies, C., Flohre, A., Hänke, S., Fischer, C., Goedhart, P.W., Inchausti, P., 2010. Persistent negative effects of pesticides on biodiversity and biological control potential on European farmland. *Basic Appl. Ecol.* 11, 97–105. <https://doi.org/10.1016/j.baae.2009.12.001>.
- Geldenhuis, M., Gaigher, R., Pryke, J.S., Samways, M.J., 2021. Diverse herbaceous cover crops promote vineyard arthropod diversity across different management regimes. *Agric. Ecosyst. Environ.* 307, 107222. <https://doi.org/10.1016/j.agee.2020.107222>.
- Gerson, U., 1992. Perspectives of non-phytoseiid predators for the biological control of plant pests. *Exp. Appl. Acarol.* 14, 383–391. <https://doi.org/10.1007/BF01200575>. Gregoire, C., Payraudeau, S., Domange, N., 2010. Use and fate of 17 pesticides applied on a vineyard catchment. *Int. J. Environ. Anal. Chem.* 90, 406–420. <https://doi.org/10.1080/03067310903131230>.
- Gessler, C., Pertot, I., Perazzolli, M., 2011. *Plasmopara viticola*: a review of knowledge on downy mildew of grapevine and effective disease management. *Phytopathologia Mediterranea* 50, 3–44. <http://www.jstor.org/stable/26458675>.
- Gibbs, K.E., Mackey, R.L., Currie, D.J., 2009. Human land use, agriculture, pesticides and losses of imperiled species. *Divers. Distrib.* 15, 242–253.
- Gobin, B., Moerkens, R., Leirs, H., Peusens, G., 2008. Earwigs in fruit orchards: phenology predicts predation effect and vulnerability to side-effects of orchard management. In: Vogt, H., Jansen, J.-P., Vinuela, E., Medina, P. (eds.), *Pesticides and Beneficial Organisms*, IOBC Wprs Bulletin. Presented at the Pesticides et organismes utiles, INRA, Unité de pathologie végétale, Monfavet, pp. 35–39.
- Gonçalves, F., Carlos, C., Aranha, J., Torres, L., 2018. Does habitat heterogeneity affect the diversity of epigeic arthropods in vineyards?: Epigeic arthropods diversity in vineyards. *Agric. For. Entomol.* 20, 366–379. <https://doi.org/10.1111/afe.12270>.
- González, E., Salvo, A., Valladares, G., 2017. Arthropod communities and biological control in soybean fields: Forest cover at landscape scale is more influential than forest proximity. *Agric. Ecosyst. Environ.* 239, 359–367. <https://doi.org/10.1016/j.agee.2017.02.002>.
- González, P.A., Dans, E.P., Acosta Dacal, A.C., Zumbado Peña, M., Pérez Luzardo, O., 2022. Differences in the levels of sulphites and pesticide residues in soils and wines and under organic and conventional production methods. *Journal of Food Composition and Analysis* 112, 104714. <https://doi.org/10.1016/j.jfca.2022.104714>.
- Guidotti, T.L., 2010. Hydrogen Sulfide: Advances in Understanding Human Toxicity. *International Journal of Toxicology* 29, 569–581. <https://doi.org/10.1177/1091581810384882>.
- Güven, B., Göven, M.A., 2003. Side effects of pesticides used in cotton and vineyard areas of Aegean Region on the green lacewing, *Chrysoperla carnea* (Steph.) (Neuroptera: Chrysopidae), in the laboratory. *IOBCWPRS Bull* 26, 21–24.

- Gurr, G.M., Wratten, S.D., Luna, J.M., 2003. Multi-function agricultural biodiversity: pest management and other benefits. *Basic Appl. Ecol.* 4, 107–116. <https://doi.org/10.1078/1439-1791-00122>.
- Gunstone, T., Cornelisse, T., Klein, K., Dubey, A., Donley N., 2021. Pesticides and Soil Invertebrates: A Hazard Assessment. *Frontiers in Environmental Science* 9, 643847. <https://doi.org/10.3389/fenvs.2021.643847>.
- Gutierrez, A.P., Ponti, L., Cooper, M.L., Gilioli, G., Baumgärtner, J., Duso, C., 2012. Prospective analysis of the invasive potential of the European grapevine moth *Lobesia botrana* (Den. & Schiff.) in California. *Agric. For. Entomol.* 14, 225–238. <https://doi.org/10.1111/j.1461-9563.2011.00566.x>.
- Guyomard, H., Bureau, J.-C., Chatellier, V., Detang-Dessendre, C., Dupraz, P., Jacquet, F., Reboud, X., Requillart, V., Soler, L.-G., Tysebaert, M., 2020. The Green Deal and the CAP: policy implications to adapt farming practices and to preserve the EU's natural resources. European Parliament, Policy Department for Structural and Cohesion Policies, Brussels, Belgium.

H

- Habel, J.C., Ulrich, W., Biburger, N., Seibold, S., Schmitt, T., 2019. Agricultural intensification drives butterfly decline. *Insect Conservation and Diversity*, 12, 289-295. <https://doi.org/10.1111/icad.12343>.
- Hall, M.E., Loeb, G.M., Cadle-Davidson, L., Evans, K.J., Wilcox, W.F., 2018. Grape Sour Rot: A Four-Way Interaction Involving the Host, Yeast, Acetic Acid Bacteria, and Insects. *Phytopathology*® 108, 1429–1442. <https://doi.org/10.1094/PHYTO-03-18-0098-R>.
- Hallmann, C.A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., Stenmans, W., Müller, A., Sumser, H., Hören, T., Goulson, D., de Kroon, H., 2017. More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PLOS ONE* 12, e0185809. <https://doi.org/10.1371/journal.pone.0185809>.
- Hanna, R., Zalom, F. G., Willson, L. T., 1997. Sulfur can suppress mite predators in vineyards. *California Agriculture* 51, 19-21.
- Hartig, F., Lohse, L., 2022. DHARMA: Residual Diagnostics for Hierarchical (Multi-Level/Mixed) Regression Models. <https://cran.r-project.org/web/packages/DHARMA/index.html>.
- Herrero-Hernández, E., Andrades, M.S., Álvarez-Martín, A., Pose-Juan, E., Rodríguez-Cruz, M.S., Sánchez-Martín, M.J., 2013. Occurrence of pesticides and some of their degradation products in waters in a Spanish wine region. *Journal of Hydrology* 486, 234-245. <https://doi.org/10.1016/j.jhydrol.2013.01.025>.
- Herrmann, J.D., Bailey, D., Hofer, G., Herzog, F., Schmidt-Entling, M.H., 2010. Spiders associated with the meadow and tree canopies of orchards respond differently to habitat fragmentation. *Landsc. Ecol.* 25, 1375–1384. <https://doi.org/10.1007/s10980-010-9518-6>.
- Hermann, D., Stenzel, K., 2019. FRAC Mode-of-action Classification and Resistance Risk of Fungicides. In: Jeschke, P., Witschel, M., Krämer, W., Schirmer, U., *Modern Crop Protection Compounds*. 3rd ed, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. pp. 589-608.
- Herzog, K., Schwander, F., Kassemeyer, H.-H., Bieler, E., Dürrenberger, M., Trapp, O., Töpfer, R., 2022. Towards Sensor-Based Phenotyping of Physical Barriers of Grapes to Improve Resilience to Botrytis Bunch Rot. *Front. Plant Sci.* 12, 808365. <https://doi.org/10.3389/fpls.2021.808365>.
- Hill, K., Schlamp, H.A., 1984. Der Einsatz der Waschmethode zur Ermittlung des Raubmilbenbesatzes auf Reblättern. *Weinwissenschaft* 39: 214–255.
- Hill, M.P., Macfadyen, S., Nash, M.A., 2017. Broad spectrum pesticide application alters natural enemy communities and may facilitate secondary pest outbreaks. *PeerJ* 5, e4179. <https://doi.org/10.7717/peerj.4179>.

- Hluchý, M., Pospíšil, Z., 1992. Damage and economic injury levels of eriophyid and tetranychid mites on grapes in Czechoslovakia. *Exp. Appl. Acarol.* 14: 95–106.
- Hluchý, M., 1993. Zur biologischen Bekämpfung der Kräuselmilbe *Calepitrimerus vitis* Nalepa (Acari, Eriophyidae) auf der Weinrebe durch die Raubmilbe *Typhlodromus pyri* Scheuten (Acari, Phytoseiidae). *J. Appl. Entomol.* 116, 449–458. <https://doi.org/10.1111/j.1439-0418.1993.tb01221.x>.
- Hoffmann, C., Michl, G., 2003. Parasitoide von Traubenwicklern – ein Werkzeug der natürlichen Schädlingsregulation? *Dtsch. Weinbaujahrbuch* 55, 120–134.
- Hoffmann, C., Köckerling, J., Biancu, S., Gramm, T., Michl, G., Entling, M., 2017. Can Flowering Greencover Crops Promote Biological Control in German Vineyards? *Insects* 8, 121. <https://doi.org/10.3390/insects8040121>.
- Hogg, B.N., Daane, K.M., 2010. The role of dispersal from natural habitat in determining spider abundance and diversity in California vineyards. *Agric. Ecosyst. Environ.* 135, 260–267. <https://doi.org/10.1016/j.agee.2009.10.004>.
- Hole, D.G., Perkins, A.J., Wilson, J.D., Alexander, I.H., Grice, P.V., Evans, A.D., 2005. Does organic farming benefit biodiversity? *Biological Conservation* 122, 113-130. <https://doi.org/10.1016/j.biocon.2004.07.018>.
- Holland, J.M., Ewald, J.A., Aebischer, N.J., 2005. Field studies of pesticide effects on terrestrial invertebrates, in: Liess, M. (ed.), *Effects of Pesticides in the Field*. Presented at the EU & SETAC Europe Workshop, Society of Environmental Toxicology and Chemistry, Pensacola, FL, pp. 70–73.
- Huth, C., 2011. Untersuchungen zur Lebensweise und zur Populationskontrolle des Gemeinen Ohrwurms *Forficula auricularia* L. (Insecta, Dermaptera) in Rebanlagen. PhD thesis, Johannes Gutenberg-Universität Mainz.
- Huth, C., Schirra, K.-J., Seitz, A., Louis, F., 2011. A beneficial species becomes a pest – the common earwig *Forficula auricularia* (Linnaeus 1758). In: Calonnec, A. (ed.), *Integrated protection and production in viticulture*. Proceedings of the Meeting at Staufen Im Breisgau (Germany), 01-04 November, 2009, IOBC WPRS Bulletin 67: 249-256.

I

- Intrieri, C., Filippetti, I., Allegro, G., Valentini, G., Pastore, C., Colucci, E., 2011. The semi-minimal-pruned hedge: A novel mechanized grapevine training system. *Am. J. Enol. Vitic.* 62: 312–318.
- IPBES, 2016. The assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production, S. G. Potts, V. L. Imperatriz-Fonseca, H. T. Ngo, eds. (Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany, 2016).
- Isaia, M., Bona, F., Badino, G., 2006. Influence of Landscape Diversity and Agricultural Practices on Spider Assemblage in Italian Vineyards of Langa Astigiana (Northwest Italy). *Environ. Entomol.* 35, 297–307. <https://doi.org/10.1603/0046-225X-35.2.297>.
- Islam, N., Bint-E-Naser, S.F., Khan, M.S., 2017. Pesticide Food Laws and Regulations. In: Khan, M.S., Rahman, M.S. (eds.), *Pesticide Residue in Foods*. Springer International Publishing, Cham, pp. 53–86. https://doi.org/10.1007/978-3-319-52683-6_4.
- ISTAT, 2011. Statistiche in Breve. In: Istituto nazionale di statistica (ed.), *Utilizzo Dei Prodotti Fitosanitari Nella Coltivazione Della Vite*. Annata Agraria 2009-2010. Servizio Agricoltura, Roma.

IUCN 2023. The IUCN Red List of Threatened Species. International Union for Conservation of Nature and Natural Resources. <https://www.iucnredlist.org/search/stats>. (accessed on 24 July 2023).

J

Jacquet, F., Jeuffroy, M.H., Jouan, J., Le Cadre, E., Litrico, I., Malausa, T., Reboud, X., Hyghe, C., 2022. Pesticide-free agriculture as a new paradigm for research. *Agron. Sustain. Dev.* 42, 8. <https://doi.org/10.1007/s13593-021-00742-8>.

James, D.G., Whitney, J., 1993. Mite populations on grapevines in south-eastern Australia: Implications for biological control of grapevine mites (Acarina: Tenuipalpidae, Eriophyidae). *Exp. Appl. Acarol.* 17, 259–270. <https://doi.org/10.1007/BF02337275>.

James, D.G., Price, T.S., Wright, L.C., Perez, J., 2002. Abundance and phenology of mites, leafhoppers, and thrips on pesticide-treated and untreated wine grapes in Southcentral Washington. *J Agric Urban Entomol* 19: 45–54.

James, D.G., Prischmann, D., 2010. The impact of sulfur on biological control of spider mites in Washington State vineyards and hop yards. In: Sabelis, M.W., Bruin, J. (eds.), *Trends in Acarology*. Springer Netherlands, Dordrecht, pp. 477–482. https://doi.org/10.1007/978-90-481-9837-5_79.

Jansen, J.-P., Lauvaux, S., Gruntowy, J., Denayer, J., 2017. Possible synergistic effects of fungicide-insecticide mixtures on beneficial arthropods. *IOBC-WPRS Bulletin Pesticides and Beneficial Organisms* 125, 28–35.

Ji, C., Song, Q., Chen, Y., Zhou, Z., Wang, P., Liu, J., Sun, Z., Zhao, M., 2020. The potential endocrine disruption of pesticide transformation products (TPs): The blind spot of pesticide risk assessment. *Environment International* 137, 105490. <https://doi.org/10.1016/j.envint.2020.105490>.

JKI, 2022. Statistische Erhebung von Pflanzenschutzmitteln in der Praxis. <https://papa.julius-kuehn.de/index.php?menuid=43> (accessed on 29.06.2023).

Johann, L., Horn, T.B., Carvalho, G.S., Ferla, N.J., 2014. Diversity of mites (Acari) in vineyard agroecosystems (*Vitis vinifera*) in two viticultural regions of Rio Grande do Sul state, Brazil. *Acarologia* 54, 137–154. <https://doi.org/10.1051/acarologia/20142122>.

Jubb, G.L., Masteller, E.C., Lehman, R.D., 1985. Survey of arthropods in vineyards of Erie County, Pennsylvania: Acari. *Int. J. Acarol.* 11, 201–207. <https://doi.org/10.1080/01647958508683415>.

Judt, C., Guzm, G., Winter, S., Zaller, J.G., Paredes, D., 2019. Diverging Effects of Landscape Factors and Inter-Row Management on the Abundance of Beneficial and Herbivorous Arthropods in Andalusian Vineyards (Spain). *Insects* 10, 14. <https://doi.org/10.3390/insects10100320>.

K

Kaczmarek, M., Entling, M.H., Hoffmann, C., 2022. Using malaise traps and metabarcoding for biodiversity assessment in vineyards: Effects of weather and trapping effort. *Insects* 13(6): 507.

Kaczmarek, M., Entling, M.H., Hoffmann, C., 2023. Differentiating the effects of organic management, pesticide reduction, and landscape diversification for arthropod conservation in viticulture. *Biodivers. Conserv.* <https://doi.org/10.1007/s10531-023-02621-y>.

Karg, W., 1994. Raubmilben, nützliche Regulatoren im Naturhaushalt. *Die Neue Brehm-Bücherei* Bd. 624, Westarp Wissenschaften, Magdeburg.

- Katayama, N., Bouam, I., Koshida, C., Baba, Y.G., 2019. Biodiversity and yield under different land-use types in orchard/vineyard landscapes: A meta-analysis. *Biol. Conserv.* 229, 125–133. <https://doi.org/10.1016/j.biocon.2018.11.020>.
- Kehoe, R., Frago, E., Sanders, D., 2021. Cascading extinctions as a hidden driver of insect decline. *Ecological Entomology* 46, 743–756. [10.1111/een.12985](https://doi.org/10.1111/een.12985).
- Kehrli, P., Karp, J., Burdet, J.P., Deneulin, P., Danthe, E., Lorenzini, F., Linder, C., 2012. Impact of processed earwigs and their faeces on the aroma and taste of ‘Chasselas’ and ‘Pinot Noir’ wines. *Vitis* 51, 87–93.
- Khederi, S.J., Khanjani, M., 2014. Natural predatory survey on vineyards infested by grape erineum mite, *Colomerus vitis* (Pagenstecher) (Acari: Eriophyidae) in western Iran 3, p. 6.
- Kinn, D.N., Doutt, R.L., 1972. Initial survey of arthropods found in North Coast vineyards of California. *Environ. Entomol.* 1: 508–513.
- Kishimoto, H., 2002. Species composition and seasonal occurrence of spider mites (Acari: Tetranychidae) and their predators in Japanese pear orchards with different agrochemical spraying programs. *Appl. Entomol. Zool.* 37, 603–615. <https://doi.org/10.1303/aez.2002.603>.
- Klein, A.-M., Vaissière, B.E., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., Tscharntke, T., 2007. Importance of pollinators in changing landscapes for world crops. *Proc. R. Soc. B.* 274, 303–313. <http://doi.org/10.1098/rspb.2006.3721>.
- Klittich, C.J., 2008. Milestones in Fungicide Discovery: Chemistry that changed agriculture. *Plant Health Progress* 9. <https://doi.org/10.1094/PHP-2008-0418-01-RV>.
- Knop, N.F., Hoy, M.A., 1983. Factors Limiting the Utility of *Homeopronematus anconai* (Acari:Tydeidae) in Integrated Pest Management in San Joaquin Valley Vineyards. *J Econ Entomol* 76, 1181–1186.
- Knudsen, S.H. Regulating cumulative risk. *Minn. Law Rev.* 2017, 101, 2313–2396.
- Kolb, S., Uzman, D., Leyer, I., Reineke, A., Entling, M.H., 2020. Differential effects of semi-natural habitats and organic management on spiders in viticultural landscapes. *Agric. Ecosyst. Environ.* 287, 106695.
- Komárek, M., Čadková, E., Chrastný, V., Bordas, F., Bollinger, J.-C., 2010. Contamination of vineyard soils with fungicides: A review of environmental and toxicological aspects. *Environ. Int.* 36, 138–151. <https://doi.org/10.1016/j.envint.2009.10.005>.
- Krantz, G.W., 1978. *A Manual of Acarology*. Oregon State University Book Stores, Inc., Corvallis, OR, USA.
- Kratschmer, S., Pachinger, B., Schwantzer, M., Paredes, D., Guzmán, G., Gómez, J.A., Entrenas, J.A., Guernion, M., Burel, F., Nicolai, A., Fertil, A., Popescu, D., Macavei, L., Hoble, A., Bunea, C., Kriechbaum, M., Zaller, J.G., Winter, S., 2019. Response of wild bee diversity, abundance, and functional traits to vineyard inter-row management intensity and landscape diversity across Europe. *Ecol. Evol.* 9, 4103–4115. <https://doi.org/10.1002/ece3.5039>.
- Kraus, C., Pennington, T., Herzog, K., Hecht, A., Fischer, M., Voegele, R.T., Hoffmann, C., Töpfer, T., Kicherer, A., 2018. Effects of canopy architecture and microclimate on grapevine health in two training systems. *Vitis* 57: 53–60.
- Kremen, C., Miles, A., 2012. Ecosystem services in biologically diversified versus conventional farming systems: Benefits, externalities, and trade-offs. *Ecology and Society* 17, 40.

L

- Lamichhane, J.R., Osdaghi, E., Behlau, F., Köhl, J., Jones, J.B., Aubertot, J.-N., 2018. Thirteen decades of antimicrobial copper compounds applied in agriculture. A review. *Agron. Sustain. Dev.* 38, 28. <https://doi.org/10.1007/s13593-018-0503-9>.
- Landis, D.A., Wratten, S.D., Gurr, G.M., 2000. Habitat Management to Conserve Natural Enemies of Arthropod Pests in Agriculture. *Annu. Rev. Entomol.* 45, 175–201. <https://doi.org/10.1146/annurev.ento.45.1.175>
- Langellotto, G.A., Denno, R.F., 2004. Responses of invertebrate natural enemies to complex-structured habitats: a meta-analytical synthesis. *Oecologia* 139: 1–10.
- Laurin, M.-C., Bostanian, N.J., 2007. Short-term contact toxicity of seven fungicides on *Anystis baccarum*. *Phytoparasitica* 35, 380–385. <https://doi.org/10.1007/BF02980701>.
- Lechenet, M., Bretagnolle, V., Bockstaller, C., Boissinot, F., Petit, M.-S., Petit, S., Munier-Jolain, N.M., 2014. Reconciling Pesticide Reduction with Economic and Environmental Sustainability in Arable Farming. *PLoS ONE* 9, e97922. <https://doi.org/10.1371/journal.pone.0097922>.
- Lemperle, E., 2007. *Weinfehler erkennen. Bestimmen – Vermeiden – Abhilfe*. Eugen Ulmer KG, Stuttgart, Germany.
- Le Navenant, A., Brouchoud, C., Capowiez, Y., Rault, M., Suchail, S., 2021. How lasting are the effects of pesticides on earwigs? A study based on energy metabolism, body weight and morphometry in two generations of *Forficula auricularia* from apple orchards. *Sci. Total Environ.* 758, 143604. <https://doi.org/10.1016/j.scitotenv.2020.143604>.
- Letourneau, D.K., Armbrrecht, I., Rivera, B.S., Lerma, J.M., Carmona, E.J., Daza, M.C., Escobar, S., Galindo, V., Gutiérrez, C., López, S.D., Mejía, J.L., Rangel, A.M.C., Rangel, J.H., Rivera, L., Saavedra, C.A., Torres, A.M., Trujillo, A.R., 2011. Does plant diversity benefit agroecosystems? A synthetic review. *Ecol. Appl.* 21, 9-21.
- Lewis, K.A., Tzilivakis, J., Warner, D., Green, A., 2016. An international database for pesticide risk assessments and management. *Hum. Ecol. Risk Assess. Int. J.* 22, 1050–1064. <https://doi.org/10.1080/10807039.2015.1133242>.
- Liess, M., von der Ohe, P.C., 2005. Analysing effects of pesticides on invertebrate communities in streams. *Environmental Toxicology and Chemistry* 24, 954–965.
- Linder, C., Droz, P., Dupuis, D., 2006. Viticulture intégrée et bio-organique: synthèse de sept ans d'observations. *Rev. Suisse Vitic Arboric Hortic* 38, 9.
- Linhart, C., Panzacchi, S., Belpoggi, F., Clausing, P., Zaller, J., Hertoge, K., 2021. Year-round pesticide contamination of public sites near intensively managed agricultural areas in South Tyrol. *Environ Sci Eur* 33, 1. <https://doi.org/10.1186/s12302-020-00446-y>.
- Losey, J.E., Vaughan, M., 2006. The economic value of ecological services provided by insects. *Bioscience* 56, 311–323.

M

- Mäder, P., 2002. Soil Fertility and Biodiversity in Organic Farming. *Science* 296, 1694–1697. <https://doi.org/10.1126/science.1071148>.
- Malagnoux, L., Marliac, G., Simon, S., Rault, M., Capowiez, Y., 2015. Management strategies in apple orchards influence earwig community. *Chemosphere* 124, 156–162. <https://doi.org/10.1016/j.chemosphere.2014.12.024>.

- Mansour, F., Nentwig, W., 1988. Effects of agrochemical residues on four spider taxa: Laboratory methods for pesticide tests with web-building spiders. *Phytoparasitica* 16, 317–325. <https://doi.org/10.1007/BF02979507>.
- Marchesini, E., Dalla Montà, L., 1994. Observations on natural enemies of *Lobesia botrana* (Den. & Schiff.) (Lepidoptera Tortricidae) in Venetian vineyards (*). *Boll Zool Agr Bachic* 26, 201–230.
- Markheiser, A., Rid, M., Biancu, S., Gross, J., Hoffmann, C., 2018. Physical factors influencing the oviposition behaviour of European grapevine moths *Lobesia botrana* and *Eupoecilia ambiguella*. *J. Appl. Entomol.* 142, 201–210.
- Markó, V., Bogya, S., Kondorosy, E., Blommers, L.H.M., 2010. Side effects of kaolin particle films on apple orchard bug, beetle and spider communities. *Int. J. Pest Manag.* 56, 189–199. <https://doi.org/10.1080/09670870903324206>.
- Marliac, G., Mazzia, C., Pasquet, A., Cornic, J.-F., Hedde, M., Capowiez, Y., 2016. Management diversity within organic production influences epigeal spider communities in apple orchards. *Agric. Ecosyst. Environ.* 216, 73–81. <https://doi.org/10.1016/j.agee.2015.09.026>.
- Martínez-Bracero, M., González-Fernández, E., Wójcik, M., Alcázar, P., Fernández-González, M., Kasprzyk, I., Rodríguez-Rajo, F.J., Galán, C., 2020. Airborne fungal phytopathological spore assessment in three European vineyards from different bioclimatic areas. *Aerobiologia* 36, 715–729. <https://doi.org/10.1007/s10453-020-09664-6>.
- Masoni, A., Frizzi, F., Brühl, C., Zocchi, N., Palchetti, E., Chelazzi, G., Santini, G., 2017. Management matters: A comparison of ant assemblages in organic and conventional vineyards. *Agric. Ecosyst. Environ.* 246, 175–183. <https://doi.org/10.1016/j.agee.2017.05.036>
- McGourty, G., 2004. Cover cropping systems for organically farmed vineyards. *Pract. Winer* 1–7.
- McMurty, J.A., Croft, B.A., 1997. Life-styles of phytoseiid mites and their roles in biological control. *Annu. Rev. Entomol.* 42, 291–321.
- Meissner, G., 2015. Untersuchungen zu verschiedenen Bewirtschaftungssystemen im Weinbau unter besonderer Berücksichtigung der biologisch-dynamischen Wirtschaftsweise und des Einsatzes der biologisch-dynamischen Präparate. Justus-Liebig-Universität Gießen, Geisenheim.
- Mestre, L., Schirmel, J., Hetz, J., Kolb, S., Pfister, S.C., Amato, M., Sutter, L., Jeanneret, P., Albrecht, M., Entling, M.H., 2018. Both woody and herbaceous semi-natural habitats are essential for spider overwintering in European farmland. *Agric. Ecosyst. Environ.* 267, 141–146. <https://doi.org/10.1016/j.agee.2018.08.018>.
- Mezière, D., Gary, C., Barbier, J.M., Rio, P., Bernos, L., Clément, C., Constant, N., Delière, L., Forget, D., Grosman, J., Molot, B., Sauvage, D., Sentenac, G., 2009. TOME III: Analyse comparative de différents systèmes en viticulture, Ecophyto R&D. vers des systèmes de culture économes en produits phytosanitaires. MEEDDAT-MAP- INRA.
- Michalko, R., Pekár, S., 2016. Different hunting strategies of generalist predators result in functional differences. *Oecologia* 181, 1187–1197. <https://doi.org/10.1007/s00442-016-3631-4>.
- Michalko, R., Pekár, S., Dul'a, M., Entling, M.H., 2019. Global patterns in the biocontrol efficacy of spiders: A meta analysis. *Glob. Ecol. Biogeogr.* 28, 1366–1378. <https://doi.org/10.1111/geb.12927>.
- Migula, P., Głowacka, E., 1996. Heavy metals as stressing factors in the red wood ants (*Formica polyctena*) from industrially polluted forests. *Fresenius J Anal Chem* 354: 653–659.
- Mikhail A. Beketov, B., Kefford, J., Schäfer, R.B., Liess, M., 2013. Pesticides reduce regional biodiversity of stream invertebrates. *Proceedings of the National Academy of Sciences* 110, 11039–11043. <https://doi.org/10.1073/pnas.1305618110>.

- Miles, M., Green, E., 2004. Effects of the fungicide zoxamide, alone and in combination with mancozeb, to beneficial arthropods under laboratory and field conditions, in: IOBC / WPRS. Presented at the Pesticides and Beneficial Organisms, IOBC WPRS Bulletin, Ponte de Lima, Portugal, pp. 45–57.
- Möth, S., Walzer, A., Redl, M., Petrović, B., Hoffmann, C., Winter, S., 2021. Unexpected Effects of Local Management and Landscape Composition on Predatory Mites and Their Food Resources in Vineyards. *Insects* 12, 180. <https://doi.org/10.3390/insects12020180>.
- Möth, S., Richart-Cervera, S., Comsa, M., Herrera, R.A., Hoffmann, C., Kolb, S., Popescu, D., Reiff, J.M., Rusch, A., Tolle, P., Walzer, A., Winter, S., 2023. Local management and landscape composition affect predatory mites in European wine-growing regions. *Agric. Ecosyst. Environ.* 344, 108292. <https://doi.org/10.1016/j.agee.2022.108292>.
- Mohr, H.D. (ed.), 2005. *Farbatlas Krankheiten, Schädlinge und Nützlinge an der Weinrebe*. Ulmer, Stuttgart, Germany.
- Morgan, C.V.G., Anderson, N.H., Swales, J.E., 1958. Influence of some Fungicides on Orchard Mites in British Columbia. *Can. J. Plant Sci.* 38, 94–105. <https://doi.org/10.4141/cjps58-015>.
- Mullin, C.A., Chen, J., Fine, J.D., Frazier, M.T., Frazier, J.L., 2015. The formulation makes the honey bee poison. *Pestic. Biochem. Physiol.* 120, 27–35. <https://doi.org/10.1016/j.pestbp.2014.12.026>.
- Muneret, L., Auriol, A., Bonnard, O., Richart-Cervera, S., Thiéry, D., Rusch, A., 2019a. Organic farming expansion drives natural enemy abundance but not diversity in vineyard-dominated landscapes. *Ecol. Evol.* 9, 13532–13542. <https://doi.org/10.1002/ece3.5810>.
- Muneret, L., Auriol, A., Thiéry, D., Rusch, A., 2019b. Organic farming at local and landscape scales fosters biological pest control in vineyards. *Ecol. Appl.* 29, e01818. <https://doi.org/10.1002/eap.1818>.
- Muneret, L., Mitchell, M., Seufert, V., Aviron, S., Djoudi, E.A., Pétilion, J., Plantegenest, M., Thiéry, D., Rusch, A., 2018a. Evidence that organic farming promotes pest control. *Nat. Sustain.* 1, 361–368. <https://doi.org/10.1038/s41893-018-0102-4>.
- Muneret, L., Thiéry, D., Joubard, B., Rusch, A., 2018b. Deployment of organic farming at a landscape scale maintains low pest infestation and high crop productivity levels in vineyards. *J. Appl. Ecol.* 55, 1516–1525. <https://doi.org/10.1111/1365-2664.13034>.

N

- Nakai, Z., Shimizu, K., Oida, H., Sonoda, S., 2021. Host plant and humidity effects on phytoseiid mite, *Gynaeseius liturivorus* (Acari: Phytoseiidae) egg hatchability. *Exp. Appl. Acarol.* 84: 135–147.
- Nash, M.A., Hoffmann, A.A., Thomson, L.J., 2010. Identifying signature of chemical applications on indigenous and invasive nontarget arthropod communities in vineyards. *Ecol. Appl.* 20, 1693–1703. <https://doi.org/10.1890/09-1065.1>.
- Nentwig, W., Blick, T., Bosmans, R., Gloor, D., Hänggi, A., Kropf, C., 2023. Spiders of Europe. *Araneae – Spiders Eur.* URL <https://araneae.nmbe.ch> (accessed on 5.11.23).
- Nesselhauf, L., 2018. *Wine and innovation – Consumer acceptance of new grape varieties and wine packaging*. PhD thesis, Georg-August-University Göttingen.
- Nesselhauf, L., Fleuchaus, R., Theuvsen, L., 2020. What about the environment? A choice-based conjoint study about wine from fungus-resistant grape varieties. *International Journal of Wine Business Research* 32, 96-121. <https://doi.org/10.1108/IJWBR-09-2018-0049>.

- Newton, I., 2004. The recent declines of farmland bird populations in Britain: An appraisal of causal factors and conservation actions. *Ibis* 146, 579–600. <https://doi.org/10.1111/j.1474-919X.2004.00375.x>.
- Nicòtina, M., Capone, G.C., 2007. Side Effects of some Fungicides on the Population of *Kampimodromus aberrans* (Oudemans) and *Euseius finlandicus* (Oudemans) (Parasitiformes, Phytoseiidae) on Grapevines in Campania (South Italy). *Acta Hort.* 353–360. <https://doi.org/10.17660/ActaHortic.2007.754.46>.
- Niedobová, J., Hula, V., Michalko, R., 2016. Sublethal effect of agronomical surfactants on the spider *Pardosa agrestis*. *Environmental Pollution* 123, 84–89. <https://doi.org/10.1016/j.envpol.2016.02.005>.
- Nishimoto, R., 2019. Global trends in the crop protection industry. *J. Pestic. Sci.* 44, 141–147. <https://doi.org/10.1584/jpestics.D19-101>.
- Nobre, T., Meierrose, C., Oliveira, N.G.D., 2000. Comparison of Sampling Techniques for Vineyard Foliage Spiders (Araneae), in: *Proceedings of the 18th European Colloquium on Arachnology*. Bratislava, pp. 201–206.

O

- Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R.B., Simpson, G.I., Solymos, P., Stevens, M.H.H., Szoecs, E., Wagner, H., 2018. *Vegan: Community Ecology Package*.
- Olivier, C., Vincent, C., Saguez, J., Galka, B., Weintraub, P.G., Maixner, M., 2012. Leafhoppers and Planthoppers: Their Bionomics, Pathogen Transmission and Management in Vineyards, in: Bostanian, N.J., Vincent, C., Isaacs, R. (eds.), *Arthropod Management in Vineyards*: Springer Netherlands, Dordrecht, pp. 253–270. https://doi.org/10.1007/978-94-007-4032-7_11.
- Oliver, T.H., Isaac, N.J.B., August, T.H., Woodcock, B.A., Roy, D.B., Bullock, J.M., 2015. Declining resilience of ecosystem functions under biodiversity loss. *Nat Commun* 6, 10122. <https://doi.org/10.1038/ncomms10122>.
- Ollerton, J., Erenler, H., Edwards, M., Crockett, R., 2014. Extinctions of aculeate pollinators in Britain and the role of large-scale agricultural changes. *Science*, 346, 1360–1362.
- Olotu, M.I., Maniania, N.K., Ekesi, S., Seguni, Z.S., Du Plessis, H., 2013. Effect of fungicides used for powdery mildew disease management on African weaver ant *Oecophylla longinoda* (Hymenoptera: Formicidae), a biocontrol agent of sap-sucking pests in cashew crop in Tanzania. *Int J Trop Insect Sci* 33: 283–290.
- Omkar, K.B., 2021. Thrips. In: Omkar, K.B. (ed.), *Polyphagous pests of crops*. Springer, Singapore.
- Orpet, R.J., Crowder, D.W., Jones, V.P., 2019. Biology and Management of European Earwig in Orchards and Vineyards. *J. Integr. Pest Manag.* 10, 21. <https://doi.org/10.1093/jipm/pmz019>.
- Ostandie, N., Muneret, L., Giffard, B., Thiéry, D., Rusch, A., 2021. The shape of the predator biomass distribution affects biological pest control services in agricultural landscapes. *Funct. Ecol.* 35, 193–204. <https://doi.org/10.1111/1365-2435.13684>.

P

- Paiola, A., Assandri, G., Brambilla, M., Zottini, M., Pedrini, P., Nascimbene, J., 2020. Exploring the potential of vineyards for biodiversity conservation and delivery of biodiversity-mediated ecosystem services: A global-scale systematic review. *Sci. Total Environ.* 706, 135839. <https://doi.org/10.1016/j.scitotenv.2019.135839>.
- PAN Europe, 2023. Save Bees and Farmers. <https://www.pan-europe.info/campaigns/save-bees-and-farmers> (accessed on 21.07.23).

- Pangga, I.B., Hanan, J., Chakraborty, S., 2013. Climate change impacts on plant canopy architecture: implications for pest and pathogen management. *Eur. J. Plant Pathol.* 135: 595–610.
- Paolo Cabras, P. and Angioni, A., 2000. Pesticide Residues in Grapes, Wine, and Their Processing Products. *J. Agric. Food Chem.* 48, 965-973. <https://doi.org/10.1021/jf990727a>.
- Papura, D., Roux, P., Joubard, B., Razafimbola, L., Fabreguettes, O., Delbac, L., Rusch, A., 2020. Predation of grape berry moths by harvestmen depends on landscape composition. *Biol. Control* 150, 104358. <https://doi.org/10.1016/j.biocontrol.2020.104358>.
- Pavan, F., 1994. Contribution to the research on the causes of *Empoasca vitis* (Gothe) pullulation in vineyards. Influence of anti-mildew treatments. *Riv. Vitic. E Enol.* 47: 39–47.
- Pedneault, K., Provost, C., 2016. Fungus resistant grape varieties as a suitable alternative for organic wine production: Benefits, limits, and challenges. *Sci. Hortic.* 208, 57–77. <https://doi.org/10.1016/j.scienta.2016.03.016>.
- Pekár, S., 2012. Spiders (Araneae) in the pesticide world: an ecotoxicological review: Spiders and pesticides. *Pest Manag. Sci.* 68, 1438–1446. <https://doi.org/10.1002/ps.3397>.
- Pekár, S., 2002. Susceptibility of the spider *Theridion impressum* to 17 pesticides. *Anz. Schädlingkunde* 75, 51–55. <https://doi.org/10.1046/j.1439-0280.2002.02016.x>.
- Pekár, S., 1999. Foraging mode: a factor affecting the susceptibility of spiders (Araneae) to insecticide applications. *Pestic. Sci.* 55, 1077–1082. [https://doi.org/10.1002/\(SICI\)1096-9063\(199911\)55:11<1077::AID-PS55>3.0.CO;2-T](https://doi.org/10.1002/(SICI)1096-9063(199911)55:11<1077::AID-PS55>3.0.CO;2-T).
- Pekár, S., Haddad, C.R., 2005. Can agrobiont spiders (Araneae) avoid a surface with pesticide residues? *Pest Manag. Sci.* 61, 1179–1185. <https://doi.org/10.1002/ps.1110>.
- Pennington, T., Kraus, C., Alakina, E., Entling, M., Hoffmann, C., 2017. Minimal Pruning and Reduced Plant Protection Promote Predatory Mites in Grapevine. *Insects* 8, 86. <https://doi.org/10.3390/insects8030086>.
- Pennington, T., Reiff, J.M., Theiss, K., Entling, M.H., Hoffmann, C., 2018. Reduced fungicide applications improve insect pest control in grapevine. *BioControl* 63, 687–695. <https://doi.org/10.1007/s10526-018-9896-2>.
- Pennington, T., Kolb, S., Kaiser, J., Hoffmann, C., Entling, M.H., 2019. Does minimal pruning and reduced fungicide use impact spiders in the grapevine canopy? *J. Arachnol.* 47, 381. <https://doi.org/10.1636/0161-8202-47.3.381>.
- Perring, T.M., McMurtry, J.A., 1996. Chapter 2.3 Other predatory arthropods. *World Crop Pests*. Elsevier, pp. 471–479. [https://doi.org/10.1016/S1572-4379\(96\)80029-7](https://doi.org/10.1016/S1572-4379(96)80029-7).
- Pertot, I., Caffi, T., Rossi, V., Mugnai, L., Hoffmann, C., Grando, M.S., Gary, C., Lafond, D., Duso, C., Thiéry, D., Mazzoni, V., Anfora, G., 2017. A critical review of plant protection tools for reducing pesticide use on grapevine and new perspectives for the implementation of IPM in viticulture. *Crop Prot.* 97, 70–84. <https://doi.org/10.1016/j.cropro.2016.11.025>.
- Peverieri, G.S., Simoni, S., Goggioli, D., Liguori, M., Castagnoli, M., 2009. Effects of variety and management practices on mite species diversity in Italian vineyards. *Bull. Insectology* 62, 53–60.
- Picchi, M.S., Bocci, G., Petacchi, R., Entling, M.H., 2020. Taxonomic and functional differentiation of spiders in habitats in a traditional olive producing landscape in Italy. *Eur. J. Entomol.* 117, 18–26. <https://doi.org/10.14411/eje.2020.002>.
- Popa, E.O., Roșca, I., 2011. Main trends of the pests management in agroecosystems of grapevine plantations. *Scientific Papers Series Management, Economic Engineering in Agriculture and Rural Development* 11: 146–150.

- Potapov, P., Turubanova, S., Hansen, M.C., Tyukavina, A., Zalles, V., Khan, A., Song, X.-P., Pickens, A., Shen, Q., Cortez, J., 2022. Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. *Nat Food* 3, 19–28. <https://doi.org/10.1038/s43016-021-00429-z>.
- Potts, S. G., Biesmeijer, J. C., Kremen, C., Neumann, P., Schweiger, O., and Kunin, W. E., 2010. Global pollinator declines: trends, impacts and drivers. *Trends Ecol. Evol.* 25, 345–353. <https://doi.org/10.1016/j.tree.2010.01.007>.
- Pozzebon, A., Duso, C., Pavanetto, E., 2002. Side effects of some fungicides on phytoseiid mites (Acari, Phytoseiidae) in north-Italian vineyards. *J Pest Sci.* 75, 132–136. <https://doi.org/10.1046/j.1472-8206.2002.02037.x>.
- Pozzebon, A., Duso, C., 2008. Grape downy mildew *Plasmopara viticola*, an alternative food for generalist predatory mites occurring in vineyards. *Biol. Control* 45: 441–449. <https://doi.org/10.1016/j.biocontrol.2008.02.001>
- Pozzebon, A., Borgo, M., Duso, C., 2010. The effects of fungicides on non-target mites can be mediated by plant pathogens. *Chemosphere* 79, 8–17. <https://doi.org/10.1016/j.chemosphere.2010.01.064>.
- Pozzebon, A., Ahmad, S., Tirello, P., Lorenzon, M., Duso, C., 2014. Does pollen availability mitigate the impact of pesticides on generalist predatory mites? *BioControl* 59, 585–596. <https://doi.org/10.1007/s10526-014-9598-3>.
- Prischmann, D.A., James, D.G., Wright, L.C., Snyder, W.E., 2006. Effects of Generalist Phytoseiid Mites and Grapevine Canopy Structure on Spider Mite (Acari: Tetranychidae) Biocontrol. *Environ. Entomol.* 35, 56–67. <https://doi.org/10.1603/0046-225X-35.1.56>.
- Provost, C., Pedneault, K., 2016. The organic vineyard as a balanced ecosystem: Improved organic grape management and impacts on wine quality. *Sci. Hortic.* 208, 43–56. <https://doi.org/10.1016/j.scienta.2016.04.024>.
- Puig-Montserrat, X., Stefanescu, C., Torre, I., Palet, J., Fàbregas, E., Dantart, J., Arrizabalaga, A., Flaquer, C., 2017. Effects of organic and conventional crop management on vineyard biodiversity. *Agric. Ecosyst. Environ.* 243, 19–26. <https://doi.org/10.1016/j.agee.2017.04.005>.
- Put, J.E., Fahrig, L.E., Mitchell, G.W., 2019. Bats respond negatively to increases in the amount and homogenization of agricultural land cover. *Landsc. Ecol.* 34, 1889–1903.

Q

QGIS Development Team, 2016. QGIS Geographic System. Version 2.18.9. Open Source Geospatial Found. Proj. <http://qgis.osgeo.org>

R

R Core Team, 2015. R: A language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

R Core Team (2023) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.r-project.org/>

Rader, R., Bartomeus, I., Garibaldi, L.A., Woyciechowski, M., 2016. Non-bee insects are important contributors to global crop pollination. *PNAS* 113, 146–151. <https://doi.org/10.1073/pnas.1517092112>.

Raven, P.H., Wagner, D.L., 2021. Agricultural intensification and climate change are rapidly decreasing insect biodiversity. *Proc. Natl. Acad. Sci. U.S.A.*, <https://doi.org/10.1073/pnas.2002548117>.

- Reiff, J.M., Ehringer, M., Hoffmann, C., Entling, M.H., 2021a. Fungicide reduction favors the control of phytophagous mites under both organic and conventional viticulture. *Agric. Ecosyst. Environ.* 305, 107172. <https://doi.org/10.1016/j.agee.2020.107172>.
- Reiff, J.M., Kolb, S., Entling, M.H., Herndl, T., Möth, S., Walzer, A., Kropf, M., Hoffmann, C., Winter, S., 2021b. Organic Farming and Cover-Crop Management Reduce Pest Predation in Austrian Vineyards. *Insects* 12, 220. <https://doi.org/10.3390/insects12030220>.
- Reiff, J.M., Sudarsan, K., Hoffmann, C., Entling, M.H., 2023. Arthropods on grapes benefit more from fungicide reduction than from organic farming. *Pest Management Science* 79: 3271–3279. <https://doi.org/10.1002/ps.7505>.
- Reineke, A., Thiéry, D., 2016. Grapevine insect pests and their natural enemies in the age of global warming. *J. Pest Sci.* 89, 313–328. <https://doi.org/10.1007/s10340-016-0761-8>.
- Retallack, M.J., Thomson, L.J., Keller, M.A., 2019. Predatory arthropods associated with potential native insectary plants for Australian vineyards. *Aust. J. Grape Wine Res.* 25, 233–242. <https://doi.org/10.1111/ajgw.12383>.
- Richter, B., Hanf, J.H., 2022. Weine aus „neuen“ Rebsorten – Weine für die Zukunft? Eine Möglichkeit für zukunftsfähig(er)en Weinbau und Weinkonsum. *Berichte über Landwirtschaft – Zeitschrift für Agrarpolitik und Landwirtschaft* 100(3). Bundesministerium für Ernährung und Landwirtschaft, pp. 21.
- Ripper, W.E., 1956. Effect of Pesticides on Balance of Arthropod Populations. *Annual Review of Entomology* 1, 403–438. doi:10.1146/annurev.en.01.010156.002155.
- Roda, A., Nyrop, J., English-Loeb, G., 2003. Leaf pubescens mediates the abundance of non-prey food and the density of the predatory mite *Typhlodromus pyri*. *Experimental and Applied Acarology* 29, 193–211.
- Rose, J., Kicherer, A., Wieland, M., Klingbeil, L., Töpfer, R., Kuhlmann, H., 2016. Towards automated Large-Scale 3D phenotyping of vineyards under field conditions. *Sensors* 16, 2136. <https://doi.org/10.3390/s16122136>.
- Rosenheim, J. A., Cass, B. N., Kahl, H., Steinmann, K. P., 2020. Variation in pesticide use across crops in California agriculture: Economic and ecological drivers. *Science of The Total Environment* 733, 138683. <https://doi.org/10.1016/j.scitotenv.2020.138683>.
- Roßberg, D., Ipach, R., 2015. Erhebungen zur Anwendung von Pflanzenschutzmitteln im Weinbau. *J. Für Kult.* 6712, 2015. <https://doi.org/10.5073/jfk.2015.12.03>.
- Rusch, A., Delbac, L., Thiéry, D., 2017. Grape moth density in Bordeaux vineyards depends on local habitat management despite effects of landscape heterogeneity on their biological control. *J. Appl. Ecol.* 54, 1794–1803. <https://doi.org/10.1111/1365-2664.12858>.
- Rusch, A., Delbac, L., Muneret, L., Thiéry, D., 2015. Organic farming and host density affect parasitism rates of tortricid moths in vineyards. *Agric. Ecosyst. Environ.* 214, 46–53. <https://doi.org/10.1016/j.agee.2015.08.019>.
- Russo, P.; Berbegal, C.; De Ceglie, C.; Grieco, F.; Spano, G.; Capozzi, V., 2019. Pesticide Residues and Stuck Fermentation in Wine: New Evidences Indicate the Urgent Need of Tailored Regulations. *Fermentation* 5, 23. <https://doi.org/10.3390/fermentation5010023>.

S

- Sabarwal, A.; Kumar, K.; Singh, R.P., 2018. Hazardous effects of chemical pesticides on human health: Cancer and other associated disorders. *Environ. Toxicol. Pharmacol.* 63, 103–114.

- Sáenz-Romo, M.G., Veas-Bernal, A., Martínez-García, H., Campos-Herrera, R., Ibáñez-Pascual, S., Martínez-Villar, E., Pérez-Moreno, I., Marco-Mancebón, V.S., 2019. Ground cover management in a Mediterranean vineyard: Impact on insect abundance and diversity. *Agric. Ecosyst. Environ.* 283, 106571. <https://doi.org/10.1016/j.agee.2019.106571>.
- Samu, F., Matthews, G.A., Lake, D., Vollrath, F., 1992. Spider webs are efficient collectors of agrochemical spray. *Pestic. Sci.* 36, 47–51. <https://doi.org/10.1002/ps.2780360108>.
- Samu, F., Vollrath, F., 1992. Spider orb web as bioassay for pesticide side effects. *Entomol. Exp. Appl.* 62, 117–124. <https://doi.org/10.1111/j.1570-7458.1992.tb00650.x>.
- Sánchez-Bayo, F., Wyckhuys, K.A.G., 2019. Worldwide decline of the entomofauna: A review of its drivers. *Biol. Conserv.* 232, 8–27. <https://doi.org/10.1016/j.biocon.2019.01.020>.
- Sánchez-Bayo, F., 2021. Indirect Effect of Pesticides on Insects and Other Arthropods. *Toxics* 9, 177.
- Santos, J.A., Fraga, H., Malheiro, A.C., Moutinho-Pereira, J., Dinis, L.-T., Correia, C., Moriondo, M., Leolini, L., Dibari, C., Costafreda-Aumedes, S., Kartschall, T., Menz, C., Molitor, D., Junk, J., Beyer, M., Schultz, H.R., 2020. A Review of the Potential Climate Change Impacts and Adaptation Options for European Viticulture. *Appl. Sci.* 10, 3092. <https://doi.org/10.3390/app10093092>.
- Schaefer, M. (ed), 2017. *Brohmer – Fauna von Deutschland: Ein Bestimmungsbuch unserer heimischen Tierwelt*. 24th ed. Quelle & Meyer Verlag, Wiebelsheim.
- Schindler, B., Gavish-Regev, E., Keasar, T., 2022. Parasitoid wasp community dynamics in vineyards following insecticide application. *Front. Environ. Sci.* 9: 785669.
- Schmidt, M.H., Thies, C., Nentwig, W., Tschamtker, T., 2008. Contrasting responses of arable spiders to the landscape matrix at different spatial scales. *J. Biogeogr.* 35, 157–166. <https://doi.org/10.1111/j.1365-2699.2007.01774.x>.
- Schmidt-Jeffris, R.A., 2023. Nontarget pesticide impacts on pest natural enemies: progress and gaps in current knowledge. *Current Opinion in Insect Science* 58, 101056. <https://doi.org/10.1016/j.cois.2023.101056>.
- Schneider, M.K., Lüscher, G., Jeanneret, P., Arndorfer, M., Ammari, Y., Bailey, D., Balázs, K., Báldi, A., Choisis, J.-P., Dennis, P., Eiter, S., Fjellstad, W., Fraser, M.D., Frank, T., Friedel, J.K., Garchi, S., Geijzendorffer, I.R., Gomiero, T., Gonzalez-Bornay, G., Hector, A., Jerkovich, G., Jongman, R.H.G., Kakudidi, E., Kainz, M., Kovács-Hostyánszki, A., Moreno, G., Nkwiine, C., Opio, J., Oschatz, M.-L., Paoletti, M.G., Pointereau, P., Pulido, F.J., Sarthou, J.-P., Siebrecht, N., Sommaggio, D., Turnbull, L.A., Wolfrum, S., Herzog, F., 2014. Gains to species diversity in organically farmed fields are not propagated at the farm level. *Nat. Commun.* 5, 4151. <https://doi.org/10.1038/ncomms5151>.
- Schlick-Steiner, B.C., Steiner, F.M., Moder, K., Bruckner, A., Fiedler, K., Christian, E., 2006. Assessing ant assemblages: pitfall trapping versus nest counting (Hymenoptera, Formicidae). *Insectes Sociaux* 53, 274–281. <https://doi.org/10.1007/s00040-006-0869-6>.
- Schliesske, J., 1995. *Gallmilben an Obstgehölzen: Morphologie und Symptomatologie*. Schriftenreihe der Deutschen Phytomedizinischen Gesellschaft, Ulmer Verlag, Stuttgart.
- Schruff, V.G., 1972. Das Vorkommen von Milben aus der Familie Tydeidae (Acari) an Reben. *J Appl Entomol* 71, 124–133.
- Schruff, V.G., 1969. Das Vorkommen räuberischer Milben aus den Familien Cunaxidae und Stigmaeidae (Acari) an Reben. *Wein-Wiss.* 24, 320–326.
- Schulz, R., Bundschuh, M., Gergs, R., Brühl, C.A., Diehl, D., Entling, M.H., Fahse, L., Frör, O., Jungkunst, H.F., Lorke, A., Schäfer, R.B., Schaumann, G.E., Schwenk, K., 2015. Review on environmental alterations propagating

- from aquatic to terrestrial ecosystems. *Sci. Total Environ.* 538, 246-261. <https://doi.org/10.1016/j.scitotenv.2015.08.038>.
- Schulz, R., Bub, S., Petschick, L.L., Stehle, S., Wolfram, J., 2021. Applied pesticide toxicity shifts toward plants and invertebrates, even in GM crops. *Science* 372, 81–84. <https://doi.org/10.1126/science.abe1148>.
- Schwab, A. L., Knott, R., Schottdorf, W., 2001. Environmental and economic benefit of new fungus-tolerant grape varieties and their usability for different training systems. *Proceedings of the 12th GESCO congress 2001 in Montpellier, France, I*, 201-204.
- Schwartz, A., 1993. Occurrence of Natural Enemies of Phytophagous Mites on Grapevine Leaves Following Application of Fungicides for Disease Control. *South Afr. J. Enol. Vitic.* 14. <https://doi.org/10.21548/14-1-2170>.
- Seibold, S., Gossner, M.M., Simons, N.K., Blüthgen, N., Müller, J., Ambarlı, D., Ammer, C., Bauhus, J., Fischer, M., Habel, J.C., Linsenmair, K.E., Nauss, T., Penone, C., Prati, D., Schall, P., Schulze, E.-D., Vogt, J., Wöllauer, S., Weisser, W.W., 2019. Arthropod decline in grasslands and forests is associated with landscape-level drivers. *Nature* 574, 671–674. <https://doi.org/10.1038/s41586-019-1684-3>.
- Shapira, I., Gavish-Regev, E., Sharon, R., Harari, A.R., Kishinevsky, M., Keasar, T., 2018. Habitat use by crop pests and natural enemies in a Mediterranean vineyard agroecosystem. *Agric. Ecosyst. Environ.* 267, 109–118. <https://doi.org/10.1016/j.agee.2018.08.012>.
- Sharma, A., Kumar, V., Shahzad, B., Tanveer, M., Preet, G., Sidhu, S., Handa, N., Kohli, S.K., Yadav, P., Bali, A.S., Parihar, R.D., Dar, O.I., Singh, K., Jasrotia, S., Bakshi, P., Ramakrishnan, M., Kumar, S., Bhardwaj, R., Thukral, A.K., 2019. Worldwide pesticide usage and its impacts on ecosystem. *SN Appl. Sci.* 1, 1446. <https://doi.org/10.1007/s42452-019-1485-1>.
- Singh, A., Dhiman, N., Kar, K.A., Singh, D., Purohit, M.P., Ghosh, D., Patnaik, S., 2020. Advances in controlled release pesticide formulations: Prospects to safer integrated pest management and sustainable agriculture. *J. Hazard. Mater.* 385, 121525.
- Sivčev, B.V., Sivčev, I.L., Ranković-Vasić, Z.Z., 2010. Natural process and use of natural matters in organic viticulture. *J. Agric. Sci.* 55, 195–215.
- Sommer, K., Clingeffer, P., Shulman, Y., 1995. Comparative study of vine morphology, growth, and canopy development in cane-pruned and minimal-pruned Sultana. *Aust. J. Exp. Agric.* 35: 265-273.
- Sorensen, J.T., Kinn, D.N., Douth, R.L., Cate, J.R., 1976. Biology of the Mite, *Anystis agilis* (Acari: Anystidae): a California Vineyard Predator. *Ann. Entomol. Soc. Am.* 69, 905–910. <https://doi.org/10.1093/aesa/69.5.905>.
- Statista Research Department, 2023a. Forecast about the development of the world population from 2022 to 2100. <https://www.statista.com/statistics/262618/forecast-about-the-development-of-the-world-population/> (accessed on 24.07.2023).
- Statista Research Department, 2023b. Global pesticide use per area of cropland 1990-2020. <https://www.statista.com/statistics/1263369/global-pesticide-use-per-area/> (accessed on 20.06.2023).
- Stehle, S., Schulz, R., 2015. Agricultural insecticides threaten surface waters at the global scale. *Proceedings of the National Academy of Sciences*, 112(18), 5750-5755. www.pnas.org/content/112/18/5750.full.pdf.
- Strasser A., Coray M., 2009. Klimaschutz mit pilzresistenten Rebsorten – Fallstudie eines langjährigen Bioweinbaubetriebes. 10th Wissenschaftstagung Ökologischer Landbau, Zürich, February 11.-13, 2009. https://orgprints.org/id/eprint/13902/1/Strasser_13902.pdf
- Sun, S., Sidhu, V., Rong, Y., Zheng, Y., 2018. Pesticide Pollution in Agricultural Soils and Sustainable Remediation Methods: a Review. *Curr Pollution Rep* 4, 240–250. <https://doi.org/10.1007/s40726-018-0092-x>.

T

The R Development Core Team, 2015. R: A language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

The World Bank Group, 2023. Agricultural land (% of land area). <https://data.worldbank.org/indicator/AG.LND.AGRI.ZS>. (accessed on 24.07.23).

Thiéry, D., Louâpre, P., Muneret, L., Rusch, A., Sentenac, G., Vogelweith, F., Iltis, C., Moreau, J., 2018. Biological protection against grape berry moths. A review. *Agron. Sustain. Dev.* 38, 15. <https://doi.org/10.1007/s13593-018-0493-7>.

Thiéry, D., Moreau, J., 2005. Relative performance of European grapevine moth (*Lobesia botrana*) on grapes and other hosts. *Oecologia* 143, 548–557. <https://doi.org/10.1007/s00442-005-0022-7>.

Thiollet-Scholtus, M., Muller, A., Abidon, C., Grignon, J., Keichinger, O., Koller, R., Langenfeld, A., Ley, L., Nassr, N., Rabolin-Meinrad, C., Wohlfahrt, J., 2021. Multidimensional assessment demonstrates sustainability of new low-input viticulture systems in north-eastern France. *Eur. J. Agron.* 13.

Thomazoni, D., Soria, M.F., Degrande, P.E., Faccenda, O., Silvie, P.J., 2013. Arthropods biodiversity index in Bollgard® cotton (Cry1Ac) in Brazil. *Interciencia* 38, 849–856.

Thomson, L., 2012. Pesticide impacts on beneficial species. *Grape Wine Res. Dev. Corp. Adel.* 7.

Thomson, L.J., Glenn, D.C., Hoffmann, A.A., 2000. Effects of sulfur on *Trichogramma* egg parasitoids in vineyards: measuring toxic effects and establishing release windows. *Aust J Exp Agric* 40, 1165–1171.

Thomson, L.J., Hoffmann, A.A., 2006. Field validation of laboratory-derived IOBC toxicity ratings for natural enemies in commercial vineyards. *Biol. Control* 39, 507–515. <https://doi.org/10.1016/j.biocontrol.2006.06.009>.

Thomson, L.J., McKenzie, J., Sharley, D.J., Nash, M.A., Tsitsilas, A., Hoffmann, A.A., 2010. Effect of woody vegetation at the landscape scale on the abundance of natural enemies in Australian vineyards. *Biol. Control* 54, 248–254. <https://doi.org/10.1016/j.biocontrol.2010.05.018>.

Tixier, M.-S., Baldassar, A., Duso, C., Kreiter, S., 2013. Phytoseiidae in European grape (*Vitis vinifera* L.): bio-ecological aspects and keys to species (Acari: Mesostigmata). *Zootaxa* 3721: 101–142.

Töpfer, R., Hausmann, L., Harst, M., Maul, E., Zyprian, E., Eibach, R., 2011. New Horizons for Grapevine Breeding. *Fruit Veg. Cereal Sci. Biotechnol.* 5, 79–100.

Töpfer, R., Trapp, O., 2022. 200 years Mendel: the grapevine breeding perspective. *Journal für Kulturpflanzen* 74, 257–262. <https://doi.org/10.5073/JfK.2022.11-12.05>.

Tscharntke, T., Bommarco, R., Clough, Y., Crist, T.O., Kleijn, D., Rand, T.A., Tylianakis, J.M., van Nouhuys, S., Vidal, S., 2008. Reprint of “Conservation biological control and enemy diversity on a landscape scale” [*Biol. Control* 43 (2007) 294–309] q. *Biol. Control*.

U

Uhler, J., Redlich, S., Zhang, J., Hothorn, T., Tobisch, C., Ewald, J., Thorn, S., Seibold, S., Mitesser, O., Morinière, J., Bozicevic, V., Benjamin, C.S., Englmeier, J., Fricke, U., Ganuza, C., Haensel, M., Riebl, R., Rojas-Botero, S., Rummler, T., Uphus, L., Schmidt, S., Steffan-Dewenter, I., Müller, J., 2021. Relationship of insect biomass and richness with land use along a climate gradient. *Nat Commun* 12, 5946. <https://doi.org/10.1038/s41467-021-26181-3>.

Umweltbundesamt, 2020. Pestizide. <https://www.umweltbundesamt.de/themen/wasser/fluesse/zustand/pestizide-0#undefined> (accessed on 20.06.2023).

Uzman, D., Pliester, J., Leyer, I., Entling, M.H., Reineke, A., 2019. Drivers of entomopathogenic fungi presence in organic and conventional vineyard soils. *Appl. Soil Ecol.* 133, 89–97. <https://doi.org/10.1016/j.apsoil.2018.09.004>.

V

van Lexmond, M.B., Bonmatin, JM., Goulson, D., Noome, D.A., 2015. Worldwide integrated assessment on systemic pesticides. *Environ Sci Pollut Res* 22, 1–4. <https://doi.org/10.1007/s11356-014-3220-1>.

Vecchio, R., Pomarici, E., Giampietri, E., Borrello, M., 2022. Consumer acceptance of fungus-resistant grape wines: Evidence from Italy, the UK, and the USA. *PLoS ONE* 17, e0267198. <https://doi.org/10.1371/journal.pone.0267198>.

Venables, W.N., Ripley, B.D., 2002. *Modern applied statistics with S*, 4th ed. Springer.

Veres, A., Petit, S., Conord, C., Lavigne, C., 2013. Does landscape composition affect pest abundance and their control by natural enemies? A review. *Agric. Ecosyst. Environ.* 166, 110–117. <https://doi.org/10.1016/j.agee.2011.05.027>

Vogelweith, F., Thiéry, D., 2017. Cover crop differentially affects arthropods, but not diseases, occurring on grape leaves in vineyards: Cover crop effect on grapevine leaf communities. *Aust. J. Grape Wine Res.* 23, 426–431. <https://doi.org/10.1111/ajgw.12290>.

W

Wan, N.-F., Fu, L., Dainese, M., et al. 2023. The impact of pesticides on non-target organisms. PREPRINT (Version 1) available at Research Square. <https://doi.org/10.21203/rs.3.rs-2549816/v1>.

Wickham, H., 2023. *modelr*. Modelling Functions that Work with the Pipe. <https://modelr.tidyverse.org>.

Wiedemann-Merdinoglu, S., Hoffmann, C., 2010. New resistant grape varieties: Bottlenecks and conditions for adoption in different European grapevine-growing regions. Pesticide use in viticulture, available data on current practices and innovations, bottlenecks and need for research in this field and specific leaflets analysing the conditions of adoption of some innovations, grapevine case study – Guide number 5. ENDURE Deliverables. <http://www.endure-network.eu/content/download/5586/43605/file/Grapevine%20Case%20Study%20Guide%20Number%205.pdf>

Wilson, H., Miles, A.F., Daane, K.M., Altieri, M.A., 2015. Landscape Diversity and Crop Vigor Influence Biological Control of the Western Grape Leafhopper (*E. elegantula* Osborn) in Vineyards. *PLOS ONE* 10, e0141752. <https://doi.org/10.1371/journal.pone.0141752>.

Wingerter, C., Eisenmann, B., Kortekamp, A., Bogs, J., 2022. *BIO Web of Conferences* 50, 02006. <https://doi.org/10.1051/bioconf/20225002006>.

Winkler, A., Jung, J., Kleinhenz, B., Racca, P., 2020. A review on temperature and humidity effects on *Drosophila suzukii* population dynamics. *Agric. For. Entomol.* 22, 179–192. <https://doi.org/10.1111/afe.12381>.

Wisniewska, J., Prokopy, R.J., 1997. Pesticide Effect on Faunal Composition, Abundance, and Body Length of Spiders (Araneae) in Apple Orchards. *Environ. Entomol.* 26, 763–776. <https://doi.org/10.1093/ee/26.4.763>.

Wolf, S., Zeisler, C., Sint, D., Romeis, J., Traugott, M., Collatz, J., 2018. A simple and cost-effective molecular method to track predation on *Drosophila suzukii* in the field. *J. Pest Sci.* 91, 927–935. <https://doi.org/10.1007/s10340-017-0948-7>.

Woltz, J.M., Lee, J.C., 2017. Pupation behavior and larval and pupal biocontrol of *Drosophila suzukii* in the field. *Biol. Control* 110, 62–69. <https://doi.org/10.1016/j.biocontrol.2017.04.007>.

Wyckhuys, K.A.G., Heong, K.L., Sánchez-Bayo, F., Bianchi, F.J.J.A., Lundgren, J.G., Bentley, J.W., 2019. Ecological illiteracy can deepen farmers' pesticide dependency. *Environ. Res. Lett.* 14, 093004. <https://doi.org/10.1088/1748-9326/ab34c9>.

X

Xuéreb, A., Thiéry, D., 2006. Does natural larval parasitism of *Lobesia botrana* (Lepidoptera: Tortricidae) vary between years, generation, density of the host and vine cultivar? *Bull. Entomol. Res.* 96, 105–110. <https://doi.org/10.1079/BER2005393>.

Y

Yarwood, C.E., 1943. Association of thrips with powdery mildews. *Mycologia* 35: 189–191.

Z

Zaller, J.G., Brühl, C.A., 2019. Editorial: Non-target Effects of Pesticides on Organisms Inhabiting Agroecosystems. *Front. Environ. Sci.* 7, 75. <https://doi.org/10.3389/fenvs.2019.00075>.

Zaller, J.G., Kruse-Platz, M., Schleichriemen U., Gruber, E., Peer, M., Nadeem, I., Formayer, H., Hutter, H.-P., Landler, L., 2022. Pesticides in ambient air, influenced by surrounding land use and weather, pose a potential threat to biodiversity and humans. *Science of the Total Environment* 838, 156012. <https://doi.org/10.1016/j.scitotenv.2022.156012>.

Zuur, A., Ieno, E.N., Walker, N., Seveliev, A.A., Smith, G.M., 2009. Mixed Effects Models and Extensions in Ecology with R, in: *Statistics for Biology and Health*. Springer, New York, NY, USA.

Danksagung

Mein Dank gilt zunächst meinen Betreuern Prof. Dr. Martin Entling und Dr. Christoph Hoffmann, die von der ersten Sekunde an noch mehr Vertrauen in mich hatten als ich selbst. Ohne Euch wäre das ganze hier nicht möglich gewesen, **danke!** Großartig waren auch die vielen Freiräume, die Ihr mir während der Zeit zugestanden habt und Eure Unterstützung bei so vielen anderen kleinen und großen Hirngespinnsten.

Martin, Deine kontinuierliche Rückenstärkung zu fast jeder Tages- und Nachtzeit hat mir über viele Unsicherheiten hinweg geholfen. Ebenso Dein gut gemeinter Pragmatismus: *Dann ist das eben so* ist ein Satz, der mich davor bewahrt hat an so manchen Stellen zu verzweifeln.

Christoph, Dein unglaubliches Wissen über Milben und Hymenopteren in Taxonomie und Lebensweise hat meine Bestimmungsarbeit unglaublich bereichert. Du hast auch von Anfang an auf liebevolle und unkomplizierte Weise ermöglicht, dass meine Kinder in den Arbeitsablauf integriert werden konnten.

Des Weiteren gilt mein Dank den Mitarbeitern des JKI Siebeldingen, die mich nicht nur immer ertragen, sondern auch tatkräftig unterstützt haben. Insbesondere Getraud Michl, meiner persönlichen Zoologie-Heldin, Sonja Anslinger, Laura Götze und Argyroula Tsormpatzidou, die sich monatelang um die Traubenwicklerzucht gekümmert haben und Thomas Gramm mit dem Parzellenspritzplan.

Und auch Keerthi Sudarsan, Marvin Ehringer, Konrad Theiss, Rosalie Shrestha, Paul Mason, Ken Mauser und Anja Hollander haben mir mit ihren Praktika, Modul- und Abschlussarbeiten nicht nur einige Arbeit abgenommen, sondern mit viel Freude die gemeinsame Zeit (und meinen Wortschatz) bereichert: *harvestmen = daddy longleg, weird.*

Dr. Theresa Pennington, die mir während des Masterstudiums mit den Prädationsversuchen das Projekt schmackhaft gemacht und mir einen Berg Daten hinterlassen hat. Deine Vorarbeit war ein guter Wegweiser.

Sebastian Kolb, ohne den die Burnout-Feldarbeit 2019 unerträglich gewesen und ohne den wir nie zu unserem grandiosen *Branding* gekommen wären. Die Fantastischen Zwei kamen, um die Welt der Spinnen und Insekten zu retten. Und dann verloren wir uns im Größenwahn. . . Und wofür braucht man eigentlich Gleitgel im Labor? Natürlich um bis spät in die Nacht präparierte Palpen und Epigynen von Spinnen am Kamerabino zu fotografieren. Danke für deinen trockenen Humor!



Auch wenn meine Eltern in aller Bescheidenheit nicht erwähnt werden möchten, wäre ich wohl ohne ihre fortwährende Unterstützung nie so weit gekommen. Danke, dass ihr mir so vieles ermöglicht (und ich spreche nicht nur vom Babysitten während der Klausurphase) und mir immer den Rücken gestärkt habt.

Meine Kinder, die mich nicht nur mitunter entbehren mussten, sondern mir auch immer wieder aufgezeigt haben mit welcher Faszination man die kleinen Details bewundern kann und wie schön die Welt ist, die uns umgibt.

Meinem Mann verdanke ich die Gelassenheit. Du wusstest jedes noch so große Problem zu relativieren. Und ohne dich wären die Kinder und ich vermutlich schon längst verhungert. . .

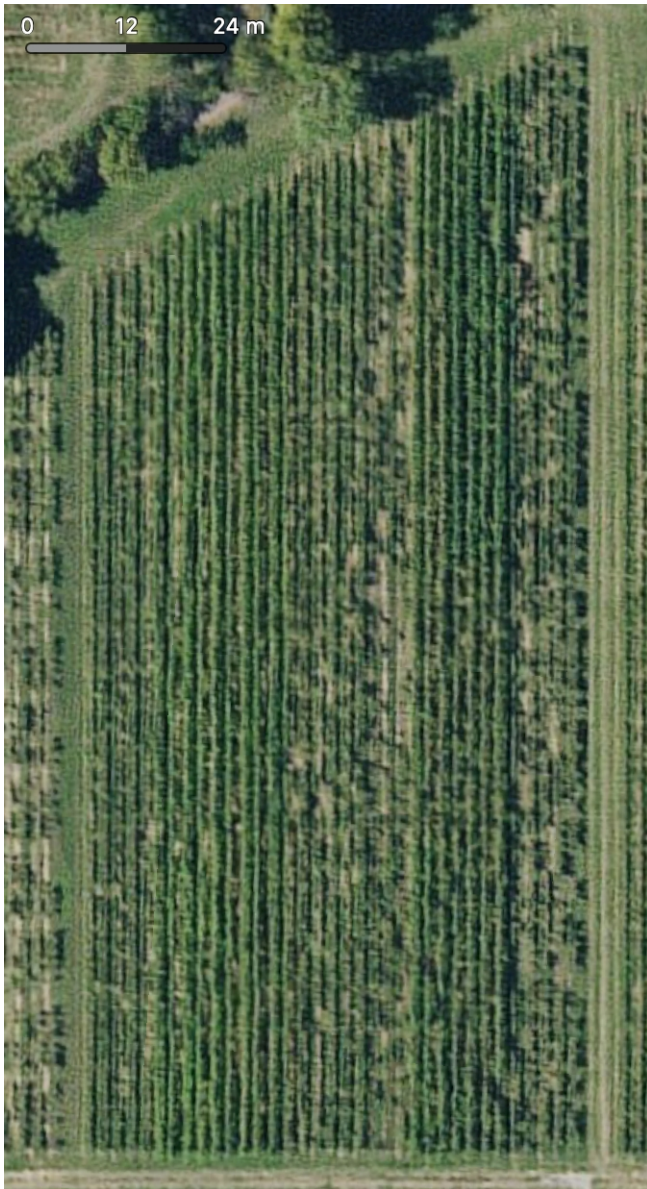
APPENDIX



CHAPTER II

Consistent benefits of fungicide reduction on arthropod predators and predation rates in viticulture: a five-year experiment

Figure S1 Experimental vineyard, planted with four fungus-resistant grapevine cultivars (Reberger, Villarís, Felicia, Gf 84-58-988), cultivated in two different pruning systems (trellis systems, minimal pruning), and treated with three different fungicide spraying intensities (standard, reduced, minimal), resulting in 24 plots.



Villarís		Felicia		Gf 84-58-988		Reberger	
trellis system	minimal pruning	trellis system	minimal pruning	trellis system	minimal pruning	trellis system	minimal pruning
standard spraying (10-13)	standard spraying (10-13)	standard spraying (10-13)	standard spraying (10-13)	standard spraying (10-13)	standard spraying (10-13)	standard spraying (10-13)	standard spraying (10-13)
reduced spraying (4-7)	reduced spraying (4-7)	reduced spraying (4-7)	reduced spraying (4-7)	reduced spraying (4-7)	reduced spraying (4-7)	reduced spraying (4-7)	reduced spraying (4-7)
minimal spraying (2-4)	minimal spraying (2-4)	minimal spraying (2-4)	minimal spraying (2-4)	minimal spraying (2-4)	minimal spraying (2-4)	minimal spraying (2-4)	minimal spraying (2-4)

Table S1 Spraying regimes of the five study years in the experimental vineyard. Displayed are the applied amounts of plant protection products per hectare and spraying event (with respective BBCH number describing the phenological development of grapes) for the two different pruning systems. Spraying events that accounted for the three different spraying intensities are marked with “x”.

2015	sprayings			copper (g ha ⁻¹)		sulfur (kg ha ⁻¹)		potassium bicarbonate (kg ha ⁻¹)		
	BBCH	minimal	reduced	standard	trellis system	minimal pruning	trellis system	minimal pruning	trellis system	minimal pruning
	13			x	150	450	4.5	13.5		
	55			x	100	167	3.6	6.0		
	55			x	100	167	3.6	6.0		
	57	x	x	x	150	225	4.2	6.3		
	65	x	x	x	100	150	4.2	6.3		
	69		x	x	100	140	4.8	6.7		
	69-73		x	x	250	350	3.2	4.6		
	73-75			x	200	280	3.2	4.6		
	75-77			x	200	280	3.2	4.6		
	79			x	200	233	3.2	3.4		
	79			x	200	233			4.0	4.7
	79			x	200	233			6.0	7.0
	79-81			x					6.0	7.0
2016	sprayings			copper (g ha ⁻¹)		sulfur (kg ha ⁻¹)		potassium bicarbonate (kg ha ⁻¹)		
	BBCH	minimal	reduced	standard	trellis system	minimal pruning	trellis system	minimal pruning	trellis system	minimal pruning
	53-55			x	100	167	3.6	6.0		
	55-57			x	200	333	3.6	6.0		
	57		x	x	600	800	3.6	5.4		
	60	x	x	x	300	420	3.6	5.0		
	60-65	x	x	x	300	420	5.0	7.0		
	68-69		x	x	300	400	4.0	5.3		
	69-73			x	300	400	4.0	5.3		
	73-75			x	200	267	4.0	5.3		
	75			x	200	267	4.0	5.3		
	75-77			x	200	267	4.0	5.3		
	79			x	200	267			5.0	6.7
	81			x	200	267			6.0	8.0
2017	sprayings			copper (g ha ⁻¹)		sulfur (kg ha ⁻¹)		potassium bicarbonate (kg ha ⁻¹)		
	BBCH	minimal	reduced	standard	trellis system	minimal pruning	trellis system	minimal pruning	trellis system	minimal pruning
	55	x		x	150	250	4.0	6.7		
	57		x	x	150	250	4.0	5.6		
	60-65	x	x	x	200	350	4.0	7.0		
	65-68		x	x	200	350	4.0	7.0		
	73		x	x	200	350	4.0	7.0		
	75			x	300	420	4.0	7.0		
	75-77			x	300	420	4.0	7.0		
	79			x	250	350	4.0	7.0		
	79			x	200	280	4.0	7.0		
	81			x	200	280			6.0	8.4

2018	sprayings			copper (g ha ⁻¹)		sulfur (kg ha ⁻¹)		potassium bicarbonate (kg ha ⁻¹)	
	minimal	reduced	standard	trellis system	minimal pruning	trellis system	minimal pruning	trellis system	minimal pruning
55-57			x	200	200	4.0	8.0		
55-57		x	x	250	350	4.0	8.0		
57		x	x	250	350	4.0	5.6		
60-65	x	x	x	250	250	4.0	4.0		
60-65	x	x	x	375	375	6.0	6.0		
69-73	x	x	x	300	333	4.0	5.3		
69-73	x	x	x	300	300	4.0	4.0		
73-75		x	x	400	400	6.7	6.7		
75-77			x	267	267	5.3	5.3		
79			x	267	267	6.7	6.7		
79			x	267	267			6.7	6.7
79			x	300	300			7.5	7.5
79-81			x	275	375			7.5	7.5

2019	sprayings			copper (g ha ⁻¹)		sulfur (kg ha ⁻¹)		potassium bicarbonate (kg ha ⁻¹)	
	minimal	reduced	standard	trellis system	minimal pruning	trellis system	minimal pruning	trellis system	minimal pruning
55-57			x	135	240	3.6	5.0		
55-57			x	150	300	4.0	8.0		
57		x	x	400	400	8.0	8.0		
57-60	x	x	x	420	420	5.6	5.6		
65	x	x	x	300	300	5.6	5.6		
69-73	x	x	x	200	200	5.3	5.3		
73			x	200	200	5.3	5.3		
75-77			x	225	225	6.0	6.0		
77-79			x	270	270	5.3	5.3		
79			x	225	225			7.5	7.5
79			x	225	225			7.5	7.5
79-81			x	200	200			8.0	8.0

Table S2 Sampling dates for leaf mesofauna, macrofauna, and predation rates for each study year in the experimental vineyard.

	2015	2016	2017	2018	2019
Leaf collection	July September	June July August 2x September 2x October	June 2x July August September	Mai June July August	June July August September
Beat-sheet sampling	July August September	June July August 2x September	April Mai June 3x July 2x August 2x	Mai June July 2x August	June July August September
Bait exposition	July September	June July August September	June August	Mai June July 2x August	June July August September

Table S3 Arthropod grapevine leaf fauna, arthropods in the vine canopy sampled via beat-sheet, and predation rates on *L. botrana* eggs with respect to two pruning systems (trellis, minimal) and three fungicide spraying frequencies (2, 4, 12) in five consecutive years. Displayed are model-predicted means \pm 95% confidence interval (N=24 vineyard plots).

	2015			2016			2017			2018			2019																	
	trellis		minimal			trellis		minimal			trellis		minimal			trellis		minimal												
	2	4	12	2	4	12	2	4	12	2	4	12	2	4	12	2	4	12	2	4	12	2	4	12	2	4	12			
Leaf mesofauna [individuals m ⁻²]																														
Phytoseiidae	71.50	63.44	39.33	119.26	109.12	76.45	68.66	65.00	52.21	86.43	84.36	76.60	144.08	112.90	42.56	113.20	91.46	38.97	137.63	128.19	96.47	157.12	150.89	128.35	103.47	93.97	63.93	180.99	169.48	130.32
	+18.84	+14.80	+11.97	+30.74	+24.77	+22.31	+18.11	+15.01	+16.62	+22.54	+19.21	+23.92	+37.24	+24.99	+16.50	+29.47	+20.42	+15.19	+44.88	+34.22	+25.99	+51.06	+40.11	+34.26	+28.07	+21.83	+20.01	+48.34	+38.61	+39.61
	-14.91	-12.00	-9.18	-24.44	-20.19	-17.27	-14.33	-12.20	-12.61	-17.88	-15.65	-18.23	-29.59	-20.46	-11.89	-23.38	-16.69	-10.93	-33.84	-27.01	-20.48	-38.54	-31.69	-27.04	-22.08	-17.72	-15.24	-38.15	-31.45	-30.47
Tydeidae	130.39	111.89	60.68	179.40	145.80	63.60	286.40	248.53	140.92	463.82	381.17	173.86	50.19	40.70	17.60	49.46	37.99	13.22	278.08	273.46	255.76	622.97	580.19	436.51	52.39	45.48	25.85	122.22	100.50	45.94
	+74.49	+55.62	+39.37	+102.22	+72.30	+41.24	+162.96	+121.65	+97.51	+262.96	+186.26	+120.14	+29.54	+20.11	+16.15	+97.51	+29.11	+12.24	+207.17	+162.64	+152.15	+463.26	+344.34	+259.23	+32.15	+23.47	+18.60	+74.12	+51.11	+32.55
	-47.41	-37.15	-23.88	-65.12	-48.33	-25.02	-167.82	-81.67	-57.63	-167.82	-125.12	-71.05	-18.60	-13.46	-8.42	-57.63	-18.33	-6.35	-118.72	-101.98	-162.64	-265.69	-216.09	-162.64	-19.92	-15.48	-10.82	-46.14	-33.88	-19.05
Cal. vitis	255.13	273.95	364.18	241.39	220.67	154.11	25.46	24.74	22.05	51.58	42.67	19.98	73.67	65.63	41.33	175.04	132.75	43.92	44.18	47.22	61.63	107.17	97.52	66.87	152.46	144.87	118.09	175.84	142.25	60.92
	+129.11	+120.72	+206.24	+122.28	+97.43	+87.94	+13.96	+11.69	+14.82	+27.29	+19.52	+13.52	+38.49	+28.89	+32.82	+90.12	+57.54	+34.69	+30.38	+25.98	+33.63	+72.39	+52.66	+36.42	+82.13	+65.63	+73.29	+94.57	+64.48	+38.32
	-85.73	-83.79	-131.67	-81.16	-67.59	-55.99	-9.02	-7.94	-8.86	-17.85	-13.39	-8.06	-25.28	-20.06	-18.29	-59.49	-40.14	-19.38	-18.00	-16.76	-21.76	-43.21	-34.20	-23.58	-53.38	-45.17	-45.22	-61.50	-44.37	-23.52
Co. vitis	181.87	191.63	236.19	168.74	156.63	116.28	10.86	10.35	8.52	27.08	22.73	11.28	39.37	33.89	18.61	97.96	74.29	24.57	69.26	70.56	76.04	131.91	118.40	76.84	66.70	63.32	51.44	98.69	82.77	40.50
	+111.82	+102.16	+163.21	+103.85	+83.65	+80.85	+7.59	+6.21	+7.46	+17.73	+12.78	+9.62	+25.26	+18.24	+18.64	+61.62	+39.11	+24.27	+56.98	+46.13	+49.64	+107.78	+76.85	+50.17	+44.12	+35.04	+39.48	+65.05	+45.57	+31.27
	-69.25	-66.64	-96.52	-64.28	-54.53	-47.69	-4.47	-3.88	-3.98	-10.72	-8.18	-5.19	-15.39	-11.86	-9.31	-37.83	-25.62	-12.21	-31.26	-27.89	-30.03	-59.32	-46.60	-30.35	-26.56	-22.56	-22.34	-39.25	-29.39	-17.65
Empoasca sp.	12.23	12.54	13.84	6.60	7.01	8.91	2.36	2.39	2.51	2.39	2.50	3.03	8.41	8.15	7.22	8.42	8.46	8.63	8.32	8.52	9.37	9.03	9.57	12.13	1.33	1.42	1.79	1.20	1.32	1.91
	+5.46	+4.87	+6.78	+3.32	+3.06	+4.70	+1.71	+1.48	+2.19	+1.72	+1.53	+2.50	+4.06	+3.34	+5.28	+4.06	+3.44	+6.17	+5.10	+4.22	+4.56	+5.43	+4.64	+5.66	+1.34	+1.16	+1.90	+1.24	+1.11	+1.98
	-3.77	-3.51	-4.55	-2.21	-2.13	-3.08	-0.99	-0.91	-1.17	-1.00	-0.95	-1.37	-2.74	-2.37	-3.05	-2.74	-2.45	-3.60	-3.16	-2.82	-3.07	-3.39	-3.13	-3.86	-0.67	-0.64	-0.92	-0.61	-0.60	-0.97
Thrips	13.50	13.80	15.09	11.34	11.09	10.15	22.09	21.83	20.84	18.44	17.44	13.93	41.86	41.75	41.29	21.36	20.38	16.87	38.95	42.06	57.19	23.75	24.53	27.92	92.62	91.06	85.07	67.24	63.23	49.44
	+6.11	+5.43	+7.56	+5.28	+4.25	+5.38	+9.38	+8.01	+10.75	+7.98	+6.56	+7.49	+16.98	+14.23	+24.91	+9.09	+7.37	+10.71	+20.22	+17.59	+23.60	+12.72	+10.63	+11.98	+37.62	+31.32	+39.52	+27.59	+22.02	+23.39
	-4.21	-3.90	-5.03	-3.60	-3.21	-3.52	-6.58	-5.86	-7.09	-5.57	-4.77	-4.87	-12.08	-10.61	-15.54	-6.37	-5.41	-6.55	-13.31	-12.40	-16.60	-8.28	-7.42	-8.38	-26.76	-23.30	-26.98	-19.56	-16.33	-15.88
Predation rates [%]																														
<i>L. botrana</i> eggs	58.74	57.32	51.97	45.21	41.01	27.78	32.27	30.19	23.10	41.61	36.18	20.69	21.30	22.14	25.86	20.96	20.26	17.67	43.90	43.28	40.85	64.47	59.08	41.66	67.12	67.79	70.51	77.83	73.08	56.78
	+17.40	+14.91	+17.28	+13.64	+10.94	+9.74	+10.11	+8.25	+8.95	+12.75	+9.71	+8.11	+7.08	+6.20	+12.37	+6.89	+5.75	+8.72	+16.98	+13.65	+12.94	+24.50	+18.28	+13.18	+20.62	+17.75	+24.53	+23.77	+19.05	+19.96
	-13.42	-11.83	-12.97	-10.48	-8.64	-7.21	-7.70	-6.48	-6.45	-9.76	-7.66	-5.83	-5.31	-4.85	-8.37	-5.24	-4.48	-5.84	-12.25	-43.28	-9.82	-17.75	-13.96	-10.01	-15.78	-14.06	-18.20	-18.21	-15.11	-14.77

	2015						2016						2017						2018						2019					
	trellis			minimal			trellis			minimal			trellis			minimal			trellis			minimal			trellis			minimal		
	2	4	12	2	4	12	2	4	12	2	4	12	2	4	12	2	4	12	2	4	12	2	4	12	2	4	12	2	4	12
Macrofauna																														
[individuals/10 vines]																														
total abundance	24.83	23.16	17.51	26.38	23.89	16.07	17.66	17.07	14.92	20.08	18.86	14.66	9.74	9.55	8.84	10.61	10.10	8.32	22.60	21.32	16.88	22.95	21.02	14.81	13.07	12.67	11.21	18.93	17.82	14.02
	+4.89	+4.06	+4.27	+5.11	+4.14	+4.03	+3.90	+3.31	+4.11	+4.26	+3.53	+4.06	+2.77	+2.31	+3.77	+2.93	+2.38	+3.58	+5.99	+4.62	+3.92	+6.10	+4.58	+3.57	+3.39	+2.83	+3.43	+4.38	+3.51	+4.03
	-4.09	-3.46	-3.44	-4.28	-3.53	-3.22	-3.19	-2.77	-3.22	-3.51	-2.97	-3.18	-2.16	-1.86	-2.64	-2.30	-1.93	-2.50	-4.74	-3.80	-3.18	-4.82	-3.76	-2.88	-2.69	-2.31	-2.62	-3.56	-2.93	-3.13
predators	14.07	13.16	10.08	15.27	13.73	8.97	10.31	10.23	9.89	12.61	12.02	9.92	7.14	7.15	7.18	6.58	6.33	5.42	15.75	15.00	12.35	13.26	12.14	8.53	7.81	7.55	6.57	7.37	6.84	5.08
	+3.47	+2.88	+3.14	+3.66	+2.95	+2.91	+2.85	+2.47	+3.31	+3.24	+2.71	+3.31	+2.39	+2.00	+3.56	+2.27	+1.87	+2.87	+4.89	+3.78	+3.33	+4.39	+3.30	+2.60	+2.66	+2.16	+2.72	+2.57	+2.04	+2.27
	-2.78	-2.36	-2.39	-2.95	-2.43	-2.20	-2.23	-1.99	-2.48	-2.58	-2.21	-2.48	-1.79	-1.56	-2.38	-1.69	-1.44	-1.88	-3.73	-3.02	-2.62	-3.30	-2.59	-1.99	-1.98	-1.68	-1.92	-1.92	-1.57	-1.57
spiders	7.92	7.14	4.74	9.71	8.82	5.98	9.68	9.45	8.57	11.67	11.45	10.63	4.19	4.10	3.76	3.88	3.82	3.58	11.99	10.99	7.75	10.32	9.51	6.86	5.47	5.03	3.62	5.24	4.85	3.57
	+2.73	+2.20	+2.23	+3.08	+2.47	+2.59	+2.99	+2.55	+3.31	+3.36	+2.86	+3.80	+1.97	+1.61	+2.79	+1.88	+1.55	+2.69	+4.67	+3.45	+2.75	+4.21	+3.14	+2.54	+2.43	+1.88	+2.14	+2.37	+1.85	+2.12
	-2.03	-1.68	-1.52	-2.34	-1.93	-1.81	-2.29	-2.01	-2.39	-2.61	-2.29	-2.80	-1.34	-1.16	-1.60	-1.27	-1.10	-1.54	-3.36	-2.62	-2.03	-2.99	-2.36	-1.85	-1.68	-1.37	-1.35	-1.63	-1.34	-1.33
earwigs	1.23	1.30	1.67	0.69	0.63	0.44	1.03	1.05	1.13	0.40	0.35	0.20	1.37	1.51	2.24	0.61	0.58	0.47	2.41	2.45	2.62	1.28	1.12	0.65	1.73	1.83	2.28	1.25	1.14	0.77
	+1.22	+1.08	+1.64	+0.93	+0.76	+0.82	+1.18	+0.96	+1.61	+0.78	+0.62	+0.62	+1.31	+1.13	+2.96	+0.86	+0.71	+1.08	+2.34	+1.86	+1.93	+1.73	+1.21	+0.86	+1.52	+1.31	+2.10	+1.31	+1.01	+1.12
	-0.61	-0.59	-0.83	-0.40	-0.34	-0.29	-0.55	-0.50	-0.67	-0.26	-0.22	-0.15	-0.67	-0.65	-1.28	-0.36	-0.32	-0.33	-1.19	-1.06	-1.11	-0.74	-0.58	-0.37	-0.81	-0.76	-1.09	-0.64	-0.53	-0.46
ants	2.94	2.80	2.29	3.88	3.18	1.44	0.08	0.07	0.05	0.43	0.34	0.14	0.29	0.32	0.49	1.09	1.04	0.88	0.78	0.81	0.92	0.46	0.41	0.26	0.08	0.08	0.11	0.09	0.08	0.06
	+2.03	+1.72	+1.93	+2.49	+1.87	+1.53	+0.58	+0.46	+0.63	+0.89	+0.57	+0.96	+0.56	+0.52	+1.24	+1.17	+0.91	+1.74	+1.38	+1.06	+1.13	+1.07	+0.76	+0.56	+0.70	+0.50	+1.02	+0.72	+0.49	+0.84
	-1.20	-1.06	-1.05	-1.52	-1.18	-0.74	-0.07	-0.06	-0.05	-0.29	-0.22	-0.12	-0.19	-0.20	-0.35	-0.56	-0.49	-0.59	-0.50	-0.46	-0.51	-0.32	-0.27	-0.18	-0.07	-0.07	-0.10	-0.08	-0.07	-0.05
leafhoppers	3.62	3.36	2.49	1.29	1.17	0.80	0.43	0.40	0.31	0.04	0.04	0.03	0.30	0.31	0.35	0.58	0.59	0.61	1.29	1.21	0.95	1.71	1.57	1.13	0.89	0.92	1.01	0.57	0.58	0.59
	+2.21	+1.85	+1.91	+1.15	+0.93	+0.98	+0.80	+0.58	+1.04	+0.55	+0.47	+0.47	+0.58	+0.49	+1.05	+0.82	+0.65	+1.47	+1.56	+1.16	+0.99	+1.87	+1.36	+1.11	+1.01	+0.84	+1.28	+0.79	+0.66	+0.93
	-1.37	-1.20	-1.08	-0.61	-0.52	-0.44	-0.28	-0.24	-0.24	-0.04	-0.04	-0.03	-0.20	-0.19	-0.26	-0.34	-0.31	-0.43	-0.71	-0.59	-0.48	-0.89	-0.73	-0.56	-0.47	-0.44	-0.57	-0.33	-0.31	-0.36

Table S4 Pairwise comparisons of the explanatory variables ‘year’ and ‘variety’ for each response variable. *P* values are displayed when the explanatory variable had significant impact in the initial model.

	Leaf mesofauna						Macrofauna						Predation rates
	Phytoseiidae	Tydeidae	Cal. vitis	Co. vitis	Empoasca sp.	Thrips	total abundance	predators	spiders	earwigs	ants	leafhoppers	<i>L. botrana</i> eggs
year													
2015 – 2016	0.992	< 0.001	< 0.001	< 0.001	< 0.001	0.029	0.016	0.638	0.007	0.715	< 0.001	< 0.001	< 0.001
2015 – 2017	0.981	< 0.001	< 0.001	< 0.001	0.707	< 0.001	< 0.001	< 0.001	< 0.001	0.999	< 0.001	< 0.001	< 0.001
2015 – 2018	< 0.001	< 0.001	< 0.001	< 0.001	0.999	< 0.001	0.718	0.998	0.118	0.299	< 0.001	0.499	0.985
2015 – 2019	< 0.001	0.003	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.007	0.469	< 0.001	0.004	< 0.001
2016 – 2017	0.863	< 0.001	< 0.001	< 0.001	< 0.001	0.023	< 0.001	< 0.001	< 0.001	0.587	0.119	0.365	0.032
2016 – 2018	< 0.001	0.144	< 0.001	< 0.001	< 0.001	< 0.001	0.388	0.474	0.897	0.026	0.172	0.006	< 0.001
2016 – 2019	< 0.001	< 0.001	< 0.001	< 0.001	0.184	< 0.001	0.186	< 0.001	< 0.001	0.050	0.984	0.068	< 0.001
2017 – 2018	< 0.001	< 0.001	0.977	< 0.001	0.867	0.639	< 0.001	< 0.001	< 0.001	0.466	0.999	0.010	< 0.001
2017 – 2019	< 0.001	0.005	0.014	0.081	< 0.001	< 0.001	< 0.001	0.999	0.874	0.657	0.031	0.558	< 0.001
2018 – 2019	0.614	< 0.001	0.002	0.455	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.996	0.048	0.252	0.004
variety													
Felicia – GF84-58-988	1.000		< 0.001	< 0.001		0.004				0.908	0.136	0.037	
Felicia – Reberger	0.002		0.117	< 0.001		0.973				0.168	0.774	0.020	
Felicia – Villaris	0.638		< 0.001	< 0.001		0.136				0.878	0.293	0.489	
GF84-58-988 – Reberger	0.002		< 0.001	< 0.001		< 0.001				0.037	0.014	0.996	
GF84-58-988 – Villaris	0.658		1.000	0.942		0.602				0.999	0.976	< 0.001	
Reberger – Villaris	0.076		< 0.001	< 0.001		0.048				0.030	0.041	< 0.001	

Table S5 Effects of natural enemy densities (Phytoseiidae, Tydeidae) on pest mite densities. Significant *p*-values are displayed in bold and direction of effects is highlighted with +/-.

densities of	Phytoseiidae (df 1)		Tydeidae (df 1)	
	X^2	<i>p</i>	X^2	<i>p</i>
<i>Cal. vitis</i>	0.064	0.799	7.925	– 0.005
<i>Co. vitis</i>	0.020	0.888	9.456	– 0.002
<i>Empoasca sp.</i>	3.927	– 0.048	2.396	0.122
Thrips	0.029	0.865	0.067	0.795

CHAPTER III

Fungicide reduction favors the control of phytophagous mites under both organic and conventional viticulture

Table S1 Mite families and their relevance for viticulture.

taxa	ingestion	relevance for viticulture
Phytoseiidae	generalist predator	feeding on Eriophyidae and Tetranychidae
Tydeidae	generalist predator	feeding on Eriophyidae
Anystidae	generalist predator	feeding on Eriophyidae and Tetranychidae
Trombidiidae	generalist predator	feeding on Eriophyidae and Tetranychidae
Bdellidae	generalist predator	feeding on Eriophyidae and Tetranychidae
Cunaxidae	generalist predator	feeding on Eriophyidae and Tetranychidae
Eriophyidae	phytophagous	pest
Tetranychidae	phytophagous	pest
Oribatida	detrivore	unknown

Table S2: Models used for statistical analyses including explanatory and response variables and degrees of freedom.

response variable (Y)	model	degrees of freedom
Number of sprayings ^A	$Y \sim \text{management} * \text{grape variety} + (1 \text{site})$	26
Phytoseiid mite density ^A		
Tydeid mite density ^B		
Phytophagous mite density ^B		
Trombidiid mite abundance ^B		
Anystid mite abundance ^B		
Phytoseid mite density ^A	$Y \sim \text{number of sprayings} + (1 \text{site})$	28
Tydeid mite density ^B		
Pest mite density ^B		

Distribution used: ^A normal; ^B negative binomial

Table S6 Number of beneficial mites determined to species level.

family	species	number
Tydeidae	<i>Tydeus goetzi</i> (Schruff)	401
Phytoseidae	<i>Typhlodromus pyri</i> (Scheuten)	397
	<i>Euseius finlandicus</i> (Oudemans)	22
	<i>Paraseiulus soleiger</i> (Ribaga)	17
Cunaxidae	<i>Haleupalus oliveri</i> (Schruff)	4

Figure S3: Study sites in the Palatinate region (Germany) with coordinates and planted grape varieties.

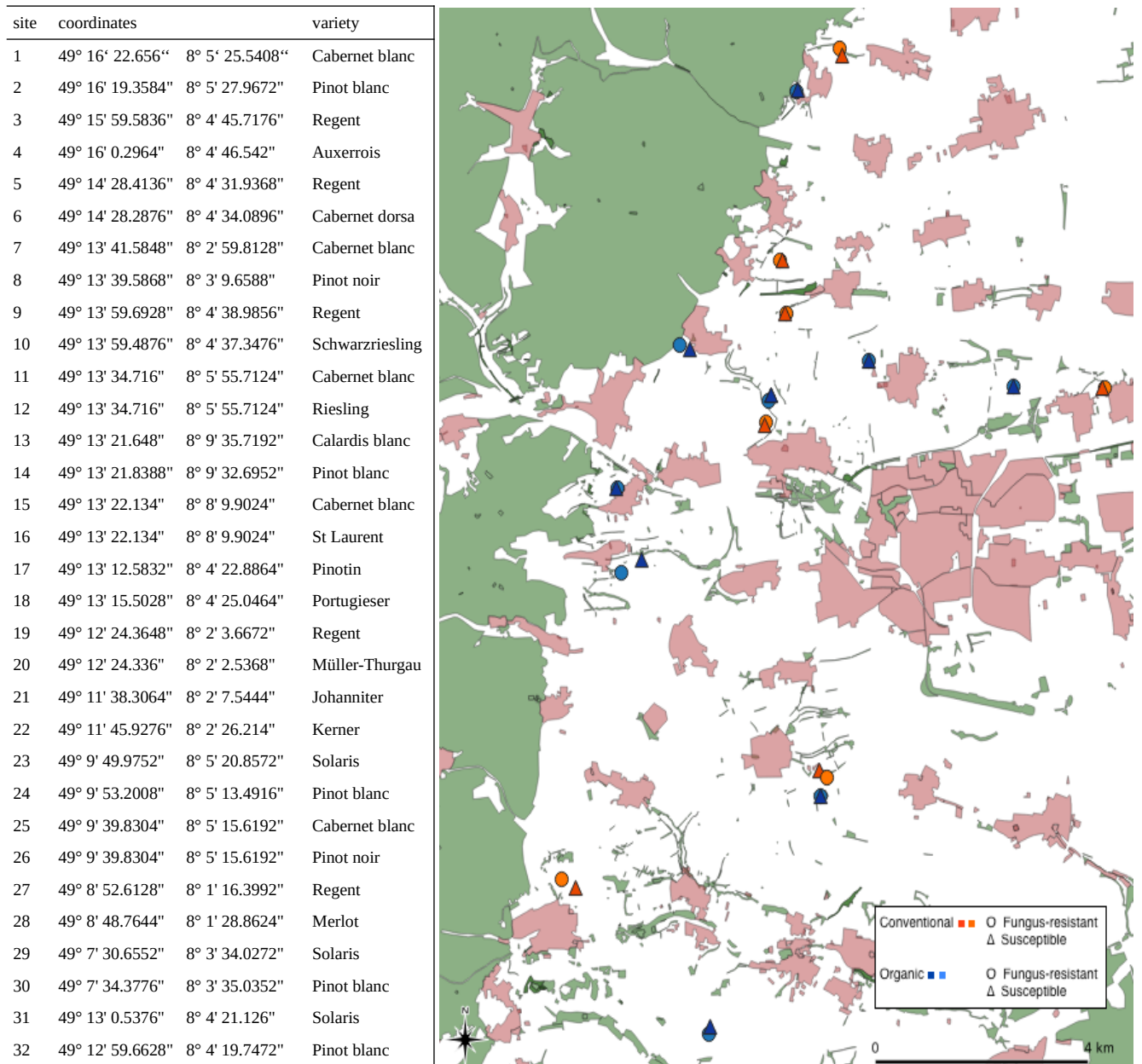


Table S4: Pesticide input in organic and conventional vineyards.

trade name	active substance	hazard class ¹	number of treated vineyards number of sprayings (mean ± standard deviation)	
			organic	conventional
<i>Fungicides</i>				
Aktuan®	Cymoxanil 100 g/kg; Dithianon 250 g/kg	1	–	1 (0.07 ±0.27)
Ampexio®	Mandipropamid 250 g/kg; Zoxamide 240 g/kg	1	–	3 (0.21 ±0.43)
Collis®	Boscalid 200 g/L; Kresoxim-methyl 100 g/L	1	–	6 (0.43 ±0.51)
Cuproxtat®	Copper 190 g/L	2	3 (1.06 ±3.15)	–
Dithane® NeoTec	Mancozeb 750 g/kg	2	–	4 (0.64 ±1.15)
Dynali®	Cyflufenamid 30 g/L; Difenoconazol 60 g/L	1	–	7 (0.71 ±0.83)
Enervin®	Ametoctradin 120g/kg; Metiram 440 g/kg	2	–	5 (0.36 ±0.50)
Fantic® F	Benylaxyl-M 37.5 g/kg; Folpet 480 g/kg	1	–	2 (0.14 ±0.36)
Folpan® 80 WDG	Folpet 800 g/kg	1	–	8 (1.36 ±1.60)
Funguran Progress®	Copper 350 g/kg	1	11 (4.00 ±4.54)	3 (0.50 ±1.16)
Kumar®	Potassium bicarbonate 850 g/kg	3	5 (0.56 ±1.25)	–
Kusabi®	Pyriofenone 300 g/L	1	–	5 (0.36 ±0.50)
Luna® Experience	Fluopyram 200 g/L; Tebuconazole 200 g/L	2	–	5 (0.36 ±0.50)
Mildicut®	Cyazofamid 25 g/L	2	–	5 (0.64 ±1.08)
Misha	Myclobutanil 200 g/L	1	–	1 (0.07 ±0.27)
Wettable Sulfur Stulln	Sulfur 796 g/kg	1	17 (5.83 ±4.68)	14 (2.79 ±2.08)
Orvego®	Ametoctradin 300 g/L; Dimetomorph 225 g/L	2	–	7 (0.64 ±0.74)
Polyram® WG	Metiram 700 g/kg	2	–	7 (1.00 ±1.18)
Profiler®	Fluopicolide 44.4 g/kg; Fosetyl 621.9 g/kg	1	–	4 (0.29 ±0.47)
Ridomil Gold® Combi	Folpet 400 g/kg; Metalaxyl-M 50 g/kg	1	–	3 (0.21 ±0.43)
Sercadis®	Fluxapyroxad 300 g/L	2	–	3 (0.21 ±0.43)
Systhane® 20	Myclobutanil 200 g/L	1	–	2 (0.14 ±0.36)
Talendo®	Proquinazid 200 g/L	1	–	6 (0.50 ±0.65)
Talius®	Proquinazid 200 g/L	1	–	1 (0.07 ±0.27)
Teldor®	Fenhexamid 500 g/kg	1	–	3 (0.21 ±0.43)
Topas®	Penconazol 100 g/L	1	–	3 (0.36 ±0.74)
Vento™ Power	Myclobutanil 45 g/L Quinoxifen 45 g/L	1	–	4 (0.29 ±0.47)
Vegas®	Cyflufenamid 51.3 g/L	1	–	1 (0.14 ± 0.53)
Veriphos®	Tripotassium phosphate 755 g/L	2	–	4 (0.29 ±0.47)
Videryo® F	Cyazofamid 40 g/L; Folpet 400 g/L	1	–	1 (0.07 ±0.27)
VinoStar®	Dimethomorph 113 g/kg; Folpet 600 g/kg	1	–	2 (0.14 ±0.36)
VitiSan®	Potassium bicarbonate 995 g/kg	2	12 (2.22 ±2.26)	1 (0.14 ±0.53)
Vivando®	Metrafenone 500 g/L	1	–	7 (0.57 ±0.65)
<i>Insecticides</i>				
Steward®	Indoxacarb 300 g/kg	1	–	2 (0.14 ±0.36)
<i>Herbicides</i>				
Durano®	Glyphosate 360 g/L	1	–	2 (0.14 ±0.36)

1 Hazard class towards predatory mites according BVL (2018): 1: harmless; 2: moderately harmful; 3: strongly harmful.

Table S5 Data used for statistical analysis including total number of fungicide applications per season, average densities of *T. pyri*, *T. goetzi*, *Co. vitis* and *Cal. vitis* per m², summed abundances of Anystidae and Trombididae and average leaf surface for 32 investigated vineyards.

site	variety	management	number of sprayings	<i>Typhlodromus pyri</i>	<i>Tydeus goetzi</i>	<i>Colomerus vitis</i>	<i>Calepitrimerus vitis</i>	Anystidae	Trombididae	average leaf area (cm ² per leaf)
1	resistant	conventional	3	164.40	81.00	61.07	21.19	2	12	154.99
2	resistant	organic	3	492.20	379.99	107.16	17.28	1	1	150.81
1	susceptible	conventional	6	278.03	220.28	129.08	20.12	3	24	133.79
2	susceptible	organic	9	84.93	31.09	177.91	36.54	3	1	130.55
3	resistant	conventional	4	331.94	84.01	47.50	10.69	3	11	152.57
4	resistant	organic	3	316.35	815.02	185.27	35.08	1	23	151.28
3	susceptible	conventional	9	162.61	103.69	112.17	19.51	2	20	156.28
4	susceptible	organic	12	122.29	186.58	324.66	52.97	2	2	140.91
5	resistant	conventional	3	435.29	1110.44	133.91	22.53	3	14	138.60
6	resistant	organic	4	275.77	26.66	169.44	26.80	3	4	145.10
5	susceptible	conventional	10	293.11	1309.74	345.82	44.89	4	26	137.89
6	susceptible	organic	15	143.18	35.03	201.15	28.95	14	9	139.14
7	resistant	conventional	6	314.16	258.92	145.46	22.68	0	9	151.99
8	resistant	organic	2	325.97	840.61	202.57	33.93	1	21	150.62
7	susceptible	conventional	10	186.33	166.16	135.63	26.36	3	11	140.58
8	susceptible	organic	10	252.50	586.41	184.25	22.76	4	3	129.57
9	resistant	conventional	4	88.87	548.09	98.13	11.98	3	19	171.18
10	resistant	organic	2	84.42	200.42	245.24	39.24	12	33	123.51
9	susceptible	conventional	7	166.35	335.93	137.86	18.53	7	32	140.55
10	susceptible	organic	11	56.38	119.37	178.03	27.69	3	7	167.85
11	resistant	organic	0	449.41	1071.01	61.07	28.76	13	9	149.92
12	resistant	organic	1	524.94	1395.65	206.86	35.59	3	25	141.58
11	susceptible	organic	10	213.88	106.42	92.77	21.66	8	9	138.64
12	susceptible	organic	9	312.73	241.64	146.97	27.60	4	43	136.65
13	resistant	conventional	9	193.54	1093.15	166.33	42.66	2	62	165.13
14	resistant	organic	2	484.51	1125.05	321.48	68.32	25	78	143.88
13	susceptible	conventional	9	308.89	201.48	110.40	22.17	3	95	139.96
14	susceptible	organic	10	248.51	477.60	412.10	103.01	24	58	119.41
15	resistant	conventional	3	333.36	1241.01	116.25	20.89	5	26	141.18
16	resistant	organic	3	177.26	43.07	118.30	22.05	4	40	167.19
15	susceptible	conventional	8	143.65	893.74	237.09	40.10	4	12	157.80
16	susceptible	organic	11	97.48	33.83	175.55	30.72	20	2	134.03

CHAPTER IV

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

Table S1 Study sites in the Palatinate region (Germany) with coordinates and planted grape varieties.

vineyard	coordinates		variety
1	49° 16' 22.656"	8° 5' 25.5408"	Cabernet blanc
2	49° 13' 15.5028"	8° 4' 25.0464"	Portugieser
3	49° 12' 24.3648"	8° 2' 3.6672"	Regent
4	49° 12' 24.336"	8° 2' 2.5368"	Müller-Thurgau
5	49° 14' 28.4136"	8° 4' 31.9368"	Regent
6	49° 14' 28.2876"	8° 4' 34.0896"	Cabernet dorsa
7	49° 12' 59.6628"	8° 4' 19.7472"	Pinot blanc
8	49° 13' 39.5868"	8° 3' 9.6588"	Pinot noir
9	49° 13' 59.6928"	8° 4' 38.9856"	Regent
10	49° 13' 59.4876"	8° 4' 37.3476"	Schwarzriesling
11	49° 13' 34.716"	8° 5' 55.7124"	Cabernet blanc
12	49° 16' 19.3584"	8° 5' 27.9672"	Pinot blanc
13	49° 13' 0.5376"	8° 4' 21.126"	Solaris
14	49° 16' 0.2964"	8° 4' 46.542"	Auxerrois
15	49° 13' 41.5848"	8° 2' 59.8128"	Cabernet blanc
16	49° 13' 21.648"	8° 9' 35.7192"	Calardis blanc
17	49° 13' 21.8388"	8° 9' 32.6952"	Pinot blanc
18	49° 13' 22.134"	8° 8' 9.9024"	Cabernet blanc
19	49° 13' 22.134"	8° 8' 9.9024"	St Laurent
20	49° 13' 12.5832"	8° 4' 22.8864"	Pinotin
21	49° 7' 30.6552"	8° 3' 34.0272"	Solaris
22	49° 7' 34.3776"	8° 3' 35.0352"	Pinot blanc
23	49° 13' 34.716"	8° 5' 55.7124"	Riesling
24	49° 11' 38.3064"	8° 2' 7.5444"	Johanniter
25	49° 15' 59.5836"	8° 4' 45.7176"	Regent
26	49° 9' 39.8304"	8° 5' 15.6192"	Cabernet blanc
27	49° 9' 53.2008"	8° 5' 13.4916"	Pinot blanc
28	49° 9' 49.9752"	8° 5' 20.8572"	Solaris
29	49° 9' 39.8304"	8° 5' 15.6192"	Pinot noir
30	49° 8' 52.6128"	8° 1' 16.3992"	Regent
31	49° 8' 48.7644"	8° 1' 28.8624"	Merlot
32	49° 11' 45.9276"	8° 2' 26.214"	Kerner

Table S2 Spraying parameters per vineyard, including the number of sprayings and the hazard quotient as well as the active ingredients of applied pesticides.

site	variety	management	number of sprayings	hazard quotient	active ingredients
1	resistant	conventional	3	0.71417	Ametoctradin, Fenhexamid, Folpet, Metiram, Myclobutanil, Sulphur
2	resistant	organic	3	0.70937	Aluminium sulphates, Potassium bicarbonate, Sulphur
1	susceptible	conventional	6	1.21558	Ametoctradin, Benalaxyl-M, Boscalid, Cyazofamid, Fenhexamid, Folpet, Kresoxim-methyl, Mancozeb, Metalaxyl-M, Metiram, Myclobutanil, Pyriofenon, Sulphur
2	susceptible	organic	9	2.20866	Aluminium sulphates, Potassium bicarbonate, Sulphur
3	resistant	conventional	4	2.76744	Folpet, Indoxcarb, Metiram, Myclobutanil, Quinoxifen, Sulphur
4	resistant	organic	3	1.60278	Copper hydroxide, Potassium bicarbonate, Sulphur
3	susceptible	conventional	9	3.67156	Ametoctradin, Copper hydroxide, Dimethomorph, Fluopyram, Folpet, Indoxcarb, Metiram, Metrafenon, Myclobutanil, Proquinazid, Quinoxifen, Sulphur, Tebuconazole
4	susceptible	organic	12	6.00706	Copper hydroxide, Potassium bicarbonate, Sulphur
5	resistant	conventional	5	0.67917	Ametoctradin, Copper hydroxide, Dimethomorph, Fluopyram, Kresoxim-methyl, Mancozeb, Penconazol, Sulphur, Tebuconazole
6	resistant	organic	4	1.54570	Copper sulfate, Potassium bicarbonate, Sulphur
5	susceptible	conventional	10	2.13251	Ametoctradin, Boscalid, Copper hydroxide, Cyazofamid, Cyflufenamid, Difenconazol, Dimethomorph, Fluopyram, Kresoxim-methyl, Mancozeb, Penconazol, Potassium bicarbonate, Proquinazid, Sulphur, Tebuconazole
6	susceptible	organic	14	4.71361	Copper sulfate, Potassium bicarbonate, Sulphur
7	resistant	conventional	6	1.00681	Ametoctradin, Cyflufenamid, Difenconazol, Dimethomorph, Fluopicolide, Fosetyl-Aluminium, Metiram, Metrafenon, Proquinazid, Pyriofenon, Sulphur
8	resistant	organic	2	1.00468	Copper hydroxide, Potassium bicarbonate, Sulphur
7	susceptible	conventional	10	1.35816	Ametoctradin, Benalaxyl-M, Boscalid, Cyazofamid, Cyflufenamid, Cymoxanil, Difenconazol, Dimethomorph, Dithianon, Fluopicolide, Fluopyram, Folpet, Fosetyl-Aluminium, Kresoxim-methyl, Mandipropamid, Metiram, Metrafenon, Potassium phosphonate, Proquinazid, Pyriofenon, Sulphur, Tebuconazole, Zoxamid
8	susceptible	organic	10	4.74649	Copper hydroxide, Potassium bicarbonate, Sulphur
9	resistant	conventional	4	0.56822	Cyflufenamid, Difenconazol, Fluopicolide, Folpet, Fosetyl-Aluminium, Mancozeb, Metalaxyl-M, Metiram, Metrafenon, Potassium phosphonate, Sulphur
10	resistant	organic	2	0.34684	Copper hydroxide, Sulphur
9	susceptible	conventional	7	0.73956	Boscalid, Cyazofamid, Cyflufenamid, Difenconazol, Dimethomorph, Fluopicolide, Fluxapyroxad, Folpet, Fosetyl-Aluminium, Kresoxim-methyl, Mancozeb, Metalaxyl-M, Metiram, Metrafenon, Penconazol, Potassium phosphonate, Sulphur
10	susceptible	organic	11	2.51210	Copper hydroxide, Potassium bicarbonate, Sulphur
11	resistant	organic	0	0	–
12	resistant	organic	1	0.48054	Copper hydroxide, Sulphur
11	susceptible	organic	10	4.98087	Copper hydroxide, Potassium bicarbonate, Sulphur
12	susceptible	organic	9	4.01326	Copper hydroxide, Potassium bicarbonate, Sulphur
13	resistant	conventional	6	0.60721	Ametoctradin, Cyazofamid, Cyflufenamid, Difenconazol, Dimethomorph, Mancozeb, Mandipropamid, Metiram, Metrafenon, Proquinazid, Pyriofenon, Sulphur, Zoxamid
14	resistant	organic	2	0.88200	Copper hydroxide, Sulphur
13	susceptible	conventional	10	1.19271	Ametoctradin, Boscalid, Cyazofamid, Cyflufenamid, Difenconazol, Dimethomorph, Fluxapyroxad, Kresoxim-methyl, Mancozeb, Mandipropamid, Metiram, Metrafenon, Myclobutanil, Proquinazid, Pyriofenon, Quinoxifen, Sulphur, Zoxamid
14	susceptible	organic	10	4.07173	Copper hydroxide, Copper sulfate, Potassium bicarbonate, Sulphur
15	resistant	conventional	2	0.07998	Cyflufenamid, Folpet, Metrafenon
16	resistant	organic	3	1.37393	Copper hydroxide, Potassium bicarbonate, Sulphur
15	susceptible	conventional	8	1.39599	Ametoctradin, Cyflufenamid, Fluopyram, Folpet, Metrafenon, Metiram, Proquinazid, Sulphur, Tebuconazole
16	susceptible	organic	11	4.23314	Copper hydroxide, Potassium bicarbonate, Sulphur

Table S3 Identified families with corresponding order, classification into guilds according to their feeding behavior, and average abundances per vineyard.

family	number of individuals				family	number of individuals			
	conventional resistant	conventional susceptible	organic resistant	organic susceptible		conventional resistant	conventional susceptible	organic resistant	organic susceptible
<i>Aranea</i> ^{+RV}					<i>Dermaptera</i>				
Agelenidae ^A				1	Forficulidae ^{C +CM}	1335	1083	605	643
Amaurobidae ^A	1				<i>Diptera</i> ^{+RV +OM}				
Anypaenidae ^A	9	4	11	6	Acartophthalmidae ^E				1
Araneidae ^A	214	210	247	199	Agromyzidae ^B	2		2	
Cheiracanthidae ^A			5	8	Anthomyiidae ^{A,F}	1		2	2
Clubionidae ^A	3	3	5	12	Asteiidae ^{E,F}		1		
Dictynidae ^{A +RV}	102	82	133	63	Atelestidae ^A			1	3
Gnaphosidae ^A	1	2	4	5	Bibionidae ^G				1
Linyphiidae ^A	148	100	163	86	Camillidae ^{na}				2
Lycosidae ^A	5		3	3	Cecidomyiidae ^B	1	3	1	1
Mimetidae ^A		1	3	2	Ceratopogonidae ^{Aa,H}		2	3	
Philodromidae ^{A +RV}	404	298	687	432	Chironomidae ^{E,G}		2		
Pholcidae ^A			1		Chloropidae ^G	5	5	1	1
Pisauridae ^A			1	2	Dolichopodidae ^A			2	1
Salticidae ^A	118	195	219	241	Drosophilidae ^{B,G}	78	49	10	6
Segestriidae ^A			2		Empididae ^A		1		
Sparassidae ^A			2	1	Ephydriidae ^B	1			
Tetragnathidae ^A	23	19	27	14	Fanniidae ^E	1	1		1
Theridiidae ^{A +RV}	574	415	527	365	Lauxaniidae ^{B,E}		1		
Thomisidae ^{A +RV}	113	68	186	134	Muscidae ^{A,E,E}	1	1		1
Uloboridae ^A	1				Mycetophilidae ^D			2	
<i>Blattoptera</i>					<i>Periscleridae</i> ^{na}				
Blattellidae ^{A,E}	1	1	5	5	Phoridae ^{A,E}	2	2	4	2
<i>Coleoptera</i>					<i>Platypozidae</i> ^D				
Anobiidae ^{Ba}			1		Rhinophoridae ^{Ab}	1		1	
Anthicidae ^{A,E,F}	1		2	4	Sacrophagidae ^E		2		
Anthribidae ^{B,D}			2	–	Scatopsidae ^{B,E}		1	3	2
Apionidae ^B	11	8	25	17	Sciaridae ^D	18	56	37	19
Attelabidae ^B	3				Simuliidae ^H		2		
Bruchidae ^{Bc}			4		Sphaeroceridae ^E		2		
Cantharidae ^{A,F}				1	Stratiomyidae ^G		1		
Carabidae ^{A,Bb,F}	4	5	1	7	Syrphidae ^{A,E,G}	1		2	3
Chryptophagidae ^{D,E}			1		Tabanidae ^H				1
Chrysomelidae ^B	28	30	29	23	Tachinidae ^{Aa}	1			1
Cleridae ^{A,F}			1		Tephritidae ^{E,F,G}		1	1	
Coccinellidae ^{A,D,F +RV}	58	33	38	18	Tipulidae ^{na}				2
Curculionidae ^B	2	5	5	8	<i>Entomobryomorpha</i>				
Dasytidae ^F				1	Entomobryidae ^E	2	1	3	
Elateridae ^B	1	3	3	6	Isotomidae ^E	3	1	136	157
Eucnemidae ^{Ba,D}	1	2	3	2	<i>Ephemoptera</i>				
Haliplidae ^{A,B}			1		Baetidae ^{na}		1		
Kateretidae ^B				1	<i>Hemiptera</i> ^{+OM}				
Latridiidae ^{D +RV}	211	163	202	121	Acanthosomatidae ^B			1	
Malachiidae ^{A,F}		1		1	Anthocoridae ^A	15	5	10	16
Melyridae ^A	1	1	2	1	Aphididae ^B	6	11	24	10
Mycetophagidae ^D			1		Aphrophoridae ^B	2	3	3	2
Nitidulidae ^{D,E}	1	1		1	Berytidae ^{A,B}			4	
Oedemeridae ^F			1	1	Cicadellidae ^{B +SV}	323	653	398	444
Phalacridae ^{F +RV}	129	104	72	26	Cixiidae ^B			1	2
Scolytidae ^{Ba}		2			Coreidae ^B	3	2	5	1
Scraptiidae ^F			1		Delphacidae ^B			6	10
Sphindidae ^D	1		1		Eriosomatidae ^B	2	2	8	3
Staphylinidae ^{A,D,E}	4	2	2	1	Lygaeidae ^{Bb}	1	2		4
Tenebrionidae ^{B,F}	2		1	1	Membracidae ^B				1

family	number of individuals				family	number of individuals			
	conventional resistant	conventional susceptible	organic resistant	organic susceptible		conventional resistant	conventional susceptible	organic resistant	organic susceptible
<i>Hemiptera (cont.)</i>					<i>Lepidoptera (cont.)</i>				
Microphysidae ^A			3	1	Geometridae ^B	12	6	39	42
Miridae ^{ABb}	24	35	27	27	Gracillariidae ^B		3	1	
Nabidae ^A	21	13	39	19	Hepialidae ^B	1	2	2	4
Pemphigidae ^B	1				Lycaenidae ^B		1		
Pentatomidae ^{AB}	16	7	24	16	Noctuidae ^B	5	8	25	20
Piesmatidae ^B	1				Plutellidae ^B	3	4	2	
Pyrrhocoridae ^B	5		13	9	Pterophoridae ^B	2			1
Reduviidae ^A		1	1	1	Pyrilidae ^B		1	1	
Rhopalidae ^{Bb}	4	3	3	3	Tineidae ^B		2	1	1
Rhyparochromidae ^B	6	25	12	15	Tortricidae ^B	10	10	22	19
Saldidae ^A				1	Yponomeutidae ^B		2		2
Tettigometridae ^B			1		<i>Mecoptera</i>				
Tingidae ^B				1	Panopidae ^E	2			
<i>Hymenoptera</i>					<i>Neuroptera ^{+OM}</i>				
Agaonidae ^F	1	1		1	Chrysopidae ^A	33	53	39	55
Apidae ^F	1	1			Hemerobiidae ^A	1	1	3	2
Bethylidae ^{Ab}			1		<i>Opiliones</i>				
Braconidae ^{Ab}	6	9	14	7	Phalangidae ^A	15	17	37	46
Ceraphronidae ^{Ab}	1		4	2	<i>Oribatida</i>				
Chalcididae ^{Ab}			1		Chamobatidae ^E				1
Chrysididae ^{Ab}			1		Oribatellidae ^E		1		
Colletidae ^F			1		Phenopelopidae ^E	1		1	1
Cynipidae ^B	1				<i>Orthoptera</i>				
Diapriidae ^{Ab}	1		2	3	Meconematidae ^A			1	
Elasmidae ^{Ab}		1			Tettigoniidae ^B	1			
Encyrtidae ^{Ab}	1	2	1	3	<i>Polyxenida</i>				
Eucoilidae ^{Ab}				1	Polyxenidae ^B		11		
Eulophidae ^{Ab}	7	7	5	10	<i>Pseudoscorpiones</i>				
Eupelmidae ^{Ab}	23	2	2	4	Chernetidae ^A			1	
Eurytomidae ^{Ab}	1		2	3	<i>Psocoptera</i>				
Figitidae ^{Aa}	1			1	Caeciliusidae ^B				1
Formicidae ^A	238	224	72	120	Ectobiidae ^{E,Ba}	4	5		
Halictidae ^F			2	1	Ectopsocidae ^E	25	20	50	15
Ichneumonidae ^{Ab}	6	6	12	7	Elipsocidae ^D	2	11	3	3
Megaspilidae ^{Ab}		1			Lachesillidae ^D	4	1	2	
Mymaridae ^{Ab}	1	1	1	1	Mesopsocidae ^D		1		
Platygastridae ^{Ab}	4	1	4	5	Peripsocidae ^D		1		1
Pompilidae ^{Ab}	1				Stenopsocidae ^D		1	1	
Proctotrupidae ^{Ab}		2			Trichopsocidae ^E				2
Pteromalidae ^{Ab}	2	1	7	4	<i>Thysanoptera</i>				
Scelionidae ^{Ab}	4		4	3	Aeolothripidae ^{AB}	3	5	3	4
Torymidae ^{Ab}	1	1	1	2	Limnephilidae ^B				1
Vespidae ^C	4				Phlaeothripidae ^B	1	1	2	1
<i>Isopoda</i>					Thripidae ^B	2		1	1
Philosciidae ^E				1	<i>Trombidiformes</i>				
<i>Lepidoptera</i>					Anystidae ^A	18	26	63	82
Coleophoridae ^B	1				Cunaxidae ^A	7	6	2	3
Crambidae ^B		1			Trombididae ^A	153	220	234	134
Epemeriidae ^B				1	<i>Symphyleona</i>				
Erebidae ^B		2	1		Sminthuridae ^E	3		6	

Corresponding orders are displayed in *italic*. Guilds are given as superscript characters: **A** carnivore (including **a** parasitic, **b** parasitoid), **B** herbivore (including **a** xylophagy, **b** granivore), **C** omnivore, **D** fungivore, **E** detritivore, **F** palynivore, **G** nectarivore, **H** haematophagous. Multiple characters indicate that families contain several guilds according to single genera and species determined.

For the most abundant families and orders statistical differences are highlighted with **+RV** (increase in resistant varieties), **+SV** (increase in susceptible varieties), **+OM** (increase under organic management), **+CM** (increase under organic management).

CHAPTER VI

Arthropods in the spotlight – identifying predators of vineyard pest insects with infrared photography.

Table S1: Model parameters and output for the three fitted models. Model formula included response variable ~ management*variety + (1 | site).

response variable	Model parameters		Model output p-values (Chi-square values)		
	distribution	df residuals	management	variety	management *variety
<i>L. botrana</i> egg predation	tweedie	25	0.1223 (2.3871)	0.9451 (0.0047)	0.0829 (3.0071) .
<i>L. botrana</i> pupae predation	Gaussian	26	0.1187 (2.4351)	0.3622 (0.8304)	0.0802 (3.0618) .
<i>D. melanogaster</i> pupae predation	Gaussian	26	0.6317 (0.2298)	0.8663 (0.0283)	0.1387 (2.1922)

Table S2: Exposed and consumed eggs and pupae of *L. botrana* and *D. melanogaster* per vineyard and sampling date listed by predator.

site	conventional														organic																		
	resistant							susceptible							resistant							susceptible											
	1	3	5	7	9	13	15	1	3	5	7	9	13	15	2	4	6	8	10	11	12	14	16	2	4	6	8	10	11	12	14	16	
May																																	
<i>L. botrana</i> eggs																																	
exposed	82	53	42	47	55	218	214	59	94	45	45	75	169	203	70	109	45	63	46	33	40	182	192	83	150	61	58	34	51	29	188	166	
Forficula auricularia	7	3	-	22	32	214	-	-	-	-	5	22	111	202	-	-	-	-	10	-	-	174	-	-	-	-	-	-	-	-	-	-	-
Formicidae	-	-	-	-	-	-	-	-	13	-	-	20	-	-	10	-	-	-	-	-	6	-	-	-	-	-	-	-	-	-	-	-	-
Philodromus sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	13	-	-	-	-	-	-	-	-	-
<i>L. botrana</i> pupae																																	
exposed	10	9	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	9	10	10	10	10	10	10	10	
Forficula auricularia	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-	-	3	-	-	3	7	-	-	-	-	-	-	-	-	-	-
Formicidae	-	-	-	-	-	-	1	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Opiliones	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	4	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
<i>D. melanogaster</i> pupae																																	
exposed	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	
Forficula auricularia	5	5	-	8	5	-	5	-	-	-	5	5	10	5	-	-	-	-	5	-	-	10	5	-	-	-	-	5	-	-	-	-	-
Formicidae	-	-	-	2	-	-	3	-	-	-	-	-	-	4	-	-	-	-	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Opiliones	-	-	-	-	-	1	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	5	-	-	-	-	-	-	-	-	-	-	1
Philodromus sp.	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Blattoptera	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Vespa sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-
June																																	
<i>L. botrana</i> eggs																																	
exposed	192	138	15	20	63	60	77	193	173	20	27	64	58	46	138	137	26	22	88	59	87	44	65	182	157	31	30	78	59	50	62	63	
Forficula auricularia	124	-	-	4	-	-	-	2	4	-	5	-	-	2	-	3	3	-	7	18	19	-	-	54	7	5	13	34	-	-	-	-	
<i>L. botrana</i> pupae																																	
exposed	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	
Forficula auricularia	5	3	-	3	-	-	-	1	-	5	5	-	-	2	-	5	-	-	-	10	5	-	5	2	4	2	4	-	5	5	2	-	
<i>D. melanogaster</i> pupae																																	
exposed	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	
Forficula auricularia	9	5	5	10	-	-	-	5	10	10	5	5	-	-	5	5	2	5	-	5	10	5	-	5	5	-	5	5	-	5	5	4	
Opiliones	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	

site	conventional														organic																		
	resistant							susceptible							resistant						susceptible												
	1	3	5	7	9	13	15	1	3	5	7	9	13	15	2	4	6	8	10	11	12	14	16	2	4	6	8	10	11	12	14	16	
July																																	
<i>L. botrana</i> eggs																																	
exposed	59	67	65	33	93	51	74	37	42	32	47	109	44	55	50	55	47	56	99	107	87	61	60	48	45	44	43	96	70	87	54	48	
Forficula auricularia	-	8	-	-	36	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	62	4	-	-	-	
Formicidae	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	
Chrysopidae larvae	-	-	-	-	-	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
<i>L. botrana</i> pupae																																	
exposed	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	
Forficula auricularia	-	2	-	4	4	-	-	-	-	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6	-	8	-	-	
Chrysopidae larvae	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Opiliones	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
<i>D. melanogaster</i> pupae																																	
exposed	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	
Forficula auricularia	-	5	-	1	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	-	10	-	10	-	4	
August																																	
<i>L. botrana</i> eggs																																	
exposed	134	171	118	152	101	159	152	163	127	202	134	167	165	45	153	125	68	170	190	50	123	60	44	87	138	175	152	171	82	52	169	51	
Forficula auricularia	-	-	-	82	61	-	124	-	-	-	68	-	-	-	-	-	-	-	-	-	-	6	-	-	-	8	60	-	-	8	46	5	
Formicidae	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	15	-	-	-	-	-	-	-	-	-	-	
<i>Cheiracanthium</i> sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	40	-	
<i>L. botrana</i> pupae																																	
exposed	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	
Forficula auricularia	-	-	5	-	-	3	10	-	-	-	-	-	-	-	-	1	4	-	-	-	9	4	-	-	5	-	3	5	-	1	4	-	
Opiliones	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	-	-	-	
<i>Meconema meridionale</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
<i>Cheiracanthium</i> sp.	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
<i>Vespula</i> sp.	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
<i>D. melanogaster</i> pupae																																	
exposed	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	
Forficula auricularia	-	-	6	-	5	-	5	-	-	-	-	-	-	-	-	5	5	-	-	-	10	-	-	-	5	5	3	5	-	5	3	-	
Formicidae	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	-	-	-	-	-	-	-	-	-	-	-	

STATUS AND AUTHOR CONTRIBUTIONS OF PUBLICATIONS

CHAPTER II

Consistent benefits of fungicide reduction on arthropod predators and predation rates in viticulture: a five-year experiment

BioControl, published online 24th August 2023

doi: 10.1007/s10526-023-10213-6

Martin H. Entling, Christoph Hoffmann, Theresa Pennington, Sebastian Kolb and Jo Marie Reiff conceived the ideas and designed methodology; Jo Marie Reiff, Theresa Pennington, Sebastian Kolb, Konrad Theiss, Ekaterina Alakina, Paul Mason, Rosalie Shrestha performed the experiment; Jo Marie Reiff led the data analysis and writing. All authors contributed critically to the drafts and gave final approval for publication.

CHAPTER III

Fungicide reduction favors the control of phytophagous mites under both organic and conventional viticulture.

Agriculture, Ecosystems and Environment, published online on 5th October 2020.

doi: 10.1016/j.agee.2020.107172

Martin H. Entling, Christoph Hoffmann and Jo Marie Reiff conceived the ideas and designed methodology; Jo Marie Reiff and Marvin Ehringer performed the experiment; Jo Marie Reiff led the data analysis and writing. All authors contributed critically to the drafts and gave final approval for publication.

CHAPTER IV

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

Pest Management Science, published online on 18th April 2023.

doi: 10.1002/ps.7505

Martin H. Entling, Christoph Hoffmann and Jo Marie Reiff conceived the ideas and designed methodology; Jo Marie Reiff and Keerthi Sudarsan performed the experiment; Jo Marie Reiff led the data analysis and writing, and designed the graphical abstract. All authors contributed critically to the drafts and gave final approval for publication.

CHAPTER V

Dominant effects of fungicide sprayings on spiders in the vineyard canopy

Submitted to European Journal of Entomology on 7th July 2023 (currently in revision)

Martin H. Entling, Christoph Hoffmann and Jo Marie Reiff conceived the ideas and designed methodology; Jo Marie Reiff performed the experiment and led the data analysis and writing. All authors contributed critically to the drafts and gave final approval for publication.

CHAPTER VI

Arthropods in the spotlight – identifying predators of vineyard pest insects with infrared photography.

Submitted to Entomologia Experimentalis et Applicata on 17th April 2023 (currently in revision)

Martin H. Entling, Christoph Hoffmann and Jo Marie Reiff conceived the ideas and designed methodology; Konrad Theiss performed the experiment; Jo Marie Reiff led the data analysis and writing. All authors contributed critically to the drafts and gave final approval for publication.

BIBLIOGRAPHY

All images illustrating this work were drawn by Jo Marie Reiff. Some of them are based on original photographs.

Sources of original photographs:

Jo Marie Reiff: *pruning comparison, fungicide spraying, grape erineum mite galls, Coccinella septempunctata, Vanessa atalanta*; Marvin Ehringer: *Typhlodromus pyri, Tydeus götzi*; Sebastian Kolb: *Larinioides sclopetarius*; photomakers.org: *red grape* (CC-BY-SA 3.0 DE)

Jo Marie Reiff

born in Duisburg, Germany

EDUCATION

- 10/2014 – 11/2017 **Master of Sciences**
Environmental Sciences
RPTU Kaiserslautern-Landau, Germany
- 08/2011 – 09/2014 **Bachelor of Sciences**
Viticulture and Enology (cooperative study program)
Weincampus Neustadt, Germany / Weingut Jul. Ferd. Kimich, Deidesheim, Germany
- 08/2008 – 06/2011 **Viticultural training**
Weingut Clemens Busch, Pünderich, Germany
- 2008 **Abitur, Baccalauréat français**
Luisengymnasium, Düsseldorf, Germany

PROFESSIONAL EXPERIENCE

- since 12/2017 **Graduate Research Assistant**
RPTU Kaiserslautern-Landau
iES, Institute for Environmental Science, Landau, Germany
- 06/2017 – 09/2017 **Research Assistant**
Julius Kühn-Institute
Institute for Plant Protection in Fruit Crops and Viticulture, Siebeldingen, Germany
- 09/2016 – 10/2016 **Internship**
DHU (Deutsche Homöopathie Union)
Terra Medica, Staffort, Germany
- 05/2016 – 07/2016 **Research Assistant**
University of Koblenz-Landau
iES, Institute for Environmental Science, Landau, Germany
- 07/2015 – 10/2015 **Internship**
Julius Kühn-Institute
Institute for Plant Protection in Fruit Crops and Viticulture, Siebeldingen, Germany

Reiff, J.M.; Hoffmann, C.; Entling, M.H. (*in revision*). Dominant effects of fungicide sprayings on spiders in the vineyard canopy. *Submitted to European Journal of Entomology*

Reiff, J.M.; Theiss, K.; Hoffmann, C.; Entling, M.H. (*in revision*). Arthropods in the spotlight – identifying predators of vineyard pest insects with infrared photography. *Submitted to Entomologia Experimentalis et Applicata*

Reiff, J.M.; Pennington, T.; Kolb, S.; Theiss, K.; Ehringer, M.; Mason, P.; Shrestha, R.; Entling, M.H.; Hoffmann, C. (2023). Consistent benefits of fungicide reduction on arthropod predators and predation rates in viticulture: a five-year experiment. *Biocontrol* 68: 495-509.

Rösch, V.; Haffner, G.; **Reiff, J.M.;** Entling, M.H. (2023). Increase in breeding bird abundance and diversity with semi-natural habitat in vineyard landscapes. *PLoS ONE* 18: e0284254.

Reiff, J.M.; Sudarsan, K.; Hoffmann, C.; Entling, M.H. (2023). Arthropods on grapes benefit more from fungicide reduction than from organic farming. *Pest Management Science* 79: 3271–3279.

Beaumelle, L.; Giffard, B; Tolle, P; Winter, S; Entling, M.H.; Benítez, E.; Zaller, J.G.; Auriol, A.; Bonnard, O.; Charbonnier, Y.; Fabreguettes, O.; Joubard, B.; Kolb, S.; Ostandie, N.; **Reiff, J.M.;** Richart-Cervera, S.; Rusch, A. (2023). Biodiversity conservation, ecosystem services and organic viticulture: A glass half-full. *Agriculture, Ecosystems & Environment* 351: 108474.

Möth, S.; Richart-Cervera, S.; Comsa, M.; Alcalá Herrera, R.; Hoffmann, C.; Kolb, S.; Popescu, D.; **Reiff, J.M.;** Rusch, A.; Tolle, P.; Walzer, A.; Winter, S. (2023). Local management and landscape composition affect predatory mites in European wine-growing regions. *Agriculture, Ecosystems & Environment* 344: 108292.

Reiff, J.M.; Ehringer, M.; Hoffmann, C.; Entling, M.H. (2021): Fungicide reduction favors the control of phytophagous mites under both organic and conventional viticulture. *Agriculture, Ecosystems & Environment* 305: 107172.

Reiff, J.M.; Kolb, S.; Entling, M.H.; Herndl, T.; Möth, S.; Walzer, A.; Kropf, M.; Hoffmann, C.; Winter, S. (2021) Organic Farming and Cover-Crop Management Reduce Pest Predation in Austrian Vineyards. *Insects* 12: 220.

Pennington, T.; **Reiff, J.M.;** Theiss, K.; Entling, M.H.; Hoffmann, C. (2018): Reduced fungicide applications improve insect pest control in grapevine. *BioControl* 63: 687.

Reiff, J.M.; Möth, S.; Kolb., S.; Hoffmann, C.; Entling, M.H. (2023). Biodiversität und natürliche Schädlingskontrolle – Möglichkeiten für einen nachhaltigeren Weinbau. Working Group Meeting FDW Plant Protection 03 May 2023. *Oral presentation*

Reiff, J.M.; Kolb., S.; Hoffmann, C.; Entling, M.H. (2022). Fungicide reduction enhances beneficial arthropods in grapevine. SFE2, GfÖ & EEF Joint Meeting, International Conference on Ecological Sciences 21-25 November 2022. *Poster presentation*

Reiff, J.M.; Kolb., S.; Hoffmann, C.; Entling, M.H. (2020). Funktionelle Biodiversität im Weinbau. Bioland Weinbautagung “Ökoweinbau weitergedacht – Aktuelle Forschungsprojekte” 11 February 2020. *Oral presentation*

Reiff, J.M.; Ehringer, M.; Entling, M.H.; Hoffmann, C. (2019). Reduced Pesticide Application promotes Natural Pest Mite Control in Vineyards. IOBC/WPRS Working Group Integrated Protection in Viticulture, 05-08 November 2019. *Poster presentation*

Reiff, J.M.; Sudarsan, K.; Mason, P.; Ehringer, M.; Entling, M.H.; Hoffmann, C. (2019). Reduced Pesticide Application promotes Natural Pest Control in Vineyards. PLANT 2030 Status Seminar, 13-15 March 2019. *Poster presentation*

Reiff, J.M.; Pennington, T.; Hoffmann, C.; Entling, M.H. (2018). Biologische Schädlingskontrolle in Weinbergen unter innovativem Management. Working Group Meeting FDW Plant Protection 11 April 2018. *Oral presentation*

Pennington, T.; **Reiff, J.M.;** Entling, M.H.; Hoffmann, C. (2018). Arthropod Biodiversity and Natural Pest Suppression in Vineyards under Innovative Management. PLANT 2030 Status Seminar, 05-07 February 2018. *Poster presentation*

OTHER PUBLICATIONS

Hoffmann, C.; Pennington, T.; **Reiff, J.M.;** Kolb, S.; Entling, M.H. (2020). Artenvielfalt und natürliche Schädlingskontrolle. In: Neue Reben im Minimalschnitt im Spalier – Die wichtigsten Fakten aus Forschung und Praxis. Forschungsprojekt novisys, Julius Kühn-Institut, Siebeldingen, 18-19.


Reiff, J.M.; Kolb, S.; Entling, M.; Hoffmann, C. (2023). Krabbelnde Vielfalt – BIODIVERSITÄT Wie man Nützlinge im Weinberg fördert und die natürliche Schädlingskontrolle verbessert. Der deutsche Weinbau 14, 34-36.

DECLARATION

I hereby declare that I independently conducted the work presented in this thesis entitled *Arthropod functional biodiversity under reduced fungicide sprayings in vineyards*. All used assistances are mentioned and involved contributors are either co-authors of or are acknowledged in the respective publication. This thesis has never been submitted elsewhere for an examination, as a thesis or for evaluation in a similar context to any department of this university or any scientific institution. I am aware that a violation of the aforementioned conditions can have legal consequences.

Landau in der Pfalz, 09.08.2023

Place, date



Signature
