Insects decline with host plants but co-extinctions seem unlikely

Marlon Bassi[1], Ingmar R. Staude[1,2]

1. Institute of Biology, Leipzig University, Leipzig, Germany
2. German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Leipzig, Deutschland

Abstract

It is commonly assumed that the loss of wild plant populations leads to co-extinctions, especially among specialized insects. Despite global declines in both terrestrial insects and plants, the relationship between these trends remains elusive. Here, we address this gap by analyzing the relationship between population trends of insects and their host plants in Germany, encompassing over 150,000 interactions among 3429 plant and 2239 insect species, including both symbiotic pollinators (bees and hoverflies) and parasitic herbivores (butterflies, moths, and sawflies). Our findings reveal generally positive relationships between the short- and long-term population trends of insects and their host plants across taxa, except in the more generalist hoverflies. However, when we simulated extinctions of threatened host plants, we found that 97% of the insect species studied could potentially survive by using alternative, non-threatened host plants. Even the most specialized insects may persist because they tend to specialize in common, non-threatened plant species. Our findings suggest the declining abundance of many plant species can contribute to insect decline yet challenge the frequent assumption that the extinction of threatened plant species will necessarily trigger an extinction wave of associated insects. Interaction networks seem to be more resilient.

Keywords: pollinators, herbivores, population trends, plant-insect interaction, Apiformes, Lepidoptera, Symphyta, Syrphidae

Significance statement: Whether plant extinctions cause further extinctions in associated insects is crucial for understanding the consequences of biodiversity loss but remains underexplored. We examine the relationships between bees, butterflies, moths, sawflies, hoverflies, and their host plants in Germany, showing that insect abundance trends parallel those of their plants. However, simulations of threatened plant extinctions reveal that interaction webs are highly resilient, with few co-extinctions among insects. Even highly specialized insects may persist because they focus on common, not threatened, plant species. Our research questions the frequent assumption that the high extinction risk of plant species will lead to a collapse in insect diversity.

Introduction

A prevailing consensus in ecology literature suggests that changes in plant biodiversity severely impact insect diversity (Carroll et al. 2023), particularly among specialized species (Moir et al. 2014). Insect populations are changing, with common species declining disproportionately, and terrestrial insects facing widespread reductions overall (van Klink et al. 2020, 2023). This loss of abundance mirrors a concerning trend of decreasing plant diversity (Wagner et al. 2021). For example, studies conducted in countries like Germany have reported declines of up to 76% in insect biomass in certain locations (Hallmann et al. 2017) and declining trends in 70% of plant species (Eichenberg et al. 2021). Despite these findings, the latest report from the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) does not identify the decrease in plant diversity as a primary driver of insect declines (Brondízio et al. 2019). Moreover, empirical studies directly linking plant and insect diversity trends through their interactions are scant (Schuldt et al. 2019), highlighting a fundamental research gap. These insights are essential for comprehending the full consequences of plant diversity change on insect diversity and ecosystem functionality, given the multitude of ecosystem services provided by insects, which are vital for human well-being (Schowalter 2013).

Despite limited empirical evidence, the presumed connection between host plant and insect population trends has several logical supporting arguments. One such argument is that plants play a crucial role in the life cycles of insect species, with many insects exhibiting high levels of specialization (Ødegaard et al. 2005). Research indicates that insect specialists, characterized by their reliance on a few host plant species and genera (mono- to oligolectic/-phagous) or specific habitats, are particularly susceptible to population declines (Koh et al. 2004). Some taxa, like sawflies, are highly monophagous, depending on a single plant species during their larval stage (Lacourt 2020), making them likely to be vulnerable to plant declines. Conversely, less specialized taxa, like hoverflies, which rely on functional plant types rather than specific species, may be more resilient to plant population declines due to redundant plant-insect interactions (Sanders et al. 2018). Thus, it is likely that insect taxa with high specialization levels show strong ties between the decline of functionally linked plant and insect species (Koh et al. 2004, Biesmeijer et al. 2006, Scheper et al. 2014).

But even for taxa with relatively high specialization levels, there is evidence suggesting that insect specialists specialize on more common plants, which are less likely to be threatened. For example, the strictly oligolectic Viper's Bugloss Mason Bee (*Osmia adunca*) exclusively relies on viper's bugloss (*Echium vulgare*) or other related *Echium* species in Central Europe (Burger et al. 2010), where these plants are common and non-threatened. Such interaction asymmetry, where insect specialists utilize "generalist" plants, could imply that insect specialists are not actually declining due to reductions in their plant resources, since the latter remain widespread and common (Vázquez and Aizen 2004). The universality of this pattern across different insect taxa is still largely unknown. However, for butterflies, Narango et al. (2020) found that in North America, a limited number of common, primarily woody plant genera sustain most of the butterfly diversity, even of specialists, a pattern also observed in southern Germany (Pearse and Altermatt 2013). This suggests that even amid declines in numerous plant species, common and non-threatened plants may continue to support a broad range of insect species, encompassing both generalists and specialists.

Another perspective on this topic is provided by studies investigating whether increasing the number and diversity of native plants leads to an increase in insect diversity (Nicholls and Altieri 2013; Mata et al. 2021), often in the context of gardens (Majewska and Altizer 2020). A major question here is which types of plants best support diverse insect populations, including specialized and threatened species? Is there a need for rare, specialized plants, or are common native or even non-native plants equally effective? Evidence is mixed, with some studies highlighting the benefits of native plants for specialist insects (Witt 2012, Breed et al. 2022), while others find no substantial difference to non-native plants (Zuefle et al. 2008). Importantly, it appears that the key factor is not the diversity of plants but the presence of specific species that significantly enhance insect diversity—often these are neither rare nor threatened (Warzecha et al. 2018; Purvis et al. 2021). This suggests insects might potentially withstand the decline in plant diversity to some extent, due to the resilience provided by keystone plant species or genera and host plant redundancy. Identifying these pivotal native plants is crucial for effective restoration strategies.

These key questions on how plant diversity loss affects insect diversity remain largely open, partly due to the need for extensive interaction and population trend data. Here, we synthesized such data for Germany, compiling over 150,000 plant-insect interactions involving bees (Apiforma), butterflies and moths (Lepidoptera), sawflies (Symphyta), and hoverflies (Syrphidae), across 3429 plant species and 2239 insect species. These taxa, which differ in specialization and in plant use, from larval feeding on plant tissue (butterfly and sawfly larvae) to adult nectar and pollen consumption (bee and hoverfly imagos), offer insights into diverse plant-insect relationships (Supplement S1). We collated short- and long-term population trends (10-15 and 50-150 yrs, respectively) and threat statuses from the Red List of each insect taxa and vascular plants. We used these data to examine: 1) the correlation between population trends of insects and their host plants; 2) the consequences of simulated plant extinctions on insect diversity; 3) the prevalence of keystone plant genera and the portion of plants needed to sustain insect diversity; 4) the generality of interaction asymmetries in which insect specialists might interact preferentially with non-threatened plant species. With this study we hope to provide insights into the effects of plant declines on insect diversity and inform restoration efforts.

Results

Parallel decline in insects and host plants. Across all taxa, more negative short- and long-term population trends of insect species were linked to more negative short- and long-term trends in host plant species (trends were averaged across all host plant species associated with an insect species; Fig. 1a and b). However, there were differences between insect taxa. The positive association between short-term population trends was clear for bees ($F_{2,290}$=7.0, p=0.001), butterflies and moths ($F_{2,1021}$=19, p<0.001) and sawflies ($F_{2,256}$=6.5, p=0.002), but flat for hoverflies ($F_{2,292}$=0.1, p=0.946). This pattern was similar for long-term population trends (bees: $F_{2,273}$=6.4, p=0.002; butterflies and moths: $F_{2,1019}$=33.9, p<0.001; sawflies: $F_{2,352}$=4.2, p=0.015; hoverflies: $F_{2,233}$=0.2, p=0.843) (see Fig. S1 and S2 for pairwise comparisons between negative, stable, and positive insect population trends). Comparing Red List (RL) threat statuses of insects and average RL threat statuses of host plants revealed a similar, but weaker pattern (Fig. 1c). When all taxa were considered jointly, insects classified as Critically Endangered (CR) had more threatened host plants on average than insects classified as Least Concern (LC) ($F_{4,2047}$=9.1, p<0.001 and pairwise comparisons in Fig. S3). This pattern was mainly driven by bees ($F_{4,292}$=4.8, p<0.001) and butterflies and moths ($F_{4,1058}$=5.9, p<0.001); in these taxa, CR insects had more threatened host plants than LC insects (Fig. S3). Sawflies and hoverflies revealed no such positive ties between insect and plant threat statuses ($F_{4,369}$=2.1, p=0.080 and $F_{4,313}$=1.0, p=0.425, respectively). Together, these findings are largely consistent with the hypothesis that population trends of plant species are linked to insect trends, though less so for hoverflies.

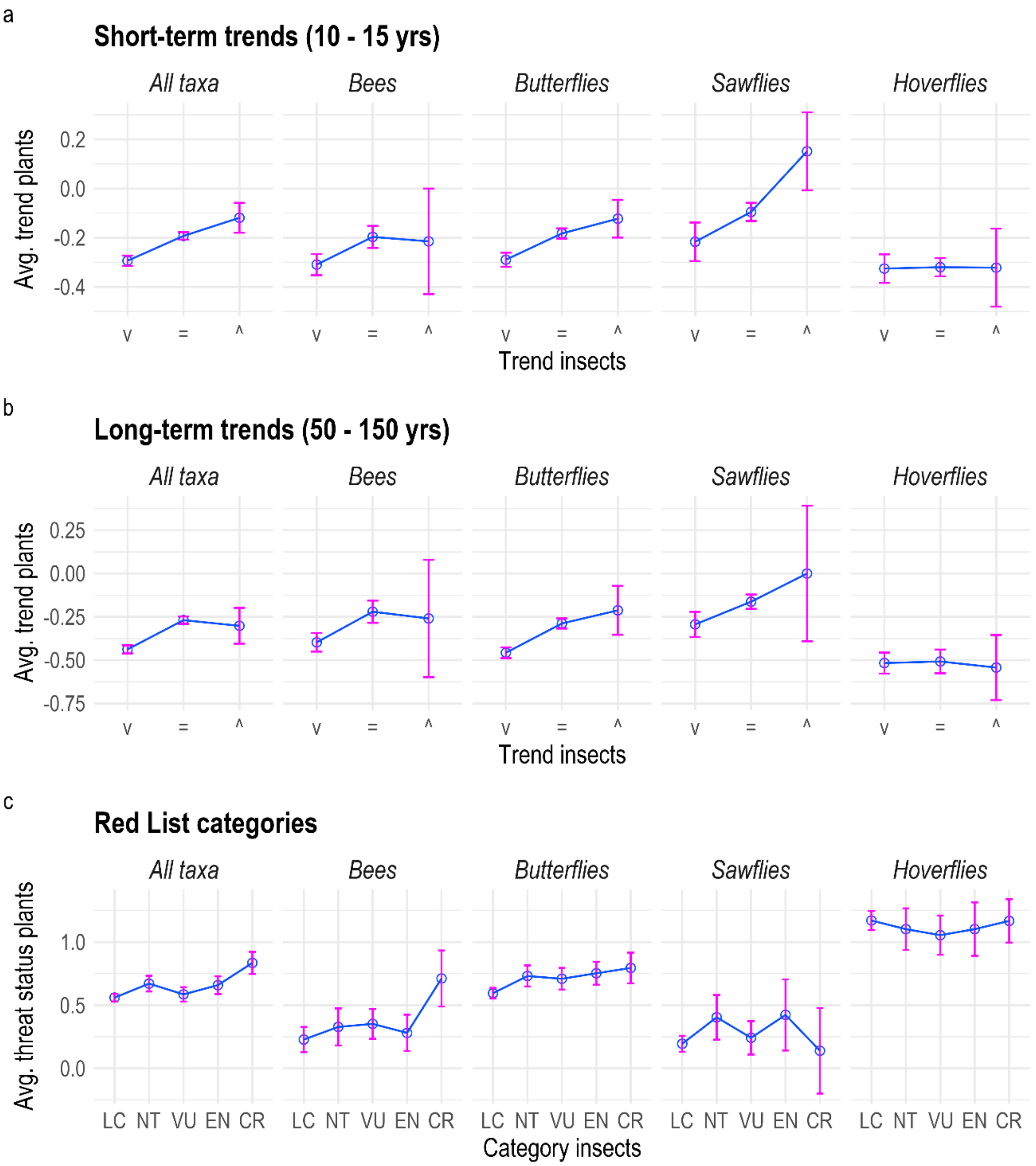

Fig. 1: Positive relationships between short- and long-term population trends, and threat statuses of insect species and their host plant species derived from respective Red Lists. (a) Short- and (b) long-term population trend and (c) threat status of insect species against the respective means of host plants. For (a) and (b), higher y-axis values signal positive population trends; for (c), they indicate increased threat statuses. Symbols “v”, “=” and “^” in (a) and (b) indicate declining, stable and increasing population trends, respectively. LC, NT, VU, EN and CR in (c) indicate IUCN Red List categories that were translated from the German red-listing system (see Methods), indicating Least Concern, Near Threatened, Vulnerable, Endangered and Critically Endangered, respectively. Displayed are means (blue dots) and 95% confidence intervals

(magenta error bars). Sample sizes for “All taxa”, Apiformes (bees), Lepidoptera (butterflies and moths), Symphyta (sawflies) and Syrphidae (hoverflies) and host plants are provided in Table S1. Raw data plots are provided in Fig. S1. Pairwise comparisons are provided in Fig. S2.

Insect diversity may be resilient to the loss of threatened flora. Given the ties between insect and plant population change, we next examined the potential impact on insect diversity in the event that all currently threatened plants were to become extinct. This analysis, focusing on species extinction or survival rather than population trends, assesses the survival of insect species following the progressive loss of threatened host plants. Starting with the most threatened (CR) and moving to the least (LC), we removed host plants, and an insect species was deemed extinct if it lost all its host plants at any given step. Removing threatened plants had little effect on the percentage of surviving insect species; 97% of all insect species combined across taxa survived the removal of all threatened host plant species (Fig. 2a). Across insect taxa, the pattern held: bees lost only 4% of their diversity, butterflies and moths 1.7%, sawflies 6.5%, and hoverflies 0.3%, following the loss of all threatened host plants. Nonetheless, this does not mean that threatened host plants were unimportant for sustaining insect diversity. Reversing the removal order (from LC to CR) showed that threatened plants alone can support a substantial portion of insect diversity: 39% with just CR plants and 69% with all threatened plants. This highlights the potential of threatened plant restoration to enhance insect diversity. Nevertheless, these findings suggest that insect extinctions may be buffered against plant extinctions, as insects often utilize additional non-threatened plant species, not solely depending on those currently threatened. This resilience was similar under a different scenario, when species removal was based on range size (Fig. 2b).

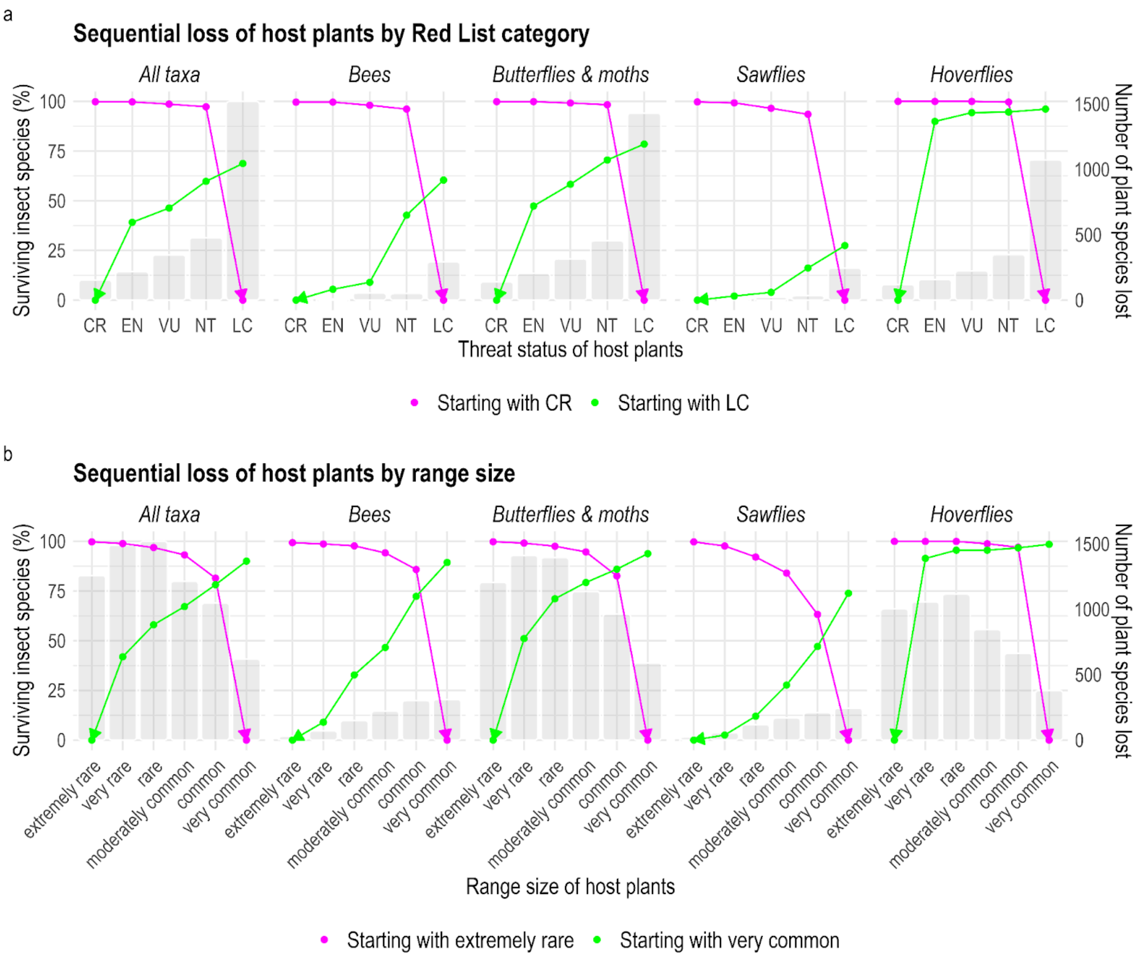

Fig. 2: Insect diversity shows resilience to the loss of threatened and rare host plants. (a) Insect species survival with progressive loss of host plants by Red List category, starting from the most threatened (CR) to the least (LC) in magenta (right arrow), and conversely from least to most threatened (LC to CR) in green (left arrow). **(b)** Insect species survival with progressive loss of host plants by range size, starting from the narrowest (extremely rare) to the widest (very common) in magenta (right arrow), and the reverse sequence in green (left arrow). Percentage of surviving insect species is indicated on the left y-axis. Percentage of persisting insect species is indicated on the left y-axis, while the gray bars indicate the number of plant species removed at each step, with the corresponding scale on the right y-axis. For Apiformes and Symphyta, the bars representing CR and EN categories are minimal as the count falls below 10 species (e.g. only 6 CR host plants for Symphyta). Abbreviations: LC, Least Concern; NT, Near Threatened; VU, Vulnerable; EN, Endangered; CR, Critically Endangered.

Keystone species. To better understand why insect taxa were largely resilient to threatened and rare host plant extinctions, we explored the role of keystone species. We found that plant-insect interactions were highly skewed. A few plant genera supported hundreds of insect species, while most interacted with only one to 20 insect species (Fig. 3a). There was substantial evidence for keystone plant genera, with 16% of plant genera supporting 90% of insect species across all taxa investigated. Just 13% of host plant genera (30 out of 237 plant genera interacting with bees) were needed to support 90% of bee species. For butterflies and moths, 16% of plant genera sustained 90% of species. Sawflies, known for their high specialization, required 36% of plant genera for 90%

diversity support. Conversely, hoverflies, which are less specialized, needed only 2% of plant genera (i.e., only umbellifers) to sustain 90% of their species (Fig. 3b). The most important keystone plant genera included cruciferous herbs (mustard plants and cabbages; *Sinapis* and *Brassica*) and knapweeds (*Centaurea*) for bees; predominantly woody plants, such as willows (*Salix*), oaks (*Quercus*), and birches (*Betula*) for butterflies and moths; again birches (*Betula*), willows (*Salix*), and plums cherries and allies (*Prunus*) for sawflies; and umbellifers (*Anthriscus, Chaerophyllum, Heracleum*) for hoverflies (Fig. 3c). To provide a more detailed focus, we included a restoration scenario listing 20 plant species that cumulatively maximize the number of distinct insect species (see Table S2).

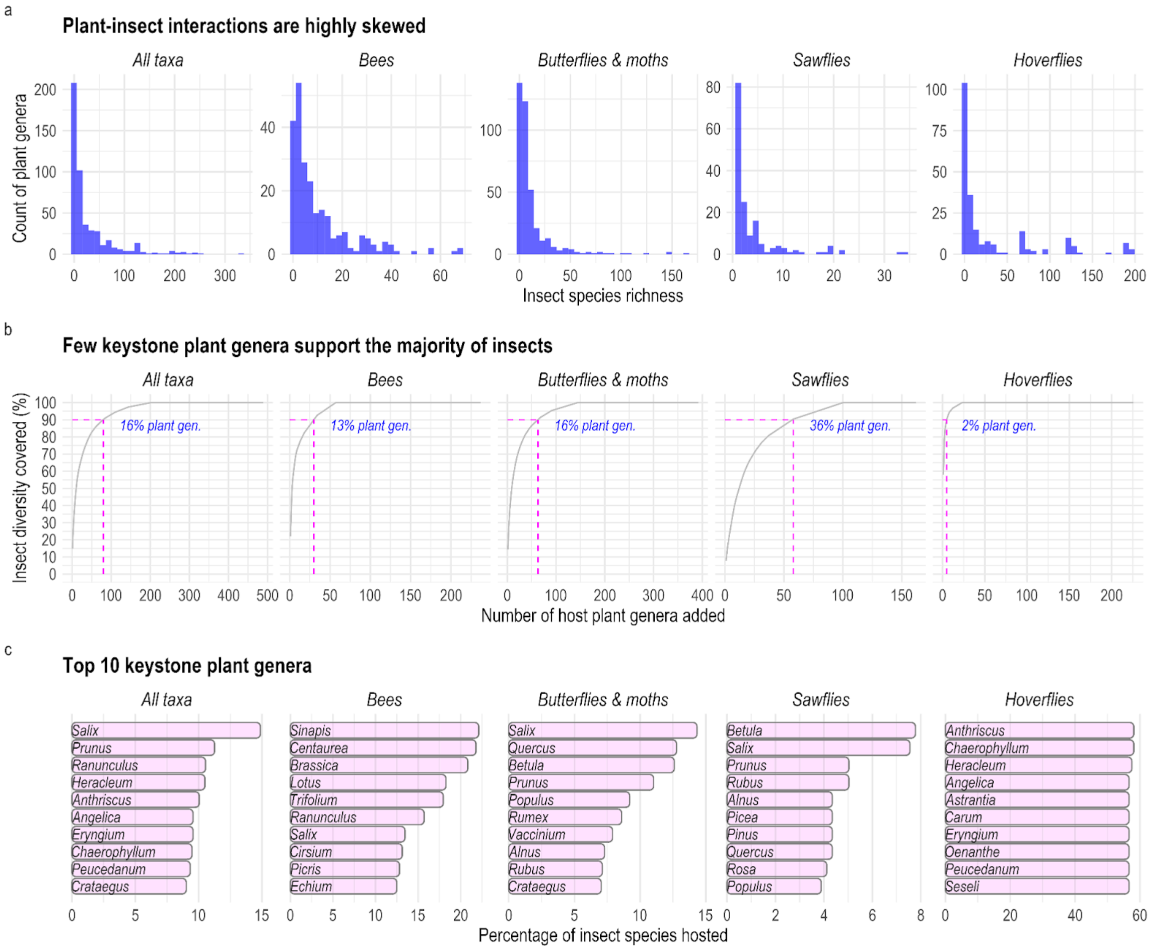

Fig. 3: A few plant genera can sustain the majority of insect diversity. **(a)** Histograms of the count of plant genera and the number of interacting insect species. **(b)** Accumulation curves of the percentage of insect diversity covered by adding new plant genera, so that each additional new plant genus maximizes the number of additional unique insect species. Stroked magenta lines and blue text annotations indicate the number of plant genera needed to sustain 90% of insect diversity. **(c)** Top 10 keystone species sorted by the absolute percentage of insect species in each taxa that a given plant genera sustains (e.g. Sinapis sustains 69 out of 312 bee species or 22%). See Supplementary Data 1 for a list of the relative contributions for all plant genera.

Asymmetrical interactions as insurance-policy for insect diversity. Finally, we examined the possibility of asymmetrical interactions, testing whether specialized insects might use less threatened plants. In the dataset of our study 16.4% of all insect species were monolectic or monophagous (specializing on a single host plant species). Sawflies showed the highest level of monophagy, with 45% specializing on a single plant species (Fig. 4a and Table S2). In contrast, hoverflies were predominantly polyphagous (using a wide range of host plants; 65%), with only 3% being monophagous. We evaluated the average threat status of host plants for specialized insects versus those with a broad host range. Contrary to the assumption that specialized insects often depend on specialized plants, we found that monophagous insects utilized plants with the lowest average threat status across the specialization spectrum. In contrast, polyphagous insects more frequently used plants with higher average threat statuses (Fig. 4b). Except for sawflies, monophagous insects consistently utilized significantly less threatened plants compared to polyphagous insects across all taxa (Fig. 4c). This suggests that specialized insects are often using non-threatened and thus rather common plant species, buffering them against extinction. Contrastingly, generalists, with a wide range of host plants, also interact with threatened and less common plant species.

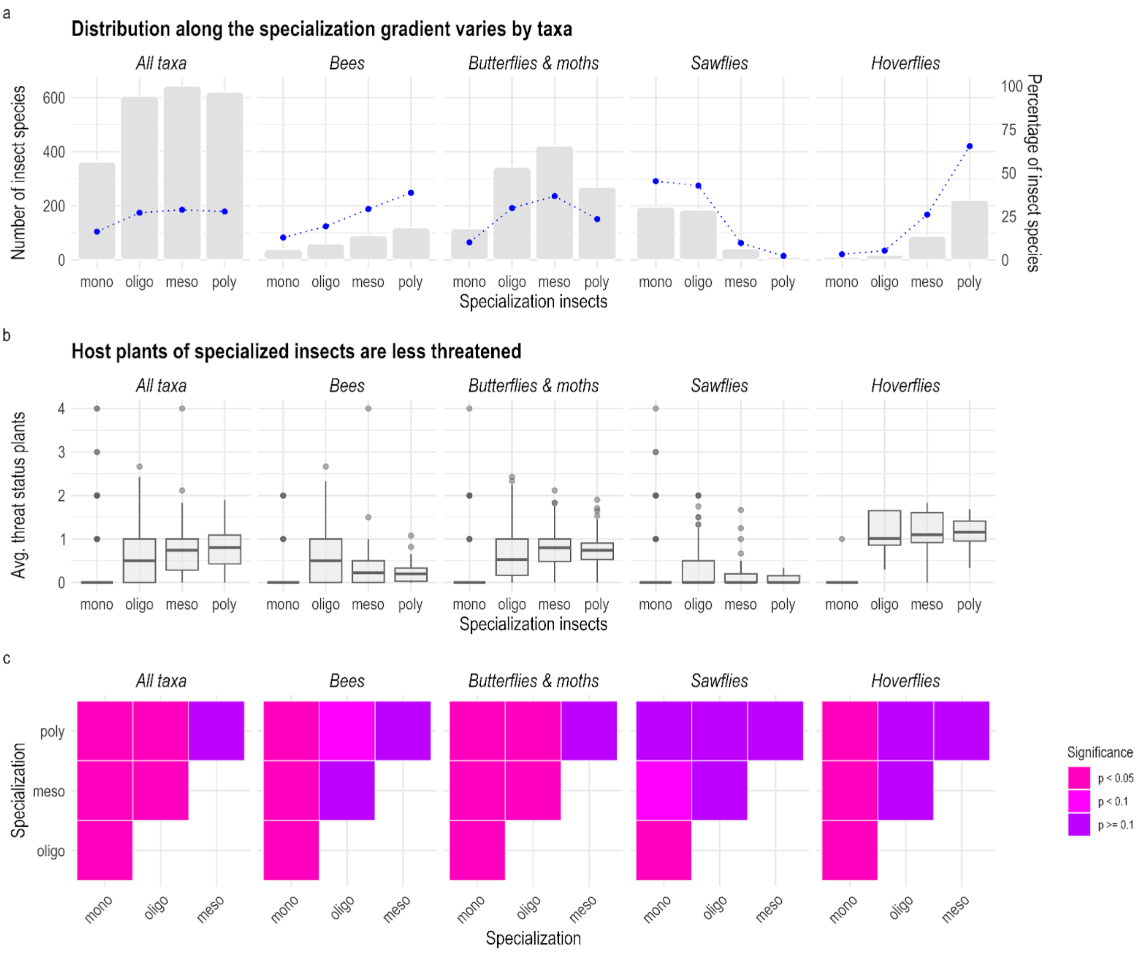

Fig. 4: The average Red List threat status of host plant species sustaining specialist insects is lower than that of generalist insects. (a) Bar plots of the number (left y-axis) and percentage (right y-axis; blue points) of insect species along the specialization gradient (see Methods for a description of the specialization gradient). **(b)** Boxplots of the degree of insect specialization against the average threat status of host plants. Box plots bound the interquartile range (IQR) divided by the median and whiskers extend up to a maximum of 1.5 × IQR beyond the box. Gray points beyond the whiskers indicate outliers. **(c)** Heatmap of pairwise comparisons of specialization levels in relation to average threat status of host plants, indicating the p-value from a

non-parametric pairwise Wilcoxon signed-rank test (tiles in pink have $p<0.05$, tiles in magenta have $p<0.1$, tiles in lilac have $p>=0.1$).

Discussion

Here, we synthesized interaction data of plants and insects with their respective population trends in Germany. Our findings indicate a positive correlation between population trends of bees, butterflies and moths, sawflies and their host plants, but not for hoverflies. Yet, when we simulated extinctions of threatened host plants, we found 97% of insect species may potentially survive by relying on alternative or non-threatened host plants. There were a few keystone plant genera, constituting only 16% of all host plant genera studied, that sustained 90% of insect diversity. Moreover, insect specialists tended to rely on non-threatened host plants. Together, this suggests that while the abundance declines of host plant species might lead to declining insect abundances, the general presence of common and non-threatened alternative host plants may potentially buffer against a collapse in insect diversity from plant extinctions.

Our results, showing parallel population trends between host plants and their associated insect species, align with earlier research from the Netherlands and the United Kingdom (Biesmeijer et al. 2006, Scheper et al. 2014). In addition, a few studies show that local plant extinctions in southern Germany preceded the local extinction of highly specialized butterfly species (Pearse and Altermatt 2013). Yet, in most cases, a clear causal relationship remains elusive, and accurately disentangling the role of multiple extinction drivers is challenging. Moreover, it remains unclear whether population trends of insect species follow population trends of their host plants or vice versa (Kehoe et al. 2021), or whether they are driven by the same external factors like habitat loss (Brondízio et al. 2019). In our study, we also cannot establish any clear causal connection. But the varying correlation strengths between insect and host plant population trends among insect taxa support the hypothesis that more specialized taxa are more closely dependent on host plant population trends. For example, sawfly trends closely paralleled plant trends, while hoverflies showed no correlation. Most sawfly species are mono- or oligophagous (88%). Hoverflies, on the other hand, are hardly specialized, with only 9% considered mono- or oligolectic. This generalist foraging behavior allows hoverflies to be relatively independent of single plant species and their population trends. Consequently, this may explain why we did not observe parallel insect-plant declines in hoverflies, but more generally in specialized insect taxa, and could be indicative of a causal link.

Population trends of plants appeared to matter for insect taxa with high specialization levels. Yet, seemingly contrary to the hypothesis that specialized insects are more vulnerable due to their dependence on declining plants, our simulations of the extinction of threatened (or narrow-ranged) plant species resulted in only a minor reduction (3%) in insect diversity, even in specialized taxa. This is likely due to host plant redundancy, also documented in previous studies (Sanders et al. 2018). Specifically, most insect species in our study relied on several host plant species and genera. Across all taxa, 83% of species were oligo- to polylectic/-phagous. In addition, a large fraction of plant species in our dataset is still non-threatened (44%). This suggests a high statistical likelihood that at least one of an insect's host plants is categorized as non-threatened, where such redundancy may act as a buffer, protecting insect species from extinction. Nonetheless, while alternative or non-threatened host plants may exist, this does not imply that the strong decline of many plant species is inconsequential for insect abundance. Many insect species use threatened plants. Our data indicate that critically endangered plant species alone are used by about 40% of all insect species. For butterflies and moths, rare plant species can sustain almost 75% of diversity. It follows that the decline of such species can evidently affect interacting insect species.

Consistent with prior research, our findings indicate that a small number of keystone plant genera can support the majority of insect diversity (Warzecha et al. 2018; Narango et al. 2020; Purvis et al. 2021), with 16% of all host plant genera studied sustaining 90% of insect diversity across taxa. The differences among insect taxa in relation to the importance of keystone plant genera coincided again with specialization levels (Supplement S1): 90% of hoverfly species, which are mostly generalist symbiotic pollen and nectar collectors (Penney et al. 2012), are supported by only 2% of their host plant genera, whereas 36% of host plant genera are required to support specialist herbivorous taxa, such as sawfly larvae. Notwithstanding, the pattern that certain plant genera support a broad range of insect diversity does not necessarily mean they are the optimal food sources for those insects. They might reflect host plant shifts, spurred by the decline of primary host plant species (Agosta 2006). For instance, a bee species might depend 80% on a declining plant species, resorting to keystone plants only when the preferred host plant is unavailable. Therefore, even with keystone genera present, the decline in plant diversity could still result in reduced fitness for insect species (e.g., due to the lower nutritional value of alternative host plants). Studies are needed to evaluate the effectiveness of keystone plant genera in restoration efforts, highlighting that while they may be beneficial for many insects, they may often serve as secondary choices and thus may not fully compensate for rare and threatened species in a restoration mixture.

Our results also lend support to the asymmetry hypothesis (Vázquez and Aizen 2004), for which comprehensive tests are hitherto scarce. Monolectic/-phagous insect species tended to forage primarily on non-threatened plant species, while polylectic/-phagous species used plants that had on average a higher threat status. It seems that highly specialized monolectic/-phagous species compensate for their dependency on a single food source by relying on mainly non-threatened plant species. Yet, our findings also reveal that specialized insect species (mono- to mesolectic/-phagous) are more threatened than generalists (polylectic/-phagous; Fig. S3), echoing previous research (Koh et al. 2004). This suggests the most specialized insects may not be primarily threatened due to declines in host plants, but due to other anthropogenic factors. Generalists, on the other hand, may be more buffered against such factors through high host plant plasticity or other hidden, covarying characteristics. These interpretations must, however, be viewed cautiously: the study's coarse, Germany-wide approach neglects regional population trends. Plants, while not nationally red-listed, may still be declining in areas where they coexist with these specialist insects. Nevertheless, these findings indicate that the more common, non-threatened plant species are critical to sustain highly specialized insects.

Clearly, our study comes with limitations. In addition to neglecting regional population trends, insect species at different sites may exhibit different trophic interactions (Tallamy et al. 2021), leading to an inflated host plant portfolio for a single insect species when viewed from a species-wide perspective, as in this study. Furthermore, any interaction data are likely biased. For many taxa, interaction data are scarce, particularly for small, less charismatic, or rare species, which are likely undersampled. Moreover, interaction data are prone to errors; for instance, an insect or its larva on a plant does not necessarily indicate foraging behavior (Taeger et al. 1998). The sources underlying the data we used are not always provided, which makes it difficult to classify how trustworthy certain interactions are. The incomplete nature of the data underscores the need for cautious interpretation. Finally, our focus on native plant interactions, neglecting the novel interactions with non-native plants in Germany, may mask potential buffering effects against native host plant decline (Bezemer et al. 2014). Yet, we believe the consistencies across the four studied insect taxa lend a degree of robustness to our findings despite these shortcomings, allowing our study to offer a macroecological perspective on the impact of plant declines on insect diversity.

Conclusion

Our study highlights the complex interactions between plants and insects, revealing partial alignments in their population trends. Yet, since insects frequently interact with multiple or common, non-threatened plant species, this could help protect insect diversity against the extinction of threatened and less common plant species. This appears to be also true for insect specialists, which tend to specialize in plant species that are, up to now, non-threatened. While a few common keystone plant genera support symbiotic pollinators, a more diverse range of plants is essential for specialized herbivores, underlining the importance of high plant diversity for maintaining insect herbivore diversity. This is crucial, given the narrow focus of media and restoration efforts on insect pollinators. Our study also holds practical insights for restoration, pinpointing keystone plant genera as potential food sources to support the four insect taxa examined. However, it is clear that viable insect populations require more than just food resources and these need to be considered in restoration as well. In sum, our findings indicate that the declining abundance of many plant species can contribute to insect decline but that the loss of rare and threatened plant species will not necessarily lead to a collapse in insect diversity.

Methods

Data synthesis. We compiled interaction data for both insect pollinators (Apiformes, Syrphidae) and herbivorous insects (Lepidoptera, Symphyta). Supplement S1 provides ecological details for each insect taxon. We compiled interaction data for these taxa from separate sources. The Apiformes-plant-interaction data were text-mined from Paul Westrich's webpage (Westrich 2023) which compiles data and information regarding most bee species occurring in Germany which allows to have a digital access to the interaction data published in ‘Die Wildbienen Deutschlands’ (Westrich 2019). Similarly, the Lepidoptera-plant-interaction data were text-mined from the 'Lepidoptera Mundi' webpage (Jonko 2023), which hosts worldwide lepidopteran species data compiled from international data bases and literature. The Symphyta-plant-interaction data were provided by the Senckenberg Deutsches Entomologisches Institut (SDEI) and cross-referenced with ‘Electronic World Catalog of Symphyta’ (Taeger et al. 2018) and 'Sawflies of Europe' (Lacourt 2020). Only plant-insect interactions deemed highly likely by the SDEI were included. The Syrphidae-plant-interaction data were compiled based on the 'Species Accounts of European Syrphidae – 2020' (Speight 2020). Text-mining was conducted in R version 4.2.2 (R Core Team 2022) using the packages rvest (Wickham 2022) and xml2 (Wickham et al. 2021).

For each insect taxon, we downloaded the most recent Red List (RL) data from the German Red List Center's website (Das Rote-Liste Zentrum 2018). For butterflies and moths, RL data were provided for the groups of snout moths (Pyralidae) with 273 species (Nuss 2011), diurnal butterflies (Papilionoidea and Hesperioidea) with 189 species (Reinhardt and Bolz 2011b), geometer moths (Geometridae and Drepanidae) with 450 species (Reinhardt and Bolz 2011a) and owlet moths (Noctuidae, Pantheidae, Lymantriidae and Nolidae) with 554 species (Wachlin and Bolz 2011). The RL data regarding bees (Apiformes) counts 561 species (Westrich et al. 2011), hoverflies (Syrphidae) 467 species (Ssymank et al. 2011) and sawflies (Symphyta) 760 species (Liston et al. 2011), respectively. Finally, we downloaded the most recent RL for vascular plants (Metzing et al. 2018). From these RLs, we extracted species' short-term population trend, long-term population trend, RL threat status, and range size. We integrated these RL data with our interaction data to assign population trends, threat statuses and range sizes to interacting plant and insect species in Germany. Our final dataset comprised 156,735 interactions of 2,239 insect species and 3,429 plant species. Not all plant or insect species had data available for all Red List categories, but the majority had data for RL indicators (Table S4).

Data carpentry. Some of the aforementioned data sources resolved host plants only to the genus level (Lepidoptera and Syrphidae) or functional group level (Syrphidae). In such cases, plant genera or functional groups were expanded to all plant species in a given genus or functional group listed in the German RL. This was necessary to calculate the average population trend and threat status of host plants, as these indicators are given by species and not by genus or functional group level. To calculate averages for host plants, it was necessary to convert these indicators (i.e., short-term trends, long-term trends and most recent RL threat status) from a categorical to a numerical scale (Table 1). For insects, we continued to use the categorical RL indicators (which have levels identical to those for plants). But we consolidated the three levels of negative population trends into a single "decline" category, due to the small sample sizes in some of the more severe decline categories.

Table 1: Conversion of Red List plant population trends and threat status from categorical to numeric for calculating average host plant trends. The threat statuses and population trends used in this study were derived from the German Red List, with their abbreviated symbols presented in brackets. Also included are English translations of the respective categories and the corresponding IUCN categories for the German threat statuses. These categorical indicators were converted into numeric variables. Species experiencing a population decrease of unknown magnitude were classified as experiencing a moderate decrease. Similarly, species threatened to an unknown extent were classified as vulnerable. This conservative approach aimed to prevent the overestimation of uncertain population declines or uncertain threat statuses.

German Red List indicator	Translation	Numeric
Short-term trend		

Sehr starke Abnahme (vvv)	Very strong decrease	-3
Starke Abnahme (vv)	Strong decrease	-2
Abnahme mäßig oder im Ausmaß unbekannt ((v))	Moderately or unknown decrease	-1
Gleich bleibend (=)	Stable	0
Deutliche Zunahme (^)	Clear increase	1
Daten ungenügend (?)	Data deficient	NA
Long-term trend		
Sehr starker Rückgang (<<<)	Very strong decrease	-3
Starker Rückgang (<<)	Strong decrease	-2
Mäßiger Rückgang (<), Rückgang, Ausmaß unbekannt ((<))	Moderately or unknown decrease	-1
Gleich bleibend (=)	Stable	0
Deutliche Zunahme (>)	Clear increase	1
Daten ungenügend (?)	Data deficient	NA
RL threat status		
Ungefährdet (*)	LC (least concern)	0
Vorwarnliste (V); Extrem selten (R)	NT (near threatened)	1
Gefährdet (3), Gefährdung unbekannten Ausmaßes (G)	VU (vulnerable)	2
Stark gefährdet (2)	EN (endangered)	3
Vom Aussterben bedroht (1)	CR (critically endangered)	4
Ausgestorben oder verschollen (0)	RE (regionally extinct)	5

Insect specialization. We used our interaction data to classify species according to their level of trophic specialization. We assigned species to four groups: mono-, oligo-, meso- and polylectic/-phagous insect species. This classification system reflects a gradient of specialization from strictly one host plant species to many host plant species of different genera of many plant families. Thresholds defining this taxonomic food specialization gradient followed Cane and Sipes (2006). Monolectic/monophagous insects were defined as species relying on one plant species (from one genus, from one family). Oligolectic/oligophagous insects were defined as species relying on more than one plant species across four or fewer plant genera within one plant family. Mesolectic/mesophagous insects were defined as species relying on more than one plant species across more than one plant genus within three or fewer plant families. Polylectic/polyphagous insects were defined as species relying on more than one plant species across more than one plant genus within more than one plant family.

Analyses. First, we examined the relationship between population trends (short-term and long-term) and RL threat statuses of insect species and their host plants. For each insect species, we averaged these indicators across its host plants to calculate the average population trend and threat status of a given insect species' host plant portfolio. We then regressed these host plant averages separately against the short- and long-term population trends (increasing (^), stable (=), decreasing (v)) and RL threat statuses (LC, NT, VU, EN, CR) of insect species, using linear models. We then calculated pairwise contrasts between insect species' population trends. For RL threat status, we only calculated pairwise contrasts against the reference level LC, to limit the number of possible pairwise comparisons. To calculate contrasts, we used the emmeans package (Lenth 2022).

Second, we examined the consequences of threatened plant extinctions on insect diversity, by simulating sequential extinctions initiating from the most (CR) to the least (LC) threatened plant species. At each step, we tallied the proportion of insect species that still had surviving host plant species in their interaction portfolio. We also examined the reverse scenario, removing plant species from the least (LC) to the most (CR) threatened, to gain insights into the ecological importance of threatened plants and to assess whether losing LC species impacts insect diversity more negatively than the loss of threatened species. These analyses were conducted for all insect species collectively and for each insect taxon separately. We repeated the process, substituting plant threat status with range size, a categorical variable from the German RL that spans from extremely rare to very common.

Third, we examined the importance of individual plant genera for the insect community aiming to identify keystone genera and determine the minimum portion of plants theoretically required to sustain insect diversity. To identify keystone genera, we summed the number of insect species that had trophic interactions with each plant genus and assessed the coverage of insect diversity by each genus, ranking them accordingly. To determine the minimum set of plant genera needed to maintain insect diversity, we developed an optimization algorithm. This algorithm begins with the genus supporting the highest number of insect species and sequentially incorporates additional genera, each time selecting the one that adds the most unique insect species, thereby maximizing diversity with the fewest genera.

Fourth, we tested the asymmetry hypothesis to determine if more specialized insects rely on less threatened plant species, with RL threat status integrating both species' population trends and commonness/rarity. We regressed the average host plant threat status of insects against insect specialization level. Given that the assumptions for a linear model were not met, due to deviation from normality in the residuals, we used a non-parametric test. Specifically, we used a Wilcoxon signed-rank test to assess the statistical certainty of the pairwise differences between specialization levels in relation to the threat status of their host plants. We then tested whether specialized insects were more threatened than generalists by regressing insect threat status against their specialization level and testing for pairwise differences using a Wilcoxon signed-rank test.

Data and code availability: All R code for text-mining, data synthesis and carpentry, analysis and visualization are provided on GitHub at https://github.com/istaude/plant-insect-trends

Acknowledgements: We thank Roel van Klink and Josiane Segar for their valuable feedback on the manuscript. Our sincere gratitude goes to Martin Speight for generously sharing his data on hoverfly-plant interactions, and to Andreas Täger from the SDEI for providing the sawfly-plant interaction data.

Conflict of interest: The authors declare no conflict of interest.

References

Agosta, S.J. (2006). On ecological fitting, plant–insect associations, herbivore host shifts, and host plant selection. *Oikos*, 114, 556–565.

Bezemer, T.M., Harvey, J.A. & Cronin, J.T. (2014). Response of native insect communities to invasive plants. *Annual review of entomology*, 59, 119–141.

Biesmeijer, J.C., Roberts, S.P.M., Reemer, M., Ohlemüller, R., Edwards, M. & Peeters, T. *et al.* (2006). Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands. *Science*, 313, 351–354.

Breed, C.A., Morelli, A., Pirk, C.W.W., Sole, C.L., Du Toit, M.J. & Cilliers, S.S. (2022). Could Purposefully Engineered Native Grassland Gardens Enhance Urban Insect Biodiversity? *Land*, 11, 1171.

Brondízio, E.S., Settele, J., Díaz, S. & Ngo, H.T. (eds.) (2019). *The global assessment report of the intergovernmental science-policy platform on biodiversity and ecosystem services.* Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), Bonn.

Burger, H., Dötterl, S. & Ayasse, M. (2010). Host-plant finding and recognition by visual and olfactory floral cues in an oligolectic bee. *Functional Ecology*, 24, 1234–1240.

Cane, J.H. & Sipes, S. (2006). Characterizing floral specialization by bees: analytical methods and a revised lexicon for oligolecty. *Plant-pollinator interactions: from specialization to generalization*.

Carroll, T., Stafford, R., Gillingham, P.K., Bullock, J.M., Brown, D. & Brown, M. *et al.* (2023). Correlated biodiversity change between plant and insect assemblages resurveyed after 80 years across a dynamic habitat mosaic. *Ecology and Evolution*, 13, e10168.

Das Rote-Liste Zentrum (2018). Die Roten Listen. URL https://www.rote-liste-zentrum.de/de/Download-Wirbellose-Tiere-1875.html.

Eichenberg, D., Bowler, D.E., Bonn, A., Bruelheide, H., Grescho, V. & Harter, D. *et al.* (2020). Widespread decline in Central European plant diversity across six decades. *Global Change Biology*, 27, 1097–1110.

Hallmann, C.A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N. & Schwan, H. *et al.* (2017). More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PLOS ONE*, 12, e0185809.

Jonko, C. (2023). Lepidoptera Mundi. URL https://lepidoptera.eu/.

Kehoe, R., Frago, E. & Sanders, D. (2021). Cascading extinctions as a hidden driver of insect decline. *Ecological Entomology*, 46, 743–756.

Koh, L.P., Sodhi, N.S. & Brook, B.W. (2004). Co-Extinctions of Tropical Butterflies and their Hostplants. *Biotropica*, 36, 272–274.

Lacourt, J. (2020). *Sawflies of Europe.* N.A.P. Editions, Verrières-le-Buisson.

Lenth, R. (2022). emmeans: Estimated marginal means, aka least-squares means. R package version 1.7. 2.

Liston, A.D., Jansen, E., Blank, S.M…, Kraus, M. & Taeger, A. (2011). Rote Liste und Gesamtartenliste der Pflanzenwespen (Hymenoptera: Symphyta) Deutschlands. *Rote Liste gefährdeter Tiere, Pflanzen und Pilze Deutschlands*, 491--556.

Majewska, A.A. & Altizer, S. (2020). Planting gardens to support insect pollinators. *Conservation Biology*, 34, 15–25.

Mata, L., Andersen, A.N., Morán-Ordóñez, A., Hahs, A.K., Backstrom, A. & Ives, C.D. *et al.* (2021). Indigenous plants promote insect biodiversity in urban greenspaces. *Ecological applications : a publication of the Ecological Society of America*, 31, e02309.

Metzing, D., Garve, E., Matzke-Hajek, G., Adler, J., Bleeker, W. & Breunig, T. *et al.* (2018). Rote Liste und Gesamtartenliste der Farn-und Blütenpflanzen (Trachaeophyta) Deutschlands. *Rote Liste gefährdeter Tiere, Pflanzen und Pilze Deutschlands*, 13–358.

Moir, M.L., Hughes, L., Vesk, P.A. & Leng, M.C. (2014). Which host-dependent insects are most prone to coextinction under changed climates? *Ecology and Evolution*, 4, 1295–1312.

Narango, D.L., Tallamy, D.W. & Shropshire, K.J. (2020). Few keystone plant genera support the majority of Lepidoptera species. *Nature Communications*, 11, 5751.

Nicholls, C.I. & Altieri, M.A. (2013). Plant biodiversity enhances bees and other insect pollinators in agroecosystems. A review. *Agron. Sustain. Dev.*, 33, 257–274.

Nuss, M. (2011). Rote Liste und Gesamtartenliste der Zünslerfalter (Lepidoptera: Pyraloidea) Deutschlands. *Rote Liste gefährdeter Tiere, Pflanzen und Pilze Deutschlands*, 327--370.

Ødegaard, F., Diserud, O.H. & Østbye, K. (2005). The importance of plant relatedness for host utilization among phytophagous insects. *Ecology Letters*, 8, 612–617.

Pearse, I.S. & Altermatt, F. (2013). Extinction cascades partially estimate herbivore losses in a complete Lepidoptera--plant food web. *Ecology*, 94, 1785–1794.

Purvis, E.E., Best, L.R. & Galpern, P. (2021). Identifying key forage plants to support wild bee diversity and a species at risk in the Prairie Pothole Region. *Insect Conservation and Diversity*, 14, 851–861.

R Core Team (2022). R: A language and environment for statistical computing. URL https://www.R-project.org/.

Reinhardt, R. & Bolz, R. (2011a). Rote Liste und Gesamtartenliste der Spanner, Eulenspinner und Sichelflügler (Lepidoptera: Geometridae et Drepanidae) Deutschlands. *Rote Liste gefährdeter Tiere, Pflanzen und Pilze Deutschlands*, 165–194.

Reinhardt, R. & Bolz, R. (2011b). Rote Liste und Gesamtartenliste der Tagfalter (Rhopalocera)(Lepidoptera: Papilionoidea et Hesperioidea) Deutschlands. *Rote Liste gefährdeter Tiere, Pflanzen und Pilze Deutschlands*, 165–194.

Sanders, D., Thébault, E., Kehoe, R. & van Frank Veen, F.J. (2018). Trophic redundancy reduces vulnerability to extinction cascades. *Proceedings of the National Academy of Sciences of the United States of America*, 115, 2419–2424.

Scheper, J., Reemer, M., van Kats, R., Ozinga, W.A., van der Linden, G.T.J. & Schaminée, J.H.J. *et al.* (2014). Museum specimens reveal loss of pollen host plants as key factor driving wild bee decline in The Netherlands. *Proceedings of the National Academy of Sciences of the United States of America*, 111, 17552–17557.

Schowalter, T.D. (2013). Insects and Sustainability of Ecosystem Services. CRC Press, Hoboken.

Schuldt, A., Ebeling, A., Kunz, M., Staab, M., Guimarães-Steinicke, C. & Bachmann, D. *et al.* (2019). Multiple plant diversity components drive consumer communities across ecosystems. *Nature Communications*, 10, 1460.

Speight, M.C. (2020). Species Accounts of European Syrphidae.

Ssymank, A., Doczkal, D., Rennwald, K. & Dziock, F. (2011). Rote Liste und Gesamtartenliste der Schwebfliegen (Diptera: Syrphidae) Deutschlands. *Rote Liste gefährdeter Tiere, Pflanzen und Pilze Deutschlands*, 13--83.

Taeger, A., Altenhofer, E., Blank S.M., Jansen, E. & Ritzau, C. (1998). Kommentare zur Biologie, Verbreitung und Gefährdung der Pflanzenwespen Deutschlands (Hymenoptera, Symphyta). In: *Pflanzenwespen Deutschlands (Hymenoptera, Symphyta). Kommentierte Bestandsaufnahme,* pp. 49–135.

Taeger, A., Liston, A.D., Prous, M., Groll, E.K., Gehroldt, T. & Blank S.M. (2018). ECatSym – Electronic World Catalog of Symphyta (Insecta, Hymenoptera). Program version 5.0 (19 Dec 2018), data version 40 (23 Sep 2018). URL https://sdei.de/ecatsym/.

Tallamy, D.W., Narango, D.L. & Mitchell, A.B. (2021). Do non-native plants contribute to insect declines? *Ecological Entomology*, 46, 729–742.

van Klink, R., Bowler, D.E., Gongalsky, K.B., Shen, M., Swengel, S.R. & Chase, J.M. (2023). Disproportionate declines of formerly abundant species underlie insect loss. *Nature*, 1–6.

van Klink, R., Bowler, D.E., Gongalsky, K.B., Swengel, A.B., Gentile, A. & Chase, J.M. (2020). Meta-analysis reveals declines in terrestrial but increases in freshwater insect abundances. *Science*, 368, 417–420.

Vázquez, D.P. & Aizen, M.A. (2004). Asymmetric specialization: A pervasive feature of plant–pollinator interactions. *Ecology*, 85, 1251–1257.

Wachlin, V. & Bolz, R. (2011). Rote Liste und Gesamtartenliste der Eulenfalter, Trägspinner und Graueulchen (Lepidoptera: Noctuoidea) Deutschlands. *Rote Liste gefährdeter Tiere, Pflanzen und Pilze Deutschlands*, 197–239.

Wagner, D.L., Grames, E.M., Forister, M.L., Berenbaum, M.R. & Stopak, D. (2021). Insect decline in the Anthropocene: Death by a thousand cuts. *Proceedings of the National Academy of Sciences of the United States of America*, 118.

Warzecha, D., Diekötter, T., Wolters, V. & Jauker, F. (2018). Attractiveness of wildflower mixtures for wild bees and hoverflies depends on some key plant species. *Insect Conserv Diversity*, 11, 32–41.

Westrich, P. (2019). *Die Wildbienen Deutschlands.* 2nd edn. Ulmer, Stuttgart (Hohenheim).

Westrich, P. (2023). Fazination Wildbienen. URL https://www.wildbienen.info.

Wickham, H. (2022). Easily Harvest (Scrape) Web Pages. URL https://CRAN.R-project.org/package=rvest.

Wickham, H., Hester, J. & Ooms, J. (2021). xml2: Parse XML. URL https://CRAN.R-project.org/package=xml2.

Witt, R. (2013). Natur für jeden Garten. Das Einsteiger-Buch ; 10 Schritte zum Natur-Erlebnis-Garten ; Planung, Pflanzen, Tiere, Menschen, Pflege ; mit Biodiversitätstest. 1st edn. Naturgarten-Verl., Ottenhofen.

Zuefle, M.E., Brown, W.P. & Tallamy, D.W. (2008). Effects of non-native plants on the native insect community of Delaware. *Biol Invasions*, 10, 1159–1169.

Supplementary Material
for
Insects decline with host plants but co-extinctions seem unlikely

Marlon Bassi[1], Ingmar R. Staude[1,2]

1. Institute of Biology, Leipzig University, Leipzig, Germany
2. German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Leipzig, Deutschland

Content

Supplements:

Supplementary Tables:

Supplementary Figures:

Supplement S1: Description of insect taxa.

Apiformes (syn. Anthophila). Bees, encompassing bumblebees, represent a diverse and globally distributed group, with more than 20,000 species identified (Ascher and Pickering 2020; Packer 2022). These insects show peak diversity in mid-latitudinal zones of both hemispheres (Orr et al. 2023). Originating from the Hymenoptera order, bees transitioned from a carnivorous wasp ancestry to pollen and nectar consumption approximately 140 to 110 million years ago, a period marked by a notable speciation burst (Danforth et al. 2013). The driving forces of this evolutionary radiation are still unclear (Rasmussen et al. 2020). Characteristic of bees are their hairy bodies and broad, relatively flat hind legs, adaptations primarily for pollen gathering. Yet, some species have evolved to transport pollen internally, without external collecting structures. A subset of bee species also adopts a parasitic lifestyle (Packer 2022). While species like the honeybee (*Apis millifera*) are known for their social living in hives, most bee species are solitary. Their reproductive and nesting habits are diverse, employing hollow trees, wood tunnels, and rock crevices, although underground nesting is most common. These nests serve as a food reserve for the larvae, enabling their development through the cocoon stage to adulthood (imago) (Packer 2022). Bees are pivotal to zoophilous pollination, playing a major role in the pollination networks of various ecosystems (Khalifa et al. 2021). Many plant species depend entirely on bees for their sexual reproduction, forming obligate symbiotic relationships (Packer 2022). This mutualism is vital for agriculture, with bees facilitating the pollination of about 90% of commercial crop varieties (Doyle et al. 2020). Some bees, classified as monolectic or oligolectic, specialize in collecting pollen from a single or a limited number of plant species, respectively. Nevertheless, strict monolecty is relatively rare, often resulting from a scarcity of suitable plant species (Cane and Sipes 2006). In Germany, approximately 30% of bee species are mono- to oligolectic (Westrich 1990), though most bees demonstrate more generalized foraging habits, supported by few key plant species (Warzecha et al. 2018).

Lepidoptera. Lepidoptera, encompassing butterflies and moths, stands out as one of the most extensively researched insect taxa, largely due to the appealing appearance of diurnal butterflies. This group, present on all continents, forms the largest monophyletic group of herbivorous insects, emerging around 245 million years ago (Misof et al. 2014). Currently, 157,424 extant species have been identified (van Nieukerken et al. 2011), with their greatest biodiversity found in the tropics (Kawahara et al. 2023). All lepidopteran species undergo complete metamorphosis (holometabolous development). Parents lay eggs on or near potential food sources for the larvae (caterpillars), without providing further care. Caterpillars exhibit a wide variety of species-specific colors, shapes, and structures, aiding in species identification. Adults (imagos) are primarily distinguished by two pairs of large wings, uniquely colored and shaped for each species. Larvae typically feed on plant tissues, especially leaves and other organs, with host specificity varying by species, though host shifts can occur (Pearse and Altermatt 2013). Adult behaviors vary: some do not feed and focus solely on reproduction before dying, while others may live for several months, possibly hibernating, and feed on nectar, sap from ripe fruits, without specific host plant fidelity (Emmel and Scoble 1994). Flowers frequented by Lepidoptera usually have a long, narrow corolla tube, offering a landing platform for diurnal butterflies or oriented horizontally for moths, facilitating access (Reddi and Bai 1984). A substantial portion of flower-visiting lepidopteran species also act as pollinators. Although their pollination efficiency may not match that of bees or hoverflies (Rader et al. 2020), lepidopterans can traverse large distances. During migration, they can serve as connectors between isolated plant populations and ecosystems, enhancing genetic diversity and ecosystem resilience (Chang et al. 2018). Furthermore, caterpillars are considered to transfer the largest amount of energy from plants to higher trophic level animals compared to other herbivores, playing a key role in ecosystem energy flow (Janzen 1988). A decrease or decline in their biomass might lead to additional negative consequences in food webs (Kehoe et al. 2021).

Symphyta. Symphyta, commonly called sawflies, are a paraphyletic (Peters et al. 2017) taxon within the Hymenoptera with about 8,885 extant species worldwide (Taeger et al. 2018). Their name derives from the incisors of female individuals to cut open plant tissue to place their eggs in (Lacourt 2020). Sawflies are a group of wasps distinguished by their absence of the characteristic wasp waist (Lacourt 2020). The imago feeds on different food sources, like nectar, pollen, plant sap and other insects or not at all (Lacourt 2020). The larvae resemble caterpillars in appearance but are distinguished by having more than four pairs of prolegs and lacking crochets. They are predominantly of a greenish hue and relatively nondescript, yet certain species feature larvae with vibrant colors and diverse appendages. These larvae externally forage on plant material similarly to caterpillars, yet some species reside within plant tissues, mining these (Jervis and Vilhelmsen 2000). Larvae are mostly monophagous to oligophagous and exhibit a rather reduced selection of possible host plants (Andreas Taeger et al. 1998). Because the larvae mainly forage on plant tissue, some Symphyta species are regarded as agricultural pests (Guignard et al. 2022). Nevertheless, sawflies serve as primary consumers, channeling biomass to numerous insectivorous species and sustaining complex food webs (Guignard et al. 2022). Moreover, the adult forms (imagos) of some sawfly species are considered important pollinators (Rader et al. 2020; Asenbaum et al. 2021).

Syrphidae. Hoverflies, a monophyletic group within the Diptera, have a global diversity of approximately 6,000 species, present everywhere except Antarctica (Doyle et al. 2020; Rotheray and Gilbert 2011). The primary characteristic of hoverflies is their bee or wasp-like appearance, mimicking the color patterns of various defensive hymenopteran species. Additionally, the adults (imagos) exhibit a distinctive hovering flight style, which is the origin of their common name (Howarth et al. 2004). The imago of syrphid species mainly forage on pollen and/or nectar. Their mouthparts show a similar structure to other flies; hence they mainly forage on rather flat flowers where they can access the pollen and nectar with these mouthparts (Penney et al. 2012). Consequently, most hoverfly imagoes show a rather wide species range of potential food plants (Warzecha et al. 2018). The larvae are mainly predators foraging on other arthropods like aphids (Rotheray and Gilbert 2011). These two reasons make hoverflies a beneficial and important organism in agricultural systems (Doyle et al. 2020). In natural ecosystems, the predatory larvae control aphid populations and reduce parasitic plant stress (Rotheray and Gilbert 2011). Moreover, the syrphid imago shows a high pollination potential (Orford et al. 2015). While hoverflies have a lower pollination capacity compared to bees (Rader et al. 2020), their ontogeny grants them a larger foraging radius (Rader et al. 2011), the ability to forage under adverse weather conditions (Grimaldi 2023), and even undertake long-distance migrations, thereby enabling long-distance pollination (Lysenkov 2009).

Table S1: Sample sizes for the analysis presented in Fig. 1. Sample sizes comprise insect species for which both plant interaction data and Red List (RL) information were available.

Taxon	Short-term trend analysis	Long-term trend analysis	RL threat status analysis
Apiformes	293	276	297
Lepidoptera	1024	1022	1063
Symphyta	295	355	374
Syrphidae	259	236	318
All taxa	1871	1889	2052

Table S2: Restoration scenario that maximized insect diversity with 20 plant species. List of 20 critical plant species, alongside their cumulative contribution to sustaining insect diversity.

Taxon	Plant sp.	Cumul. number of insect sp.	Cumul. % of insect sp.
All taxa	*Salix caprea*	282	13
	Ranunculus acris	448	20
	Quercus robur	546	24
	Lotus corniculatus	628	28
	Rubus idaeus	703	31
	Daucus carota	769	34
	Betula pubescens	827	37
	Rumex acetosella	884	39
	Prunus spinosa	938	42
	Festuca ovina	990	44
	Galium mollugo	1034	46
	Picea abies	1077	48
	Centaurea stoebe	1114	50
	Plantago major	1145	51
	Vaccinium myrtillus	1176	53
	Peucedanum officinale	1202	54
	Poa annua	1228	55
	Sinapis arvensis	1253	56
	Thymus serpyllum	1276	57
	Populus tremula	1298	58
	Achillea millefolium	1318	59
Bees	*Sinapis arvensis*	69	22
	Lotus corniculatus	122	39
	Picris hieracioides	145	46
	Salix caprea	161	52
	Echium vulgare	176	56
	Campanula rotundifolia	186	60
	Centaurea stoebe	196	63
	Daucus carota	206	66
	Trifolium pratense	214	69
	Hieracium pilosella	220	71
	Solidago gigantea	225	72
	Stachys recta	230	74
	Brassica napus	234	75
	Calluna vulgaris	237	76
	Cardamine pratensis	240	77
	Jasione montana	243	78
	Knautia arvensis	246	79
	Vaccinium myrtillus	249	80
	Anchusa officinalis	251	80
	Bryonia dioica	253	81
	Cerinthe minor	255	82
Butterflies & moths	*Salix caprea*	155	13
	Quercus robur	233	20
	Rumex acetosa	303	26
	Festuca ovina	355	31
	Vaccinium myrtillus	402	35
	Prunus spinosa	440	38
	Galium mollugo	477	41
	Artemisia vulgaris	508	44
	Plantago lanceolata	536	47
	Poa annua	561	49
	Betula nana	585	51

	Picea abies	609	53
	Thymus serpyllum	633	55
	Rubus idaeus	655	57
	Cytisus scoparius	673	58
	Lotus corniculatus	690	60
	Polygonum aviculare	706	61
	Silene vulgaris	722	63
	Dactylis glomerata	737	64
	Brassica oleracea	750	65
	Clematis vitalba	763	66
Sawflies	*Betula pubescens*	31	7
	Picea abies	50	11
	Quercus robur	68	16
	Rosa canina	84	19
	Alnus glutinosa	99	23
	Populus tremula	114	26
	Rubus idaeus	129	30
	Pinus sylvestris	143	33
	Larix decidua	153	35
	Prunus domestica	163	37
	Pteridium aquilinum	173	40
	Filipendula ulmaria	182	42
	Festuca rubra	190	43
	Salix caprea	198	45
	Lonicera xylosteum	205	47
	Plantago major	212	49
	Sorbus aucuparia	219	50
	Ranunculus repens	225	51
	Acer campestre	230	53
	Salix viminalis	235	54
	Calamagrostis arundinacea	239	55
Hoverflies	*Ranunculus repens*	170	50
	Aegopodium podagraria	228	67
	Anthriscus caucalis	266	78
	Salix alba	289	85
	Crataegus laevigata	297	88
	Euphorbia nutans	305	90
	Potentilla erecta	309	91
	Geranium robertianum	312	92
	Hedera helix	315	93
	Caltha palustris	317	94
	Campanula latifolia	319	94
	Foeniculum vulgare	321	95
	Potentilla crantzii	323	95
	Prunus padus	325	96
	Anthemis austriaca	326	96
	Asparagus officinalis	327	96
	Chaerophyllum hirsutum	328	97
	Cirsium eriophorum	329	97

Cornus sanguinea	330	97
Crepis pyrenaica	331	98
Cytisus scoparius	332	98

Table S3: Composition of the specialization levels within the single insect taxa. The absolute number of insect species and the relative proportion is shown.

Taxon	Specialization degree	Number of insect sp.	Relative proportion
Apiformes	mono	40	12.80 %
Apiformes	oligo	60	19.20 %
Apiformes	meso	92	29.50 %
Apiformes	poly	120	38.50 %
Lepidoptera	mono	116	10.10 %
Lepidoptera	oligo	343	29.80 %
Lepidoptera	meso	422	36.70 %
Lepidoptera	poly	270	23.50 %
Symphyta	mono	199	45.50 %
Symphyta	oligo	186	42.60 %
Symphyta	meso	42	9.61 %
Symphyta	poly	10	2.29 %
Syrphidae	mono	12	3.54 %
Syrphidae	oligo	18	5.31 %
Syrphidae	meso	88	26.00 %
Syrphidae	poly	221	65.20 %
All taxa	mono	367	16.40 %
All taxa	oligo	607	27.10 %
All taxa	meso	644	28.80 %
All taxa	poly	621	27.70 %

Table S4: Distribution of the number of species over the threat status gradient. The number of individual insect taxa (bees (Apiformes), butterflies (Lepidoptera), sawflies (Symphyta), hoverflies (Syrphidae)), the total number and the relative proportion (rel.) of all insect taxa, and plant species across the Red List (RL) threat status gradient are presented. These numbers reflect species for which both interaction and RL data were available. LC: Least Concern; NT: Near Threatened; VU: Vulnerable: EN: Endangered; CR: Critically Endangered; RE: Regionally Extinct; NE: Not Evaluated.

Taxon	All	rel.	LC	NT	VU	EN	CR	RE	NE
Bees	312	55.6%	104	48	74	50	21	13	2
Butterflies	1151	78.5%	579	148	141	125	70	31	57
Sawflies	437	56.7%	263	33	59	13	9	13	47
Hoverflies	339	72.6%	179	38	43	23	35	4	17
All insects	2239	68.6%	1125	267	317	211	135	61	123
Plants	3429	82.9%	1520	477	346	218	154	48	666

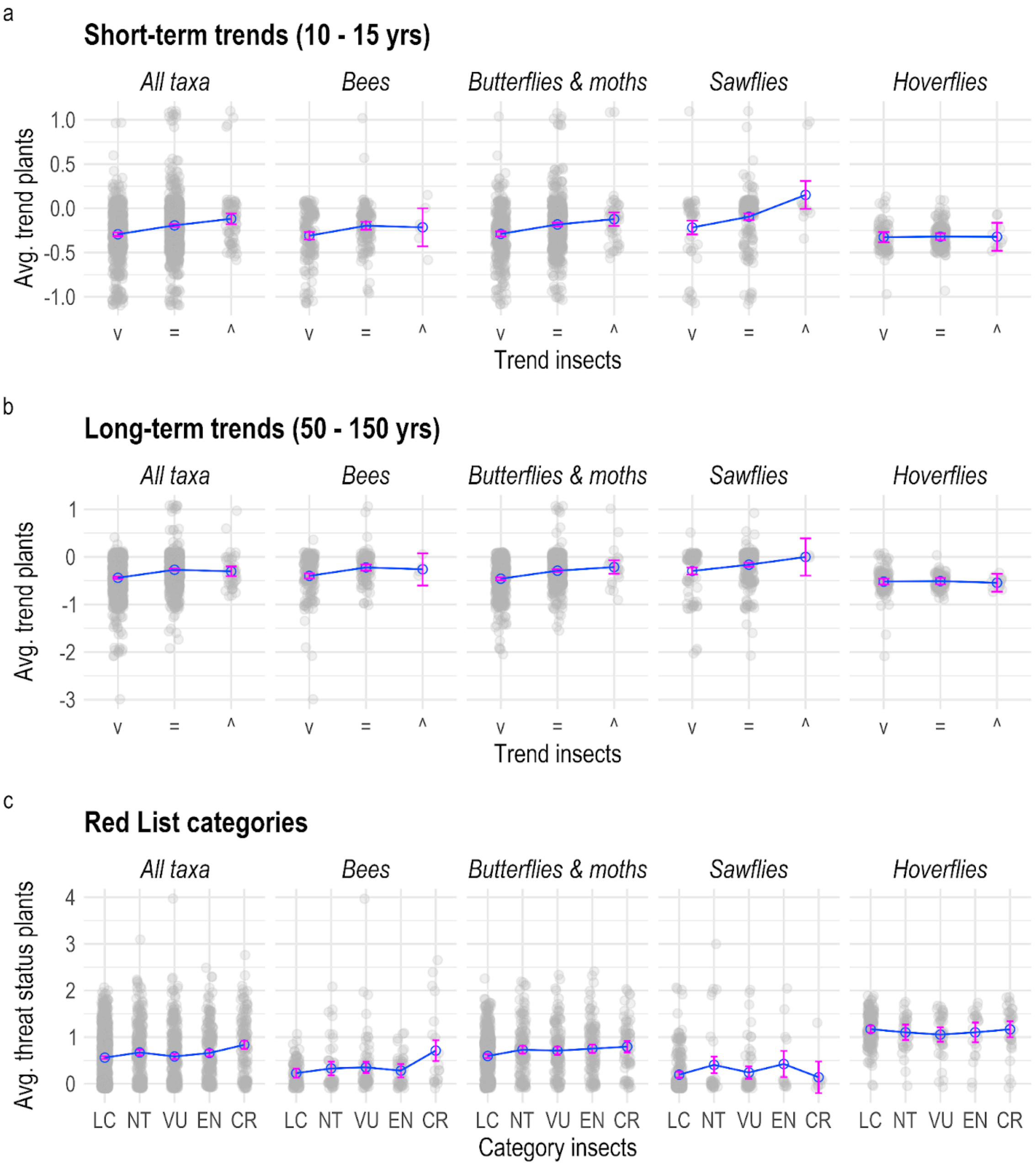

Fig. S1: Raw data plots for Fig 1. (a) Short- and **(b)** long-term population trend and **(c)** threat status of insect species against the respective means of host plants. For (a) and (b), higher y-axis values signal positive population trends; for (c), they indicate increased threat statuses. Symbols "v", "=" and "^" in (a) and (b) indicate declining, stable and increasing population trends, respectively. LC, NT, VU, EN and CR in (c) indicate IUCN Red List categories that were translated from the German red-listing system (see Methods), indicating Least Concern, Near Threatened, Vulnerable, Endangered and Critically Endangered, respectively. Displayed are means (blue dots), 95% confidence intervals (magenta error bars) and raw data points in gray circles. Sample sizes for "All taxa", Apiformes (bees), Lepidoptera (butterflies), Symphyta (sawflies) and Syrphidae (hoverflies) and host plants are provided in Table S1

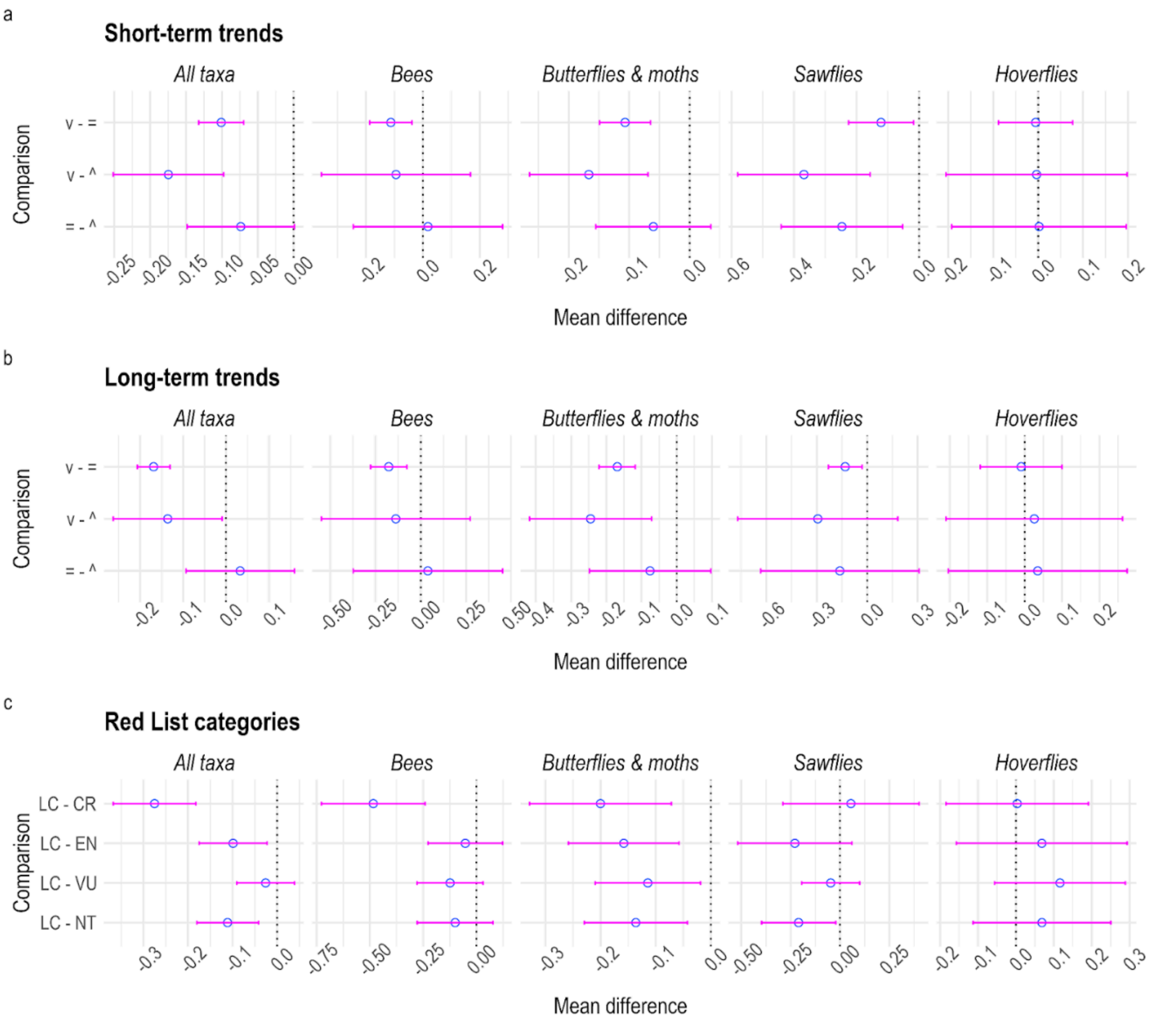

Fig. S2: Pairwise comparisons for Fig. 1 Mean differences in average host plant Red List indicator value between the different levels of **(a)** short- and **(b)** long-term population trends and **(c)** threat statuses of insect species. Symbols “v”, “=” and “^” in (a) and (b) indicate declining, stable and increasing population trends, respectively. LC, NT, VU, EN and CR in (c) indicate IUCN Red List categories that were translated from the German red-listing system (see Methods), indicating Least Concern, Near Threatened, Vulnerable, Endangered and Critically Endangered, respectively. Displayed are means (blue dots), 95% confidence intervals (magenta error bars). Sample sizes for “All taxa”, Apiformes (bees), Lepidoptera (butterflies), Symphyta (sawflies) and Syrphidae (hoverflies) and host plants are provided in Table S1.

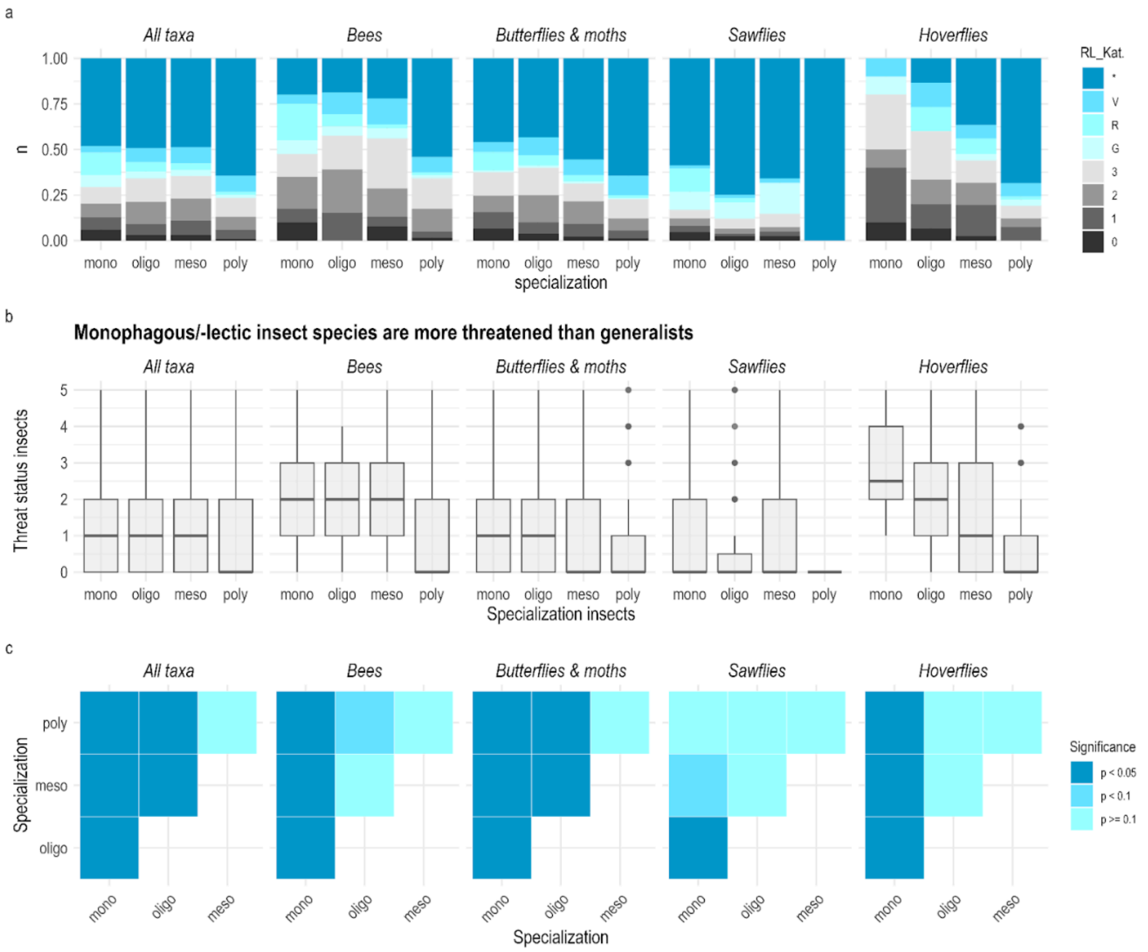

Fig. S3: Monophagous/-lectic insect species are more threatened than generalists. (a) Stacked bar plots showing the relative contribution of Red List threat levels per insect specialization level. **(b)** Boxplots indicating the median threat status of insects per specialization level after transforming the categorical RL threat level into a numeric variable (see Table S1). Box plots bound the interquartile range (IQR) divided by the median and whiskers extend up to a maximum of 1.5 × IQR beyond the box. Gray points beyond the whiskers indicate outliers. **(c)** Heatmap of pairwise comparisons of specialization levels in relation to insect threat status, indicating the p-value from a non-parametric pairwise Wilcoxon signed-rank test (tiles in dark blue have p<0.05, tiles in sky blue have p<0.1, tiles in turquoise have p>=0.1).

References

Ascher, J.S. & Pickering, J. (2020). Discover Life bee species guide and world checklist (Hymenoptera: Apoidea: Anthophila). URL http://www.discoverlife.org/mp/20q?guide=Apoidea_species.

Asenbaum, J., Schäffler, I., Etl, F., Dötterl, S., Schönenberger, J. & Chartier, M. (2021). Comparative Pollination Ecology of Five European Euphorbia Species. *International Journal of Plant Sciences*, 182, 763–777.

Cane, J.H. & Sipes, S. (2006). Characterizing floral specialization by bees: analytical methods and a revised lexicon for oligolecty. *Plant-pollinator interactions: from specialization to generalization*.

Chang, H., Guo, J., Fu, X., Liu, Y., Wyckhuys, K.A.G. & Hou, Y. *et al.* (2018). Molecular-Assisted Pollen Grain Analysis Reveals Spatiotemporal Origin of Long-Distance Migrants of a Noctuid Moth. *International Journal of Molecular Sciences*, 19, 567.

Danforth, B.N., Cardinal, S., Praz, C., Almeida, E.A.B. & Michez, D. (2013). The impact of molecular data on our understanding of bee phylogeny and evolution. *Annual review of entomology*, 58, 57–78.

Doyle, T., Hawkes, W.L.S., Massy, R., Powney, G.D., Menz, M.H.M. & Wotton, K.R. (2020). Pollination by hoverflies in the Anthropocene. *Proceedings. Biological sciences*, 287, 20200508.

Emmel, T.C. & Scoble, N.J. (1994). The Lepidoptera. Form, Function and Diversity. *The Florida Entomologist*, 77, 189.

Grimaldi, D.A. (ed.) (2023). *The complete insect. Anatomy, physiology, evolution, and ecology.* Princeton University Press, Princeton.

Guignard, Q., Slippers, B. & Allison, J. (2022). Chemical and visual ecology of the Symphyta. *Agri and Forest Entomology*, 24, 453–465.

Howarth, B., Edmunds, M. & Gilbert, F. (2004). Does the abundance of hoverfly (Syrphidae) mimics depend on the numbers of their hymenopteran models? *Evolution*, 58, 367–375.

Janzen, D.H. (1988). Ecological Characterization of a Costa Rican Dry Forest Caterpillar Fauna. *Biotropica*, 20, 120.

Jervis, M. & Vilhelmsen, L. (2000). Mouthpart evolution in adults of the basal, ‘symphytan’, hymenopteran lineages. *Biol J Linn Soc*, 70, 121–146.

Kawahara, A.Y., Storer, C., Carvalho, A.P.S., Plotkin, D.M., Condamine, F.L. & Braga, M.P. *et al.* (2023). A global phylogeny of butterflies reveals their evolutionary history, ancestral hosts and biogeographic origins. *Nat Ecol Evol*, 7, 903–913.

Kehoe, R., Frago, E. & Sanders, D. (2021). Cascading extinctions as a hidden driver of insect decline. *Ecological Entomology*, 46, 743–756.

Khalifa, S.A.M., Elshafiey, E.H., Shetaia, A.A., El-Wahed, A.A.A., Algethami, A.F. & Musharraf, S.G. *et al.* (2021). Overview of bee pollination and its economic value for crop production. *Insects*, 12, 688.

Lacourt, J. (2020). *Sawflies of Europe.* N.A.P. Editions, Verrières-le-Buisson.

Lysenkov, S.N. (2009). On the estimation of the influence of the character of insect pollinators movements on the pollen transfer dynamics. *Entmol. Rev.*, 89, 143–149.

Misof, B., Liu, S., Meusemann, K., Peters, R.S., Donath, A. & Mayer, C. *et al.* (2014). Phylogenomics resolves the timing and pattern of insect evolution. *Science (New York, N.Y.)*, 346, 763–767.

Orford, K.A., Vaughan, I.P. & Memmott, J. (2015). The forgotten flies: the importance of non-syrphid Diptera as pollinators. *Proceedings. Biological sciences*, 282.

Orr, M.C., Hughes, A.C., Chesters, D., Pickering, J., Zhu, C.-D. & Ascher, J.S. (2023). Global Patterns and Drivers of Bee Distribution. *Current biology : CB*, 33, 1624.

Packer, L.D.M. (2022). *Bees of the world. A guide to every family.* Princeton University Press, Princeton.

Pearse, I.S. & Altermatt, F. (2013). Extinction cascades partially estimate herbivore losses in a complete Lepidoptera--plant food web. *Ecology*, 94, 1785–1794.

Penney, H.D., Hassall, C., Skevington, J.H., Abbott, K.R. & Sherratt, T.N. (2012). A comparative analysis of the evolution of imperfect mimicry. *Nature*, 483, 461–464.

Peters, R.S., Krogmann, L., Mayer, C., Donath, A., Gunkel, S. & Meusemann, K. *et al.* (2017). Evolutionary History of the Hymenoptera. *Current Biology : CB*, 27, 1013–1018.

Rader, R., Cunningham, S.A., Howlett, B.G. & Inouye, D.W. (2020). Non-Bee Insects as Visitors and Pollinators of Crops: Biology, Ecology, and Management. *Annual review of entomology*, 65, 391–407.

Rader, R., Edwards, W., Westcott, D.A., Cunningham, S.A. & Howlett, B.G. (2011). Pollen transport differs among bees and flies in a human-modified landscape. *Diversity and Distributions*, 17, 519–529.

Rasmussen, C., Engel, M.S. & Vereecken, N.J. (2020). A primer of host-plant specialization in bees. *Emerging topics in life sciences*, 4, 7–17.

Reddi, C.S. & Bai, G.M. (1984). Butterflies and pollination biology. *Proc Ani Sci*, 93, 391–396.

Rotheray, G.E. & Gilbert, F. (2011). *The natural history of Hoverflies.* Forrest Text.

Taeger, A., Altenhofer, E., Blank S.M., Jansen, E. & Ritzau, C. (1998). Kommentare zur Biologie, Verbreitung und Gefährdung der Pflanzenwespen Deutschlands (Hymenoptera, Symphyta). In: *Pflanzenwespen Deutschlands (Hymenoptera, Symphyta). Kommentierte Bestandsaufnahme,* pp. 49–135.

Taeger, A., Liston, A.D., Prous, M., Groll, E.K., Gehroldt, T. & Blank S.M. (2018). ECatSym – Electronic World Catalog of Symphyta (Insecta, Hymenoptera). Program version 5.0 (19 Dec 2018), data version 40 (23 Sep 2018). URL https://sdei.de/ecatsym/.

van Nieukirken, E.J., Kaila, L., Kitching, I.J., Kristensen, N.P., Lees, D.C. & Minet, J. *et al.* (2011). Order Lepidoptera Linnaeus, 1758. In: Zhang, Z.-Q. (Ed.) Animal biodiversity: An outline of higher-level classification and survey of taxonomic richness. *Zootaxa*, 3148, 212–221-212–221.

Warzecha, D., Diekötter, T., Wolters, V. & Jauker, F. (2018). Attractiveness of wildflower mixtures for wild bees and hoverflies depends on some key plant species. *Insect Conserv Diversity*, 11, 32–41.

Westrich, Paul (1990): Die Wildbienen Baden-Württembergs. Stuttgart: Ulmer.