

Critical habitat thresholds for effective pollinator conservation in agricultural landscapes

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Title: Current policies fall short of effective pollinator conservation in agricultural landscapes

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Abstract: Biodiversity in human-dominated landscapes is declining, but evidence-based conservation targets to guide international policies for such landscapes are lacking. We present a framework for informing habitat conservation targets based on the enhancement of habitat quantity and quality and define thresholds of habitat quantity at which it becomes effective to also prioritize habitat quality. We applied this framework to pollinators, an important part of agroecosystem biodiversity, by synthesizing 59 studies from 19 countries. Given low habitat quality, hoverflies had the lowest threshold at 6% semi-natural habitat cover, followed by solitary bees (15%), bumble bees (18%), and butterflies (42%). These figures represent minimum habitat thresholds in agricultural landscapes, but when habitat quantity is restricted, marked increases in quality are required to reach similar outcomes.

Main Text: We are currently in a period of rapid biodiversity loss (1), a trend so drastic that scientists have raised the alarm of a possible global sixth mass extinction event (2). Species loss causes an associated decline in ecosystem functioning (3, 4), which jeopardizes the delivery of critical ecosystem services on which humans rely (5, 6). In an effort to slow and reverse this decline, conservation targets have been formulated for expanding protected areas, such as the Global Biodiversity Framework (GBF) target to conserve 30% of land, waters and sea by 2030 (7). The GBF also recognizes the role of human-dominated landscapes in biodiversity conservation, and indicates that restoration should be introduced in 30% of degraded ecosystems (7). Conservation in so-called working landscapes (8), namely the agricultural areas that cover 44% of global habitable land (9), is essential to ensure the provision of services such as food production, soil retention, and cultural values (6, 10), and thus the sustainability of the ecosystems in which we live (8). However, few conservation targets exist for biodiversity within working landscapes. Targets to date either remain general approximations (11, 12) or focus exclusively on ecosystem service provision (13, 14), which excludes the host of species that are not primary service providers (15). To enact biodiversity conservation in working landscapes, there is therefore an urgent need to determine evidence-based targets for international policy.

Here we present a framework to inform minimum habitat targets based on the response of species to changes in habitat quantity and quality, which can directly support conservation policies. Currently enacted conservation policies in agricultural landscapes fund local-scale greening measures that typically either aim to increase habitat quantity, for example by planting native hedgerows, or aim to improve habitat quality, for example through the extensification of grassland management (16). There is evidence that both strategies can contribute to biodiversity conservation (16), but how they interplay to impact species populations at landscape levels is unknown. Complex landscapes with greater habitat coverage generally support higher biodiversity levels in agricultural areas (3), but the need for food production imposes an inherent limit on natural habitat area in agricultural landscapes (11). It is therefore also important to invest in improving habitat quality, but these two strategies should be applied in such a way that maximizes conservation impacts. Assuming greater species abundance with larger habitat area (Fig. 1A), the effect of enhancing habitat quality on species abundance will increase with increasing habitat area (Fig. 1B), leading to a habitat quantity threshold at which it is more effective to also enhance habitat quality (Fig. 1C). An effective minimum in terms of habitat area conservation can thus be defined as the point at which the marginal benefit for the population size of a focal species group from further increasing habitat area is less than that from improving habitat quality (Fig. 1C). Investing in habitat area up until this point, and also in habitat quality improvements after this point, represents an application of conservation policy in agricultural landscapes that is most beneficial in terms of outcomes for biodiversity.

We utilize this framework to calculate minimum habitat thresholds for the conservation of pollinators, a species group linked to food production that faces multiple threats recognized at the highest levels of international policymaking (7, 17). Conservation efforts in agricultural areas generally positively impact local pollinator densities because of increased floral resource availability (18), an aspect of habitat quality that can directly indicate suitability for pollinators since they rely on floral resources to complete their life cycles (19). Pollinators have been proposed as useful bioindicators of ecosystem health (20) and are already monitored as such to estimate conservation progress (21), so they are an appropriate group with which to examine habitat conservation targets. However, to inform an evidence-based target for such policies that

are increasingly aimed at pollinators, we need to know the relative impact of increasing habitat quantity or quality for conserving pollinator populations.

To determine a minimum habitat threshold across a wide range of agroecosystems, we synthesized 59 datasets representing 24487 sampling events of 178885 individual pollinators in 1250 agricultural landscapes from 19 countries (predominantly US and in Europe, figs. S1-S2; tables S1-S2). Pollinators were sampled in various types of natural and semi-natural habitats (hereafter semi-natural habitats), but not crop fields, and included four main wild pollinator groups in temperate areas: bumble bees, solitary bees, hoverflies, and butterflies. Our systematic literature screen (see materials and methods) also identified a small number of datasets from the tropics ($n=3$), from which we could analyze bees as a pollinator group. First, we tested the effects of habitat quantity and quality on the local densities of pollinators in semi-natural habitats using mixed effects models. We focused on pollinator densities (abundance measurements) but not species richness because densities can be linearly extrapolated to landscape-level abundances in relation to habitat area (22). We used local flower abundance (percentage cover) and richness as habitat quality indicators, and the amount of semi-natural habitat in the surrounding landscape (500 m radius (23–26)) as a habitat quantity indicator. While nesting and oviposition resources are also key components of habitat quality for pollinators, we focused on floral resources because they are readily measured and are generally the most limiting resource for pollinators (27). We controlled for the possible influence of the presence of mass-flowering crops in study landscapes by including this variable as a covariate, because these crops can alter pollinator population dynamics in agroecosystems (28). To examine how these local relationships translate to landscape-level abundances (29), we extrapolated modelled pollinator densities to the landscape scale by multiplying densities by the area coverage of semi-natural habitat in a landscape. Following the method of Fijen et al. (30), we used 20 quantiles representing the range of habitat quantity and quality measured in our datasets to iteratively vary levels of these variables in our predictions. At each quantity-quality combination, we calculated the relative gain in landscape-level pollinator abundance from enhancing habitat quantity or quality by one quantile step. With these calculations we identified the landscape context in which the marginal benefit of increasing habitat quality equals that of increasing habitat quantity, that is, how much semi-natural habitat should be conserved to support pollinators before also investing in habitat quality enhancements. These baseline minimums can be used to guide conservation practice in working landscapes.

Minimum habitat thresholds depend on species group

We found habitat coverage minimums that ranged from 5.5-42.1% (Fig. 2) depending on species group. Hoverflies had the lowest minimum habitat quantity level, at 5.5% semi-natural habitat cover, and butterflies the highest, at 42.1% (Figs. 2C-2D). Bumble bees and solitary bees had similar minimums, at 17.9% and 15.1%, respectively (Figs. 2A-2B). In the tropics, however, bees seemed to benefit from greater habitat area, as the minimum habitat coverage for this group was 38.1% (Fig. 2E). Our framework suggests that above these thresholds it is more beneficial for conservation outcomes to also invest in habitat quality enhancements (Fig. 1C). These differences across species groups suggest that there is no one-size-fits-all approach to pollinator conservation in agricultural areas, but that reaching minimums of 15-18% semi-natural habitat cover has greater impact than quality enhancements for both bees and hoverflies in temperate regions, the two groups that provide the majority of pollination (and additionally in the case of aphidophagous hoverflies, pest control) services to agriculture (31). Butterfly communities might

only thrive in more complex landscapes (32–34), indicating the importance of conserving larger habitat areas in landscapes where it is feasible to do so, to ensure effective butterfly conservation.

These differences in habitat minimums can largely be explained by differences in drivers of local pollinator densities across species groups. For example, hoverflies had high densities (and in turn large total abundances; Fig. 3C; fig. S3C; fig. S5), and comparatively strong relationships with floral resource variables (significantly predicted by flower richness, marginally by flower cover; Fig. 4B), so the relative gain in landscape-level abundance from enhancing habitat quality increased more rapidly than for other species groups (Fig. 2). These high densities in relatively simple landscapes may be due to a majority of hoverfly individuals, made up by common species, utilizing cropland as oviposition sites to meet larval feeding requirements (35). Butterflies, on the other hand, were the only group that was significantly positively related to semi-natural habitat cover (Fig. 4C), and had low densities (and relatively low total abundances; Fig. 3D; fig. S3D; fig. S6). Despite a marginal relationship with flower cover (Fig. 4C), habitat quantity thus had a strong influence on landscape-level butterfly abundance, resulting in the highest minimum habitat cover estimate. While some butterflies, such as *Pieris rapae*, also can oviposit on crops, butterfly larval habitat requirements are often specialized, so butterflies are generally very sensitive to landscape simplification (36). This general reliance on surrounding habitat could explain the low butterfly densities in simplified agricultural areas (33, 37), and could be driven by the importance of larger semi-natural habitat elements that act as butterfly population sources (37).

Furthermore, bees and hoverflies had comparatively lower habitat thresholds because of weak to absent effects of semi-natural habitat cover on local densities (Figs. 4A–4B; marginal effect Fig. 4D; opposing trends Fig. 5D), which challenges the generally held assumption that these groups are positively affected by surrounding landscape habitat quantity (38). While these groups have been found to respond to landscape resources at a number of scales, landscape effects on local densities are typically observed for pollinators within crop fields (3, 38), whereas here we examine landscape effects on local densities in semi-natural habitats. This finding suggests that bee and hoverfly densities in a given patch of semi-natural habitat, and in turn the carrying capacity of a habitat, are primarily determined by local habitat parameters (39), such as habitat quality. As with hoverflies, bumble bee and tropical bee densities were positively predicted by both flower cover and richness (Figs. 5A–5B; Fig. 4D), while solitary bees were only significantly related to flower richness (Fig. 4A). These results indicate that habitat quality enhancements can support bees and hoverflies regardless of surrounding landscape context. While our results refer to pollinator densities and not species richness, the strong effects of flower richness could be due to the support of a wider diversity of pollinator species (19). Thus, our findings also suggest that when enhancing habitat quality, a particular emphasis should be placed on increasing the diversity of floral resources available to pollinators (19), rather than large displays of only a few flower species (40).

The minimum habitat threshold for tropical bees should be interpreted with caution because only three studies, representing two countries and five study years, were analyzed for this group. While conservation strategies should be context dependent, our results tentatively suggest that in general relatively large amounts of semi-natural habitat should be conserved to support bees in the tropics. This could be due to tropical bee communities being relatively dominated by social bees (e.g., Apini and Meliponini), which are typically more sensitive to habitat loss (41).

Furthermore, the low number of studies detected for inclusion in our synthesis indicates a great need for continued research on pollinators in the tropics, especially considering that these areas contain a high proportion of small farms that rely on biodiversity-mediated ecosystem service provision (42) and that are crucial to ensuring food security (43).

Conservation below, within, and beyond minimum habitat thresholds

Our framework for defining minimum habitat thresholds relies on the dual effects of habitat quantity and quality on upscaled landscape-level pollinator abundance. These thresholds assume that landscape habitat quality is low (Q1 in Fig. 2), which supports them as absolute minimums up to which habitat area conservation should be prioritized. With greater habitat quality, similar abundances are achieved with lower habitat cover than our minimums (fig. S3). However, our findings indicate that with greater habitat quality, the habitat quantity threshold actually increases (Fig. 2). This is because the gains from further improving the quality of a habitat that is already high in quality are smaller than those attained by increasing the area of high-quality habitat in the landscape. In other words, increases in habitat quality see diminishing returns in landscape-level abundances (Fig. 3). Hence, above our minimum habitat targets, the focus of conservation should be on a combination of quantity and quality enhancements. Furthermore, our data confirmed that in agricultural landscapes, both semi-natural habitat quality and quantity are typically low (44): across the temperate datasets, half of all surveys recorded flower cover and semi-natural habitat cover in the lowest quarter of the range (Fig. 3). This indicates that our framework, which is grounded in the restoration of intensive agricultural landscapes, is a realistic conceptualization that can inform conservation targets. The framework can likely be generalized to various intensive agricultural contexts for pollinator conservation but also for other species groups for which simple habitat indicators can be defined. This prevalence of simple landscapes also indicates, however, that landscapes with large areas of existing semi-natural habitat should be conserved as much as possible, since they are likely important, and rare, harbors of farmland biodiversity.

Within our calculations of habitat minimums we assumed an equal feasibility of enhancing habitat quantity and quality, which does not consider the context-dependent costs or effort to increase quantity or quality that inherently influence the relative effectiveness of applying these conservation measures. For example, increasing habitat area may in some contexts be relatively more costly due to losses in agricultural production. To achieve the same increases in landscape pollinator abundances as increasing habitat quantity, habitat quality would have to be greatly enhanced. For example, if a landscape could only sustain maximum 5% semi-natural habitat coverage, the quality of that habitat would have to be improved by increasing flower cover to approximately 4.8% and adding approximately 3.8 flower species (assuming equivalent nesting resource availability) to reach an equivalent bumble bee community size as supported by 17.9% habitat cover (fig. S3). While these numbers may sound meager, this flower cover level is greater than 82% of all observations across studies, indicating that it is a rather rare occurrence in agricultural landscapes. This tradeoff shows that in simple landscapes where increasing pollinator habitat may not be an option, efforts to enhance the quality of existing habitat should aim to significantly increase flower abundance and diversity.

Conservation tools outside of semi-natural habitats also have the potential to support pollinators. Our results showed that mass-flowering crop presence elevated bumble bee and solitary bee densities (Figs. 5C-5D; Fig. 4A), but not those of other groups (Figs. 4B-D). For bumble bees,

however, this effect only occurred in simple landscapes (Fig. 5C), possibly due to the presence of sufficient alternative floral resources in complex ones (45). Because we modelled average pollinator densities across all surveys in a given landscape regardless of crop flowering period, we likely captured an overall effect of mass-flowering crop presence, as opposed to detecting specific dilution, concentration, or spillover dynamics (46). However, these patterns are likely driven by abundant, common species that preferentially visit agricultural crops (15). This general effect suggests that mass-flowering crops, although non-permanent resources due to blooming periods and crop rotation, can complement the restoration and enhancement of semi-natural habitats in supporting part of the bee community in temperate agricultural areas.

Finally, while habitat minimums provide useful guidelines, the types of habitats relevant to specific local contexts and their configuration should also be considered in conservation. For the purposes of estimating pollinator community sizes across landscapes, we assumed equal value of different types of semi-natural habitats, as well as equal distribution of pollinators among these habitat types. This might overestimate community sizes, leading to especially conservative estimates of minimum habitat quantity due to more rapid increases in marginal benefits from habitat quality. We furthermore modelled pollinator abundances and not richness due to the complexities of inferring landscape-scale species diversity from local-scale observations (22), which requires a spatiotemporal completeness of survey methodology that is not typical of pollinator ecology studies. In reality, we know that different pollinators prefer certain habitat types, for example due to their foraging, nesting or oviposition requirements (32, 47), and that they can move between habitat types depending on their resource needs in space and time (48). This means that within the minimum recommendations for semi-natural habitat coverage, different types of semi-natural habitat (e.g., woody and herbaceous) should be conserved as much as possible (49) to increase nesting resources and the temporal continuity of floral resources (40, 48). Conserving a variety of habitat types and ensuring connectivity of habitat patches has the potential to support a more diverse pollinator community (38, 49), which is important for ecosystem functioning and resilience (50).

The minimum habitat thresholds identified in our synthesis can guide the design of conservation strategies by balancing quantity and quality enhancements for pollinators in working landscapes. The application of this framework to specific contexts or other species groups should be further informed by local knowledge and conservation priorities, such as species of conservation concern and the specific resources they need for viable populations, which is not captured by our study. Overall, our findings demonstrate that current policy targets, such as the EU Biodiversity Strategy for 2030 goal of 10% high-diversity landscape features in agricultural areas (12), and the GBF restoration indicator of 10% natural cover in agricultural lands (7), are well below the thresholds that would most benefit pollinators. Future conservation policy for working landscapes should more strongly emphasize the need to conserve and restore more semi-natural habitat areas to achieve biodiversity gains, and should compensate landowners with incentives for marked improvements in habitat quality in landscapes where increases in habitat area are not feasible.

References and Notes

1. R. Dirzo, H. S. Young, M. Galetti, G. Ceballos, N. J. B. Isaac, B. Collen, Defaunation in the Anthropocene. *Science* **345**, 401–406 (2014).

2. G. Ceballos, P. R. Ehrlich, R. Dirzo, Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines. *Proc. Natl. Acad. Sci.* **114** (2017).
3. M. Dainese, E. A. Martin, M. A. Aizen, M. Albrecht, I. Bartomeus, R. Bommarco, L. G. Carvalheiro, R. Chaplin-Kramer, V. Gagic, L. A. Garibaldi, J. Ghazoul, H. Grab, M. Jonsson, D. S. Karp, C. M. Kennedy, D. Kleijn, C. Kremen, D. A. Landis, D. K. Letourneau, L. Marini, K. Poveda, R. Rader, H. G. Smith, T. Tscharntke, G. K. S. Andersson, I. Badenhausser, S. Baensch, A. D. M. Bezerra, F. J. J. A. Bianchi, V. Boreux, V. Bretagnolle, B. Caballero-Lopez, P. Cavigliasso, A. Ćetković, N. P. Chacoff, A. Classen, S. Cusser, F. D. da Silva e Silva, G. A. de Groot, J. H. Dudenhöffer, J. Ekroos, T. Fijen, P. Franck, B. M. Freitas, M. P. D. Garratt, C. Gratton, J. Hipólito, A. Holzschuh, L. Hunt, A. L. Iverson, S. Jha, T. Keasar, T. N. Kim, M. Kishinevsky, B. K. Klatt, A.-M. Klein, K. M. Krewenka, S. Krishnan, A. E. Larsen, C. Lavigne, H. Liere, B. Maas, R. E. Mallinger, E. Martinez Pachon, A. Martínez-Salinas, T. D. Meehan, M. G. E. Mitchell, G. A. R. Molina, M. Nesper, L. Nilsson, M. E. O'Rourke, M. K. Peters, M. Plečaš, S. G. Potts, D. de L. Ramos, J. A. Rosenheim, M. Rundlöf, A. Rusch, A. Sáez, J. Scheper, M. Schleuning, J. M. Schmack, A. R. Sciligo, C. Seymour, D. A. Stanley, R. Stewart, J. C. Stout, L. Sutter, M. B. Takada, H. Taki, G. Tamburini, M. Tschumi, B. F. Viana, C. Westphal, B. K. Willcox, S. D. Wratten, A. Yoshioka, C. Zaragoza-Trello, W. Zhang, Y. Zou, I. Steffan-Dewenter, A global synthesis reveals biodiversity-mediated benefits for crop production. *Sci. Adv.* **5**, eaax0121 (2019).
4. T. H. Oliver, M. S. Heard, N. J. B. Isaac, D. B. Roy, D. Procter, F. Eigenbrod, R. Freckleton, A. Hector, C. D. L. Orme, O. L. Petchey, V. Proença, D. Raffaelli, K. B. Suttle, G. M. Mace, B. Martín-López, B. A. Woodcock, J. M. Bullock, Biodiversity and Resilience of Ecosystem Functions. *Trends Ecol. Evol.* **30**, 673–684 (2015).
5. S. Díaz, U. Pascual, M. Stenseke, B. Martín-López, R. T. Watson, Z. Molnár, R. Hill, K. M. A. Chan, I. A. Baste, K. A. Brauman, S. Polasky, A. Church, M. Lonsdale, A. Larigauderie, P. W. Leadley, A. P. E. van Oudenhoven, F. van der Plaats, M. Schröter, S. Lavorel, Y. Aumeeruddy-Thomas, E. Bukvareva, K. Davies, S. Demissew, G. Erpul, P. Failler, C. A. Guerra, C. L. Hewitt, H. Keune, S. Lindley, Y. Shirayama, Assessing nature's contributions to people. *Science* **359**, 270–272 (2018).
6. F. Isbell, A. Gonzalez, M. Loreau, J. Cowles, S. Díaz, A. Hector, G. M. Mace, D. A. Wardle, M. I. O'Connor, J. E. Duffy, L. A. Turnbull, P. L. Thompson, A. Larigauderie, Linking the influence and dependence of people on biodiversity across scales. *Nature* **546**, 65–72 (2017).
7. Convention on Biological Diversity, Kunming-Montreal Global Biodiversity Framework (2022). <https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf>.
8. C. Kremen, A. M. Merenlender, Landscapes that work for biodiversity and people. *Science* **362**, eaau6020 (2018).

9. Food and Agriculture Organization of the United Nations - processed by Our World in Data, Agriculture (2023). <https://ourworldindata.org/grapher/breakdown-habitable-land?time=latest>.
10. D. A. Landis, Designing agricultural landscapes for biodiversity-based ecosystem services. *Basic Appl. Ecol.* **18**, 1–12 (2017).
11. L. A. Garibaldi, F. J. Oddi, F. E. Miguez, I. Bartomeus, M. C. Orr, E. G. Jobbágy, C. Kremen, L. A. Schulte, A. C. Hughes, C. Bagnato, G. Abramson, P. Bridgewater, D. G. Carella, S. Díaz, L. V. Dicks, E. C. Ellis, M. Goldenberg, C. A. Huaylla, M. Kuperman, H. Locke, Z. Mehrabi, F. Santibañez, C. Zhu, Working landscapes need at least 20% native habitat. *Conserv. Lett.* **14**, e12773 (2021).
12. European Commission Directorate General for Environment, *EU Biodiversity Strategy for 2030: Bringing Nature Back into Our Lives*. (Publications Office, LU, 2021; <https://data.europa.eu/doi/10.2779/677548>).
13. A. Mohamed, F. DeClerck, P. H. Verburg, D. Obura, J. F. Abrams, N. Zafra-Calvo, J. Rocha, N. Estrada-Carmona, A. Fremier, S. K. Jones, I. C. Meier, B. Stewart-Koster, Securing Nature’s Contributions to People requires at least 20%–25% (semi-)natural habitat in human-modified landscapes. *One Earth* **7**, 59–71 (2024).
14. M. Eeraerts, A minimum of 15% semi-natural habitat facilitates adequate wild pollinator visitation to a pollinator-dependent crop. *Biol. Conserv.* **278**, 109887 (2023).
15. D. Kleijn, R. Winfree, I. Bartomeus, L. G. Carvalheiro, M. Henry, R. Isaacs, A.-M. Klein, C. Kremen, L. K. M’Gonigle, R. Rader, T. H. Ricketts, N. M. Williams, N. Lee Adamson, J. S. Ascher, A. Baldi, P. Batary, F. Benjamin, J. C. Biesmeijer, E. J. Blitzer, R. Bommarco, M. R. Brand, V. Bretagnolle, L. Button, D. P. Cariveau, R. Chifflet, J. F. Colville, B. N. Danforth, E. Elle, M. P. D. Garratt, F. Herzog, A. Holzschuh, B. G. Howlett, F. Jauker, S. Jha, E. Knop, K. M. Krewenka, V. Le Feon, Y. Mandelik, E. A. May, M. G. Park, G. Pisanty, M. Reemer, V. Riedinger, O. Rollin, M. Rundlof, H. S. Sardinias, J. Scheper, A. R. Sciligo, H. G. Smith, I. Steffan-Dewenter, R. Thorp, T. Tschardtke, J. Verhulst, B. F. Viana, B. E. Vaissiere, R. Veldtman, C. Westphal, S. G. Potts, Delivery of crop pollination services is an insufficient argument for wild pollinator conservation. *Nat Commun* **6** (2015).
16. P. Batáry, L. V. Dicks, D. Kleijn, W. J. Sutherland, The role of agri-environment schemes in conservation and environmental management. *Conserv. Biol.* **29**, 1006–1016 (2015).
17. IPBES, “The assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production” (Zenodo, 2016); <https://doi.org/10.5281/ZENODO.3402856>.
18. E. B. Lowe, R. Groves, C. Gratton, Impacts of field-edge flower plantings on pollinator conservation and ecosystem service delivery – A meta-analysis. *Agric. Ecosyst. Environ.* **310**, 107290 (2021).
19. H. Segre, D. Kleijn, I. Bartomeus, M. F. WallisDeVries, M. de Jong, M. Frank van der Schee, J. Román, T. P. M. Fijen, Butterflies are not a robust bioindicator for assessing

pollinator communities, but floral resources offer a promising way forward. *Ecol. Indic.* **154**, 110842 (2023).

20. P. G. Kevan, Pollinators as bioindicators of the state of the environment: species, activity and diversity. *Agric. Ecosyst. Environ.* **74**, 373–393 (1999).
- 5 21. Department for Environment, Food and Rural Affairs, Overview of assessment of change for all indicators and their component measures, *GOV.UK* (2024).
<https://www.gov.uk/government/statistics/england-biodiversity-indicators/overview-of-assessment-of-change-for-all-indicators-and-their-component-measures--2>.
- 10 22. H. Taki, R. Murao, K. Mitai, Y. Yamaura, The species richness/abundance–area relationship of bees in an early successional tree plantation. *Basic Appl. Ecol.* **26**, 64–70 (2018).
23. J. W. Redhead, S. Dreier, A. F. G. Bourke, M. S. Heard, W. C. Jordan, S. Sumner, J. Wang, C. Carvell, Effects of habitat composition and landscape structure on worker foraging distances of five bumble bee species. *Ecol. Appl.* **26**, 726–739 (2016).
- 15 24. M. Toivonen, A. Peltonen, I. Herzon, J. Heliölä, N. Leikola, M. Kuussaari, High cover of forest increases the abundance of most grassland butterflies in boreal farmland. *Insect Conserv. Divers.* **10**, 321–330 (2017).
25. D. Kleijn, F. van Langevelde, Interacting effects of landscape context and habitat quality on flower visiting insects in agricultural landscapes. *Basic Appl. Ecol.* **7**, 201–214 (2005).
- 20 26. M. Albrecht, A. Knecht, M. Riesen, T. Rutz, D. Ganser, Time since establishment drives bee and hoverfly diversity, abundance of crop-pollinating bees and aphidophagous hoverflies in perennial wildflower strips. *Basic Appl. Ecol.* **57**, 102–114 (2021).
27. T. H. Roulston, K. Goodell, The role of resources and risks in regulating wild bee populations. *Annu. Rev. Entomol.* **56**, 293–312 (2011).
- 25 28. A. Holzschuh, M. Dainese, J. P. González-Varo, S. Mudri-Stojnić, V. Riedinger, M. Rundlöf, J. Scheper, J. B. Wickens, V. J. Wickens, R. Bommarco, D. Kleijn, S. G. Potts, S. P. M. Roberts, H. G. Smith, M. Vilà, A. Vujić, I. Steffan-Dewenter, Mass-flowering crops dilute pollinator abundance in agricultural landscapes across Europe. *Ecol. Lett.* **19**, 1228–1236 (2016).
- 30 29. D. Kleijn, T. E. W. Linders, A. Stip, J. C. Biesmeijer, F. L. Wäckers, T. Bukovinszky, Scaling up effects of measures mitigating pollinator loss from local- to landscape-level population responses. *Methods Ecol. Evol.* **9**, 1727–1738 (2018).
- 35 30. T. P. M. Fijen, G. A. Bishop, C. Ganuza, J. Scheper, D. Kleijn, Analyzing the relative importance of habitat quantity and quality for boosting pollinator populations in agricultural landscapes. *Conserv. Biol.*, doi: 10.1111/cobi.14317 (2024).
31. R. Rader, I. Bartomeus, L. A. Garibaldi, M. P. D. Garratt, B. G. Howlett, R. Winfree, S. A. Cunningham, M. M. Mayfield, A. D. Arthur, G. K. S. Andersson, R. Bommarco, C.

- Brittain, L. G. Carvalheiro, N. P. Chacoff, M. H. Entling, B. Foully, B. M. Freitas, B. Gemmill-Herren, J. Ghazoul, S. R. Griffin, C. L. Gross, L. Herbertsson, F. Herzog, J. Hipólito, S. Jaggard, F. Jauker, A.-M. Klein, D. Kleijn, S. Krishnan, C. Q. Lemos, S. A. M. Lindström, Y. Mandelik, V. M. Monteiro, W. Nelson, L. Nilsson, D. E. Pattemore, N. de O. Pereira, G. Pisanty, S. G. Potts, M. Reemer, M. Rundlöf, C. S. Sheffield, J. Scheper, C. Schüepp, H. G. Smith, D. A. Stanley, J. C. Stout, H. Szentgyörgyi, H. Taki, C. H. Vergara, B. F. Viana, M. Woyciechowski, Non-bee insects are important contributors to global crop pollination. *Proc. Natl. Acad. Sci.* **113**, 146–151 (2016).
32. M. S. Warren, D. Maes, C. A. M. van Swaay, P. Goffart, H. Van Dyck, N. A. D. Bourn, I. Wynhoff, D. Hoare, S. Ellis, The decline of butterflies in Europe: Problems, significance, and possible solutions. *Proc. Natl. Acad. Sci.* **118**, e2002551117 (2021).
33. J. Ekroos, M. Kuussaari, Landscape context affects the relationship between local and landscape species richness of butterflies in semi-natural habitats. *Ecography* **35**, 232–238 (2012).
34. E. Öckinger, H. G. Smith, Landscape composition and habitat area affects butterfly species richness in semi-natural grasslands. *Oecologia* **149**, 526–534 (2006).
35. B. Meyer, F. Jauker, I. Steffan-Dewenter, Contrasting resource-dependent responses of hoverfly richness and density to landscape structure. *Basic Appl. Ecol.* **10**, 178–186 (2009).
36. D. L. Wagner, Insect Declines in the Anthropocene. *Annu. Rev. Entomol.* **65**, 457–480 (2020).
37. E. Öckinger, H. G. Smith, Semi-natural grasslands as population sources for pollinating insects in agricultural landscapes. *J. Appl. Ecol.* **44**, 50–59 (2007).
38. D. Senapathi, M. A. Goddard, W. E. Kunin, K. C. R. Baldock, Landscape impacts on pollinator communities in temperate systems: evidence and knowledge gaps. *Funct. Ecol.* **31**, 26–37 (2017).
39. R. Marja, T. Tscharntke, P. Batáry, Increasing landscape complexity enhances species richness of farmland arthropods, agri-environment schemes also abundance – A meta-analysis. *Agric. Ecosyst. Environ.* **326**, 107822 (2022).
40. T. P. Timberlake, I. P. Vaughan, J. Memmott, Phenology of farmland floral resources reveals seasonal gaps in nectar availability for bumblebees. *J. Appl. Ecol.* **56**, 1585–1596 (2019).
41. T. H. Ricketts, J. Regetz, I. Steffan-Dewenter, S. A. Cunningham, C. Kremen, A. Bogdanski, B. Gemmill-Herren, S. S. Greenleaf, A. M. Klein, M. M. Mayfield, L. A. Morandin, A. Ochieng', B. F. Viana, Landscape effects on crop pollination services: are there general patterns? *Ecol. Lett.* **11**, 499–515 (2008).
42. L. A. Garibaldi, L. G. Carvalheiro, B. E. Vaissière, B. Gemmill-Herren, J. Hipólito, B. M. Freitas, H. T. Ngo, N. Azzu, A. Sáez, J. Åström, J. An, B. Blochtein, D. Buchori, F. J. C. García, F. Oliveira da Silva, K. Devkota, M. de F. Ribeiro, L. Freitas, M. C. Gaglianone, M.

Goss, M. Irshad, M. Kasina, A. J. S. P. Filho, L. H. P. Kiill, P. Kwapong, G. N. Parra, C. Pires, V. Pires, R. S. Rawal, A. Rizali, A. M. Saraiva, R. Veldtman, B. F. Viana, S. Witter, H. Zhang, Mutually beneficial pollinator diversity and crop yield outcomes in small and large farms. *Science* **351**, 388–391 (2016).

43. M. Herrero, P. K. Thornton, A. M. Notenbaert, S. Wood, S. Msangi, H. A. Freeman, D. Bossio, J. Dixon, M. Peters, J. van de Steeg, J. Lynam, P. P. Rao, S. Macmillan, B. Gerard, J. McDermott, C. Seré, M. Rosegrant, Smart Investments in Sustainable Food Production: Revisiting Mixed Crop-Livestock Systems. *Science* **327**, 822–825 (2010).
44. R. A. Robinson, W. J. Sutherland, Post-war changes in arable farming and biodiversity in Great Britain. *J. Appl. Ecol.* **39**, 157–176 (2002).
45. A. S. Persson, H. G. Smith, Seasonal persistence of bumblebee populations is affected by landscape context. *Agric. Ecosyst. Environ.* **165**, 201–209 (2013).
46. T. Tschamntke, J. M. Tylianakis, T. A. Rand, R. K. Didham, L. Fahrig, P. Batáry, J. Bengtsson, Y. Clough, T. O. Crist, C. F. Dormann, R. M. Ewers, J. Fründ, R. D. Holt, A. Holzschuh, A. M. Klein, D. Kleijn, C. Kremen, D. A. Landis, W. Laurance, D. Lindenmayer, C. Scherber, N. Sodhi, I. Steffan-Dewenter, C. Thies, W. H. van der Putten, C. Westphal, Landscape moderation of biodiversity patterns and processes - eight hypotheses. *Biol. Rev.* **87**, 661–685 (2012).
47. C. Maurer, L. Sutter, C. Martínez-Núñez, L. Pellissier, M. Albrecht, Different types of semi-natural habitat are required to sustain diverse wild bee communities across agricultural landscapes. *J. Appl. Ecol.* **59**, 2604–2615 (2022).
48. Y. Mandelik, R. Winfree, T. Neeson, C. Kremen, Complementary habitat use by wild bees in agro-natural landscapes. *Ecol. Appl.* **22**, 1535–1546 (2012).
49. A. Pindar, N. E. Raine, Safeguarding pollinators requires specific habitat prescriptions and substantially more land area than suggested by current policy. *Sci. Rep.* **13**, 1040 (2023).
50. R. Winfree, J. R. Reilly, I. Bartomeus, D. P. Cariveau, N. M. Williams, J. Gibbs, Species turnover promotes the importance of bee diversity for crop pollination at regional scales. *Science* **359**, 791–793 (2018).
51. E. Pollard, A method for assessing changes in the abundance of butterflies. *Biol. Conserv.* **12**, 115–134 (1977).
52. D. Mueller-Dombois, H. Ellenberg, *Aims and Methods of Vegetation Ecology* (Wiley, New York, NY, 1974).
53. M. J. Page, D. Moher, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, L. Shamseer, J. M. Tetzlaff, E. A. Akl, S. E. Brennan, R. Chou, J. Glanville, J. M. Grimshaw, A. Hróbjartsson, M. M. Lalu, T. Li, E. W. Loder, E. Mayo-Wilson, S. McDonald, L. A. McGuinness, L. A. Stewart, J. Thomas, A. C. Tricco, V. A. Welch, P. Whiting, J. E. McKenzie, PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. *BMJ*, n160 (2021).

54. E. Grames, A. Stillamn, M. Tingley, C. Elphick, litsearchr: Automated Search Term Selection and Search Strategy for Systematic Reviews, version R package version 1.0.0 (2020).
55. E. M. Grames, A. N. Stillman, M. W. Tingley, C. S. Elphick, An automated approach to identifying search terms for systematic reviews using keyword co-occurrence networks. *Methods Ecol. Evol.* **10**, 1645–1654 (2019).
56. C. Kohl, E. J. McIntosh, S. Unger, N. R. Haddaway, S. Kecke, J. Schiemann, R. Wilhelm, Online tools supporting the conduct and reporting of systematic reviews and systematic maps: a case study on CADIMA and review of existing tools. *Environ. Evid.* **7**, 8 (2018).
57. C. D. Michener, *The Bees of the World* (Johns Hopkins University Press, Baltimore, Md, 2000).
58. C. Plateaux-Quénu, Subsociality in halictine bees. *Insectes Sociaux* **55**, 335–346 (2008).
59. J. Scheper, R. Bommarco, A. Holzschuh, S. G. Potts, V. Riedinger, S. P. M. Roberts, M. Rundlöf, H. G. Smith, I. Steffan-Dewenter, J. B. Wickens, V. J. Wickens, D. Kleijn, Local and landscape-level floral resources explain effects of wildflower strips on wild bees across four European countries. *J. Appl. Ecol.* **52**, 1165–1175 (2015).
60. K. Dijkstra, Wild plants in the Netherlands and Belgium (2024). <https://wilde-planten.nl/>.
61. J. Hilty, Illinois Wildflowers (2024). <https://www.illinoiswildflowers.info/>.
62. Minnesota Wildflowers (2024). <https://www.minnesotawildflowers.info/>.
63. NatureGate (2024). <https://luontoportti.com/en>.
64. Missouri Botanical Garden, Manual de Plantas de Costa Rica (2024). <http://legacy.tropicos.org/Project/Costa%20Rica>.
65. Missouri Botanical Garden, Harvard University Herbaria, eFloras.org (2024). <http://efloras.org/>.
66. Missouri Native Plant Society, Missouri Plants (2024). <https://missouriplants.com/>.
67. Native Plant Trust, Go Botany (2024). <https://gobotany.nativeplanttrust.org/>.
68. Real Jardín Botánico, CSIC, Flora Iberica (2024). <http://www.floraiberica.es/index.php>.
69. WFO, World Flora Online (2024). <https://worldfloraonline.org/>.
70. Bundesamt für Kartographie und Geodäsie, Digitales Basis-Landschaftsmodell (2021). <https://gdz.bkg.bund.de/index.php/default/digitale-geodaten/digitale-landschaftsmodelle/digitales-basis-landschaftsmodell-ebenen-basis-dlm-ebenen.html>.
71. Consejería de Sostenibilidad, Medio Ambiente y Economía Azul, Junta de Andalucía, Base cartográfica SIOSE Andalucía 2013 (2015).

<https://portalrediam.cica.es/geonetwork/static/eng/catalog.search#/metadata/84849016-eb54-45f2-9b9e-b4104cd2b5f1>.

72. European Environment Agency, CORINE Land Cover 2018 (raster 100 m), Europe, 6-yearly - version 2020_20u1, May 2020, version 20.01, European Environment Agency (2019); <https://doi.org/10.2909/960998C1-1870-4E82-8051-6485205EBBAC>.
73. European Environment Agency, CORINE Land Cover 2000 (raster 100 m), Europe, 6-yearly - version 2020_20u1, May 2020, version 20.01, European Environment Agency (2019); <https://doi.org/10.2909/DDACBD5E-068F-4E52-A596-D606E8DE7F40>.
74. European Environment Agency, CORINE Land Cover 2006 (raster 100 m), Europe, 6-yearly - version 2020_20u1, May 2020, version 20.01, European Environment Agency (2019); <https://doi.org/10.2909/08560441-2FD5-4EB9-BF4C-9EF16725726A>.
75. European Environment Agency, CORINE Land Cover 2012 (raster 100 m), Europe, 6-yearly - version 2020_20u1, May 2020, version 20.01, European Environment Agency (2019); <https://doi.org/10.2909/A84AE124-C5C5-4577-8E10-511BFE55CC0D>.
76. R. M. Fuller, G. M. Smith, J. M. Sanderson, R. A. Hill, A. G. Thomson, R. Cox, N. J. Brown, R. T. Clarke, P. Rothery, F. F. Gerard, Land Cover Map 2000 (25m raster, GB), NERC EDS Environmental Information Data Centre (2002); <https://doi.org/10.5285/F802EDFC-86B7-4AB9-B8FA-87E9135237C9>.
77. Geodienste, Landw. Bewirtschaftung: Nutzungsflächen (2024). https://www.geodienste.ch/services/lwb_nutzungsflaechen?locale=de.
78. G. W. Hazeu, M. Vittek, R. Schuiling, J. D. Bulens, M. H. Storm, G. J. Roerink, W. M. L. Meijninger, “LGN2018: een nieuwe weergave van het grondgebruik in Nederland” (1566–7197, Wageningen Environmental Research, Wageningen, 2020); <https://edepot.wur.nl/523996>.
79. E. S. F. Heggem, H. Mathisen, J. Frydenlund, *AR50 – Arealressurskart i målestokk 1:50 000. Et heldekkende arealressurskart for jord- og skogbruk* (NIBIO, 2019); <https://nibio.brage.unit.no/nibio-xmlui/handle/11250/2626573>.
80. Institut Cartogràfic i Geològic de Catalunya, Cubiertas del suelo (2019). <https://www.icgc.cat/es/Ambitos-tematicos/Territori-sostenible/Cubiertas-del-suelo>.
81. R. D. Morton, C. G. Marston, A. W. O’Neil, C. S. Rowland, Land Cover Map 2018 (25m rasterised land parcels, GB), NERC Environmental Information Data Centre (2020); <https://doi.org/10.5285/25C6451B-5C88-40DA-9A63-C3EC473E4874>.
82. R. D. Morton, C. S. Rowland, C. M. Wood, L. Meek, C. G. Marston, G. M. Smith, Land Cover Map 2007 (25m raster, GB) v1.2, NERC EDS Environmental Information Data Centre (2014); <https://doi.org/10.5285/A1F88807-4826-44BC-994D-A902DA5119C2>.

83. Naturvårdsverkets Metadatakatalog för Geodata, Nationella marktäckedata 2018: basskikt. <https://geodatakatalogen.naturvardsverket.se/geonetwork/srv/swe/catalog.search#/metadata/8853721d-a466-4c01-afcc-9eae57b17b39>.
84. C. S. Rowland, R. D. Morton, L. Carrasco, G. McShane, A. W. O'Neil, C. M. Wood, Land Cover Map 2015 (25m raster, GB), NERC EDS Environmental Information Data Centre (2017); <https://doi.org/10.5285/BB15E200-9349-403C-BDA9-B430093807C7>.
85. Scottish Government, Scotland Habitat and Land Cover Map - 2020 (2024). <https://www.data.gov.uk/dataset/911c87c4-a0d3-4bb8-9089-f7657980113e/scotland-habitat-and-land-cover-map-2020>.
86. L. Yang, S. Jin, P. Danielson, C. Homer, L. Gass, S. M. Bender, A. Case, C. Costello, J. Dewitz, J. Fry, M. Funk, B. Granneman, G. C. Liknes, M. Rigge, G. Xian, A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies. *ISPRS J. Photogramm. Remote Sens.* **146**, 108–123 (2018).
87. D. Zanaga, R. Van De Kerchove, W. De Keersmaecker, N. Souverijns, C. Brockmann, R. Quast, J. Wevers, A. Grosu, A. Paccini, S. Vergnaud, O. Cartus, M. Santoro, S. Fritz, I. Georgieva, M. Lesiv, S. Carter, M. Herold, L. Li, N.-E. Tsendbazar, F. Ramoino, O. Arino, ESA WorldCover 10 m 2020 v100, version v100, Zenodo (2021); <https://doi.org/10.5281/ZENODO.5571936>.
88. E. Pebesma, Simple Features for R: Standardized Support for Spatial Vector Data. *R J.* **10**, 439 (2018).
89. R. J. Hijmans, J. van Etten, M. Sumner, J. Cheng, D. Baston, A. Bevan, R. Bivand, L. Busetto, M. Canty, B. Fasoli, D. Forrest, A. Ghosh, D. Golicher, J. Gray, J. A. Greenberg, P. Hiemstra, K. Hingee, A. Ilich, I. for M. A. Geosciences, C. Karney, M. Mattiuzzi, S. Mosher, B. Naimi, J. Nowosad, E. Pebesma, O. P. Lamigueiro, E. B. Racine, B. Rowlingson, A. Shortridge, B. Venables, R. Wueest, raster: Geographic Data Analysis and Modeling, version 3.6-26 (2023); <https://cran.r-project.org/web/packages/raster/index.html>.
90. B. B. Phillips, K. J. Gaston, J. M. Bullock, J. L. Osborne, Road verges support pollinators in agricultural landscapes, but are diminished by heavy traffic and summer cutting. *J. Appl. Ecol.* **56**, 2316–2327 (2019).
91. Geofabrik, OpenStreetMap, OpenStreetMap data (2024). <https://download.geofabrik.de/europe/>.
92. Ordnance Survey, OS Open Roads, *Ordnance Survey* (2024). <https://www.ordnancesurvey.co.uk/products/os-open-roads>.
93. U.S. Geological Survey, USGS National Transportation Dataset (2024). <https://data.usgs.gov/datacatalog/data/USGS:ad3d631d-f51f-4b6a-91a3-e617d6a58b4e>.

94. Yolo County, Yolo County Street Centerlines Open Data (2024). https://yodata-yolo.opendata.arcgis.com/datasets/f6321ba62a574a60b429f21133836bc6_2/explore?location=38.649186,-121.876677,12.34.
95. Dades obertes de Catalunya, Dades del mapa de Cultius amb origen DUN 2017 (2023). https://analisi.transparenciacatalunya.cat/Medi-Rural-Pesca/Dades-del-mapa-de-Cultius-amb-origen-DUN-2017/v982-gtrg/about_data.
96. W. Han, Z. Yang, L. Di, R. Mueller, CropScape: A Web service based application for exploring and disseminating US conterminous geospatial cropland data products for decision support. *Comput. Electron. Agric.* **84**, 111–123 (2012).
97. OneSoil, OneSoil Map (2024). <https://map.onesoil.ai/>.
98. Rural Payments Agency, Crop Map of England (CROME) 2018 (2023). <https://www.data.gov.uk/dataset/fb19d34f-59e6-48e7-820a-fe5fda3019e5/crop-map-of-england-crome-2018>.
99. M. Schwieder, G. O. Tetteh, L. Blickensdörfer, A. Gocht, S. Erasmi, Agricultural land use (raster) : National-scale crop type maps for Germany from combined time series of Sentinel-1, Sentinel-2 and Landsat data (2017 to 2021), version v201, Zenodo (2024); <https://doi.org/10.5281/ZENODO.10617623>.
100. Scottish Government, Scottish Crop Map 2019 (2021). <http://www.gov.scot/publications/scottish-crop-map-2019/>.
101. Urząd Marszałkowski Województwa Małopolskiego, Mapa glebowo-rolnicza (2024). https://miip.geomalopolska.pl/mapa/glebowo_rolnicza.html.
102. R Core Team, R: A language and environment for statistical computing, R Foundation for Statistical Computing (2021); <https://www.r-project.org/>.
103. M. Brooks E., K. Kristensen, K. Benthem J. ,van, A. Magnusson, C. Berg W., A. Nielsen, H. Skaug J., M. Mächler, B. Bolker M., glmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized Linear Mixed Modeling. *R J.* **9**, 378 (2017).
104. A. H. Aldercotte, D. T. Simpson, R. Winfree, Crop visitation by wild bees declines over an 8-year time series: A dramatic trend, or just dramatic between-year variation? *Insect Conserv. Divers.* **15**, 522–533 (2022).
105. M. van de Pol, J. Wright, A simple method for distinguishing within- versus between-subject effects using mixed models. *Anim. Behav.* **77**, 753–758 (2009).
106. F. Hartig, L. Lohse, DHARMA: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models, version 0.4.6 (2022); <https://cran.r-project.org/web/packages/DHARMA/index.html>.
107. M. Santon, F. Korner-Nievergelt, N. K. Michiels, N. Anthes, A versatile workflow for linear modelling in R. *Front. Ecol. Evol.* **11**, 1065273 (2023).

108. A. F. Zuur, E. N. Ieno, C. S. Elphick, A protocol for data exploration to avoid common statistical problems: *Data exploration. Methods Ecol. Evol.* **1**, 3–14 (2010).
109. D. Lüdecke, M. Ben-Shachar, I. Patil, P. Waggoner, D. Makowski, performance: An R Package for Assessment, Comparison and Testing of Statistical Models. *J. Open Source Softw.* **6**, 3139 (2021).
110. J. Fox, S. Weisberg, *An R Companion to Applied Regression* (SAGE, Los Angeles, ed. 3rd, 2019).
111. J. Fox, S. Weisberg, Visualizing Fit and Lack of Fit in Complex Regression Models with Predictor Effect Plots and Partial Residuals. *J. Stat. Softw.* **87** (2018).
112. D. Lüdecke, ggeffects: Tidy Data Frames of Marginal Effects from Regression Models. *J. Open Source Softw.* **3**, 772 (2018).
113. H. Wickham, *Ggplot2: Elegant Graphics for Data Analysis* (Springer New York, New York, NY, 2009; <https://link.springer.com/10.1007/978-0-387-98141-3>).
114. S. Garnier, N. Ross, Bob Rudis, A. P. Camargo, M. Sciaini, C. Scherer, Rvision - Colorblind-Friendly Color Maps for R, version 0.6.2, Zenodo (2023); <https://doi.org/10.5281/ZENODO.4679423>.
115. B. Auguie, A. Antonov, gridExtra: Miscellaneous Functions for “Grid” Graphics, version 2.3 (2017); <https://cran.r-project.org/web/packages/gridExtra/index.html>.
116. A. Magrath, F. P. Molina, I. Bartomeus, Niche complementarity among pollinators increases community-level plant reproductive success. *Peer Community J.* **1**, e1 (2021).
117. S. Laha, S. Chatterjee, A. Das, B. Smith, P. Basu, Exploring the importance of floral resources and functional trait compatibility for maintaining bee fauna in tropical agricultural landscapes. *J. Insect Conserv.* **24**, 431–443 (2020).
118. N. Beyer, D. Gabriel, F. Kirsch, K. Schulz-Kesting, J. Dauber, C. Westphal, Functional groups of wild bees respond differently to faba bean *Vicia faba* L. cultivation at landscape scale. *J. Appl. Ecol.* **57**, 2499–2508 (2020).
119. N. Beyer, F. Kirsch, D. Gabriel, C. Westphal, Identity of mass-flowering crops moderates functional trait composition of pollinator communities. *Landsc. Ecol.* **36**, 2657–2671 (2021).
120. R. Bommarco, S. A. M. Lindström, C. A. Raderschall, V. Gagic, O. Lundin, Flower strips enhance abundance of bumble bee queens and males in landscapes with few honey bee hives. *Biol. Conserv.* **263**, 109363 (2021).
121. B. J. Brosi, G. C. Daily, T. M. Shih, F. Oviedo, G. Duran, The effects of forest fragmentation on bee communities in tropical countryside. *J. Appl. Ecol.* **45**, 773–783 (2008).

122. B. J. Brosi, G. C. Daily, P. R. Ehrlich, Bee community shifts with landscape context in a tropical countryside. *Ecol. Appl.* **17**, 418–430 (2007).
123. H. Cohen, G. P. Smith, H. Sardiñas, J. F. Zorn, Q. S. McFrederick, S. H. Woodard, L. C. Ponisio, Mass-flowering monoculture attracts bees, amplifying parasite prevalence. *Proc. R. Soc. B Biol. Sci.* **288**, 20211369 (2021).
124. L. J. Cole, S. Brocklehurst, D. Robertson, W. Harrison, D. I. McCracken, Riparian buffer strips: Their role in the conservation of insect pollinators in intensive grassland systems. *Agric. Ecosyst. Environ.* **211**, 207–220 (2015).
125. L. J. Cole, S. Brocklehurst, D. Robertson, W. Harrison, D. I. McCracken, Exploring the interactions between resource availability and the utilisation of semi-natural habitats by insect pollinators in an intensive agricultural landscape. *Agric. Ecosyst. Environ.* **246**, 157–167 (2017).
126. K. R. Denning, B. L. Foster, Flower visitor communities are similar on remnant and reconstructed tallgrass prairies despite forb community differences. *Restor. Ecol.* **26**, 751–759 (2018).
127. K. R. Denning, B. L. Foster, Taxon-specific associations of tallgrass prairie flower visitors with site-scale forb communities and landscape composition and configuration. *Biol. Conserv.* **227**, 74–81 (2018).
128. J. Scheper, I. Badenhauer, J. Kantelhardt, S. Kirchweiger, I. Bartomeus, V. Bretagnolle, Y. Clough, N. Gross, I. Raemakers, M. Vilà, C. Zaragoza-Trello, D. Kleijn, Biodiversity and pollination benefits trade off against profit in an intensive farming system. *Proc. Natl. Acad. Sci.* **120**, e2212124120 (2023).
129. J. Ekroos, M. Rundlöf, H. G. Smith, Trait-dependent responses of flower-visiting insects to distance to semi-natural grasslands and landscape heterogeneity. *Landsc. Ecol.* **28**, 1283–1292 (2013).
130. T. P. M. Fijen, J. A. Scheper, B. Boekelo, I. Raemakers, D. Kleijn, Effects of landscape complexity on pollinators are moderated by pollinators' association with mass-flowering crops. *Proc. R. Soc. B Biol. Sci.* **286**, 20190387 (2019).
131. C. Martínez-Núñez, D. Kleijn, C. Ganuza, D. Heupink, I. Raemakers, W. Vertommen, T. P. M. Fijen, Temporal and spatial heterogeneity of semi-natural habitat, but not crop diversity, is correlated with landscape pollinator richness. *J. Appl. Ecol.* **59**, 1258–1267 (2022).
132. J. Fründ, K. E. Linsenmair, N. Blüthgen, Pollinator diversity and specialization in relation to flower diversity. *Oikos* **119**, 1581–1590 (2010).
133. D. Goulson, G. C. Lye, B. Darvill, Diet breadth, coexistence and rarity in bumblebees. *Biodivers. Conserv.* **17**, 3269–3288 (2008).
134. D. Goulson, M. E. Hanley, B. Darvill, J. S. Ellis, M. E. Knight, Causes of rarity in bumblebees. *Biol. Conserv.* **122**, 1–8 (2005).

135. I. Grass, J. Albrecht, F. Jauker, T. Diekötter, D. Warzecha, V. Wolters, N. Farwig, Much more than bees—Wildflower plantings support highly diverse flower-visitor communities from complex to structurally simple agricultural landscapes. *Agric. Ecosyst. Environ.* **225**, 45–53 (2016).
136. A. Holzschuh, C. F. Dormann, T. Tscharntke, I. Steffan-Dewenter, Expansion of mass-flowering crops leads to transient pollinator dilution and reduced wild plant pollination. *Proc. R. Soc. B Biol. Sci.* **278**, 3444–3451 (2011).
137. A. Holzschuh, I. Steffan-Dewenter, T. Tscharntke, Agricultural landscapes with organic crops support higher pollinator diversity. *Oikos* **117**, 354–361 (2008).
138. S. Hopfenmüller, I. Steffan-Dewenter, A. Holzschuh, Trait-Specific Responses of Wild Bee Communities to Landscape Composition, Configuration and Local Factors. *PLoS ONE* **9**, e104439 (2014).
139. B. Jauker, J. Krauss, F. Jauker, I. Steffan-Dewenter, Linking life history traits to pollinator loss in fragmented calcareous grasslands. *Landsc. Ecol.* **28**, 107–120 (2013).
140. E. Kallioniemi, J. Åström, G. M. Rusch, S. Dahle, S. Åström, J. O. Gjershaug, Local resources, linear elements and mass-flowering crops determine bumblebee occurrences in moderately intensified farmlands. *Agric. Ecosyst. Environ.* **239**, 90–100 (2017).
141. A. Kovács-Hostyánszki, R. Földesi, E. Mózes, Á. Szirák, J. Fischer, J. Hanspach, A. Báldi, Conservation of pollinators in traditional agricultural landscapes – New challenges in Transylvania (Romania) posed by EU accession and recommendations for future research. *PLOS ONE* **11**, e0151650 (2016).
142. E. Krimmer, E. A. Martin, J. Krauss, A. Holzschuh, I. Steffan-Dewenter, Size, age and surrounding semi-natural habitats modulate the effectiveness of flower-rich agri-environment schemes to promote pollinator visitation in crop fields. *Agric. Ecosyst. Environ.* **284**, 106590 (2019).
143. S. Kühnel, N. Blüthgen, High diversity stabilizes the thermal resilience of pollinator communities in intensively managed grasslands. *Nat. Commun.* **6**, 7989 (2015).
144. T. Roth, M. Coll, Y. Mandelik, The Role of Uncultivated Habitats in Supporting Wild Bee Communities in Mediterranean Agricultural Landscapes. *Diversity* **15**, 294 (2023).
145. G. Marcacci, I. Grass, V. S. Rao, S. Kumar S, K. B. Tharini, V. V. Belavadi, N. Nölke, T. Tscharntke, C. Westphal, Functional diversity of farmland bees across rural–urban landscapes in a tropical megacity. *Ecol. Appl.* **32**, e2699 (2022).
146. M. Monasterolo, S. L. Poggio, D. Medan, M. Devoto, Wider road verges sustain higher plant species richness and pollinator abundance in intensively managed agroecosystems. *Agric. Ecosyst. Environ.* **302**, 107084 (2020).
147. L. A. Morandin, C. Kremen, Hedgerow restoration promotes pollinator populations and exports native bees to adjacent fields. *Ecol. Appl.* **23**, 829–839 (2013).

148. J. Morrison, J. Izquierdo, E. H. Plaza, J. L. González-Andújar, The role of field margins in supporting wild bees in Mediterranean cereal agroecosystems: Which biotic and abiotic factors are important? *Agric. Ecosyst. Environ.* **247**, 216–224 (2017).
149. A. S. Persson, M. Rundlöf, Y. Clough, H. G. Smith, Bumble bees show trait-dependent vulnerability to landscape simplification. *Biodivers. Conserv.* **24**, 3469–3489 (2015).
150. J. Piko, A. Keller, C. Geppert, P. Batáry, T. Tschardtke, C. Westphal, A. L. Hass, Effects of three flower field types on bumblebees and their pollen diets. *Basic Appl. Ecol.* **52**, 95–108 (2021).
151. E. F. Power, J. C. Stout, Organic dairy farming: impacts on insect–flower interaction networks and pollination. *J. Appl. Ecol.* **48**, 561–569 (2011).
152. G. Quinlan, M. Milbrath, C. Otto, A. Smart, D. Iwanowicz, R. S. Cornman, R. Isaacs, Honey bee foraged pollen reveals temporal changes in pollen protein content and changes in forager choice for abundant versus high protein flowers. *Agric. Ecosyst. Environ.* **322**, 107645 (2021).
153. L. G. A. Riggi, O. Lundin, Å. Berggren, Mass-flowering red clover crops have positive effects on bumblebee richness and diversity after bloom. *Basic Appl. Ecol.* **56**, 22–31 (2021).
154. J. Scheper, T. Bukovinszky, M. E. Huigens, D. Kleijn, Attractiveness of sown wildflower strips to flower-visiting insects depends on seed mixture and establishment success. *Basic Appl. Ecol.* **56**, 401–415 (2021).
155. S. C. Simanonok, C. R. V. Otto, D. A. Buhl, Floral resource selection by wild bees and honey bees in the Midwest United States: implications for designing pollinator habitat. *Restor. Ecol.* **29**, e13456 (2021).
156. D. Bourke, D. Stanley, E. O’Rourke, R. Thompson, T. Carnus, J. Dauber, M. Emmerson, P. Whelan, F. Hecq, E. Flynn, L. Dolan, J. Stout, Response of farmland biodiversity to the introduction of bioenergy crops: effects of local factors and surrounding landscape context. *GCB Bioenergy* **6**, 275–289 (2014).
157. D. A. Stanley, J. C. Stout, Quantifying the impacts of bioenergy crops on pollinating insect abundance and diversity: a field-scale evaluation reveals taxon-specific responses. *J. Appl. Ecol.* **50**, 335–344 (2013).
158. A. Magrach, J. P. González-Varo, M. Boiffier, M. Vilà, I. Bartomeus, Honeybee spillover reshuffles pollinator diets and affects plant reproductive success. *Nat. Ecol. Evol.* **1**, 1299–1307 (2017).
159. A. Magrach, A. Holzschuh, I. Bartomeus, V. Riedinger, S. P. M. Roberts, M. Rundlöf, A. Vujić, J. B. Wickens, V. J. Wickens, R. Bommarco, J. P. González-Varo, S. G. Potts, H. G. Smith, I. Steffan-Dewenter, M. Vilà, Plant-pollinator networks in semi-natural grasslands are resistant to the loss of pollinators during blooming of mass-flowering crops. *Ecography*, n/a-n/a (2017).

160. M. F. Tanis, L. Marshall, J. C. Biesmeijer, L. van Kolfshoten, Grassland management for meadow birds in the Netherlands is unfavourable to pollinators. *Basic Appl. Ecol.* **43**, 52–63 (2020).
161. S. Tarrant, J. Ollerton, M. L. Rahman, J. Tarrant, D. McCollin, Grassland Restoration on Landfill Sites in the East Midlands, UNITED KINGDOM : An Evaluation of Floral Resources and Pollinating Insects. *Restor. Ecol.* **21**, 560–568 (2013).
162. A. J. Vanbergen, B. A. Woodcock, A. Gray, F. Grant, A. Telford, P. Lambdon, D. S. Chapman, R. F. Pywell, M. S. Heard, S. Cavers, Grazing alters insect visitation networks and plant mating systems. *Funct. Ecol.* **28**, 178–189 (2014).
163. V. von Königslöw, F. Fornoff, A.-M. Klein, Pollinator enhancement in agriculture: comparing sown flower strips, hedges and sown hedge herb layers in apple orchards. *Biodivers. Conserv.*, doi: 10.1007/s10531-021-02338-w (2021).
164. V. von Königslöw, A.-C. Mupepele, A.-M. Klein, Overlooked jewels: Existing habitat patches complement sown flower strips to conserve pollinators. *Biol. Conserv.* **261**, 109263 (2021).
165. C. N. Weiner, M. Werner, K. E. Linsenmair, N. Blüthgen, Land-use impacts on plant–pollinator networks: interaction strength and specialization predict pollinator declines. *Ecology* **95**, 466–474 (2014).
166. A. Wen, K. J. Elgersma, M. E. Sherrard, L. L. Jackson, J. Meissen, M. C. Myers, Wild bee visitors and their association with sown and unsown floral resources in reconstructed pollinator habitats within an agriculture landscape. *Insect Conserv. Divers.* **15**, 102–113 (2022).
167. N. I. Wilkinson, J. D. Wilson, G. Q. A. Anderson, Agri-environment management for corncrake *Crex crex* delivers higher species richness and abundance across other taxonomic groups. *Agric. Ecosyst. Environ.* **155**, 27–34 (2012).
168. T. J. Wood, J. Gibbs, N. Rothwell, J. K. Wilson, L. Gut, J. Brokaw, R. Isaacs, Limited phenological and dietary overlap between bee communities in spring flowering crops and herbaceous enhancements. *Ecol. Appl.* **28**, 1924–1934 (2018).

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Supplementary Materials

Materials and Methods

Supplementary Text

Figs. S1 to S7

Tables S1 to S8

References (51–168)

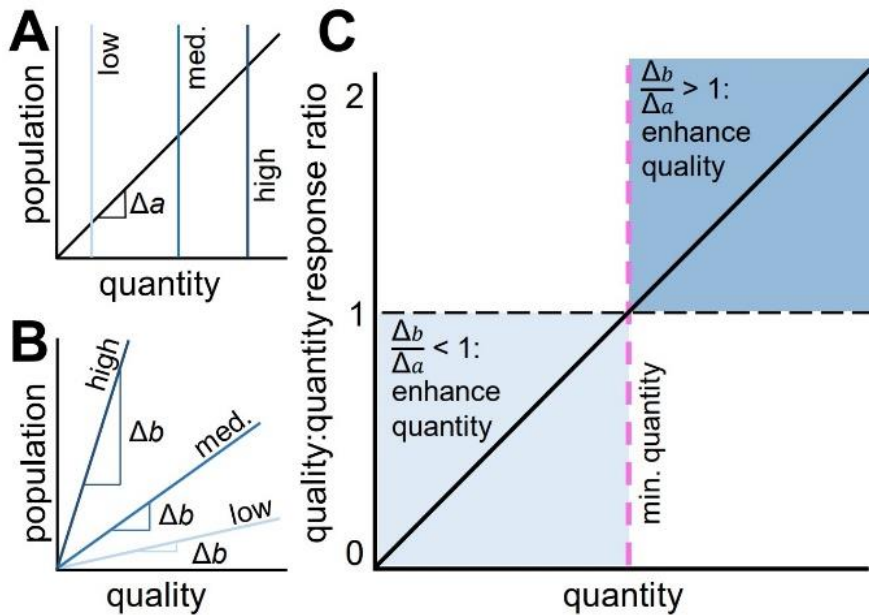


Fig. 1. Minimum habitat quantity level for application of conservation measures as defined by the relative effectiveness of enhancing habitat quantity or quality. (A) Population size increases with increasing habitat quantity (Δa), which causes (B) the effect of habitat quality on population size (Δb) to increase with increasing habitat quantity (low to high), leading to (C) increasing quality:quantity population response ratios ($\Delta b/\Delta a$) with increasing habitat quantity. The quantity level at which the population response ratio = 1 can be seen as a minimum quantity level after which application of conservation practice should also enhance habitat quality.

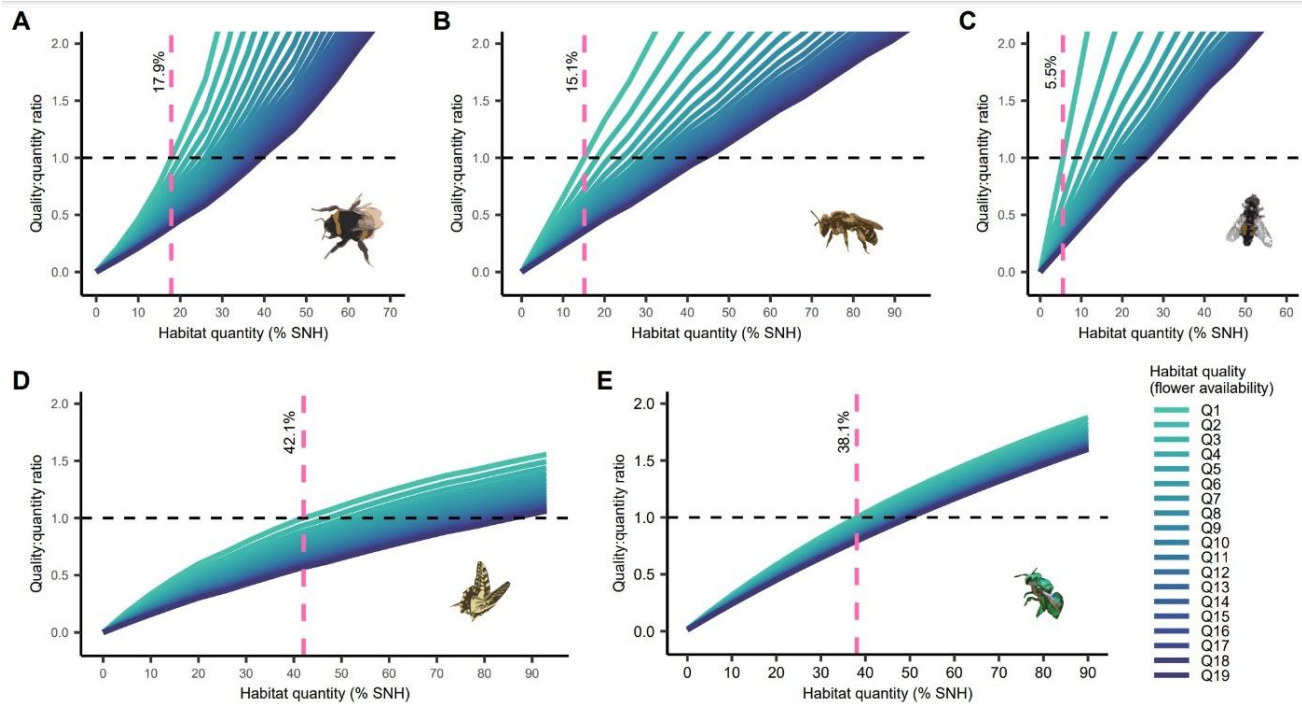


Fig. 2. Relationships between the habitat quality to quantity population response ratio and the cover of landscape semi-natural habitat (SNH) for landscape-level pollinator abundances. (A) bumble bees, (B) solitary bees, (C) hoverflies, (D) butterflies, and (E) tropical bees. Ratios < 1 indicate that increasing habitat quantity is most beneficial, while those > 1 indicate that habitat quality should also be prioritized. Minimum values of landscape SNH are marked where increasing habitat quality becomes more beneficial than increasing habitat quantity, assuming the lowest level of habitat quality (flower cover and richness quantile Q1; at Q20 the only option is to increase habitat quantity so it is not shown).

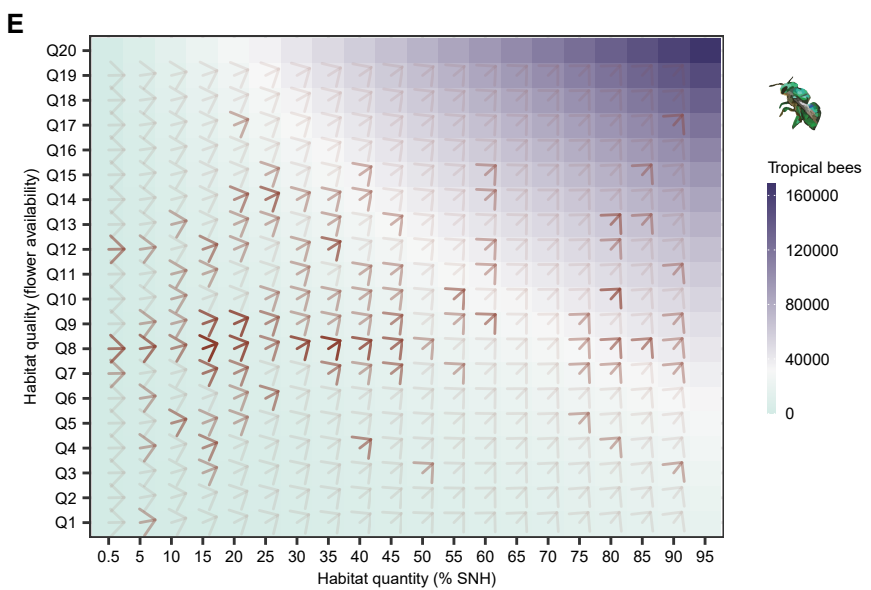
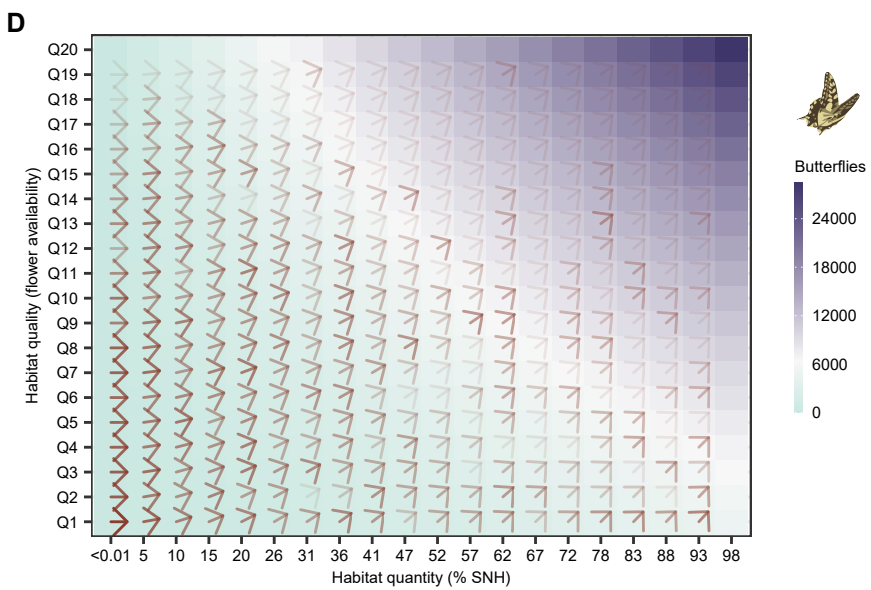
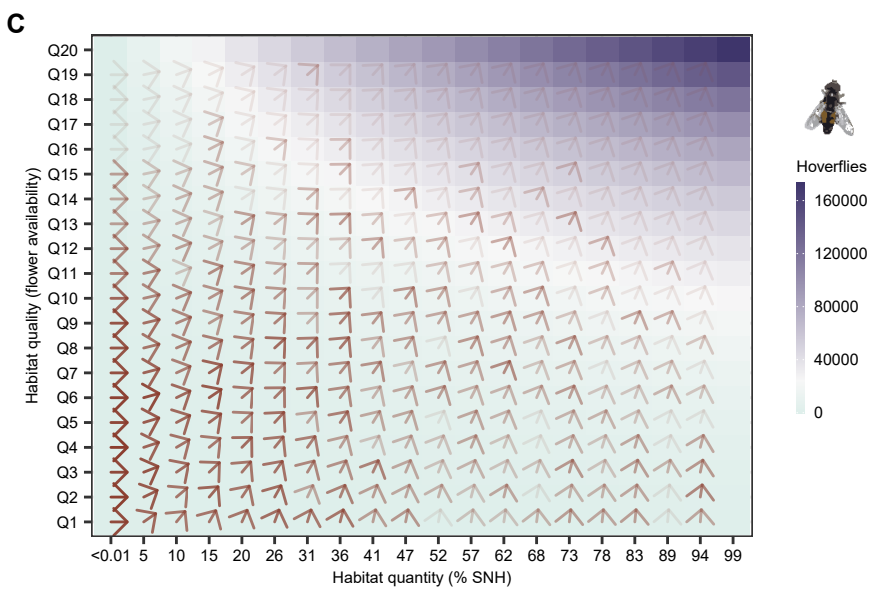
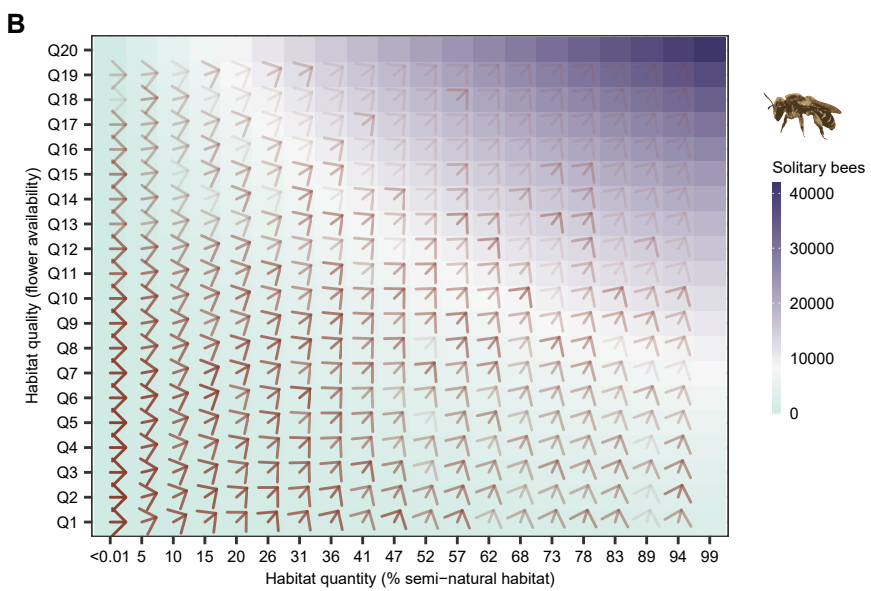
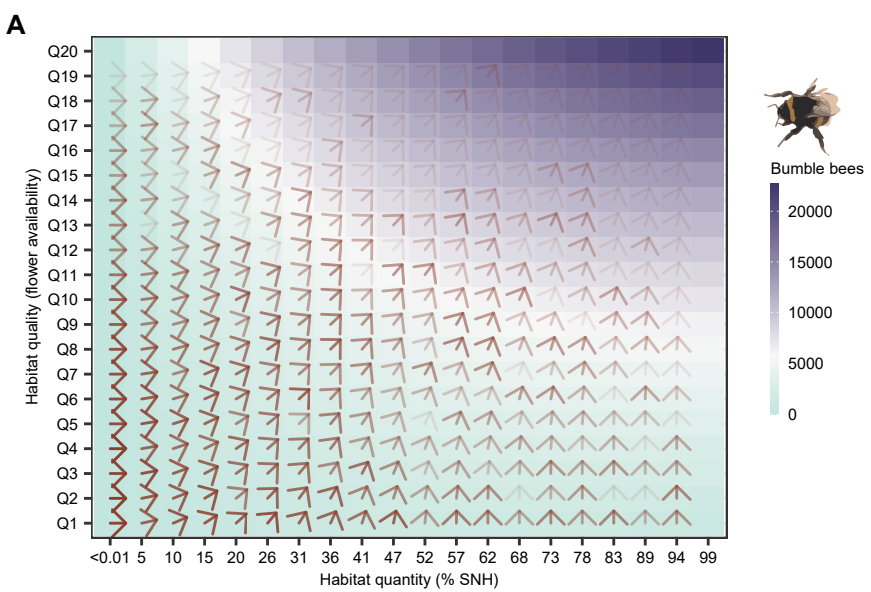


Fig. 3. The relative gain in landscape-level pollinator abundances from increasing habitat quantity or quality. (A) bumble bees, (B) solitary bees, (C) hoverflies, (D) butterflies, and (E) tropical bees. Quantity and quality are expressed across the 20 quantiles of the ranges observed in the datasets. Rightward or upward arrows indicate that increasing habitat quantity or quality is most beneficial, respectively. Arrow transparency indicates the number of samples that fall within a given quantity-quality combination (darkest arrows, highest number of samples; lightest arrows, no samples). Q1-Q20 indicate quantiles of flower availability (flower cover and richness). SNH, semi-natural habitat.

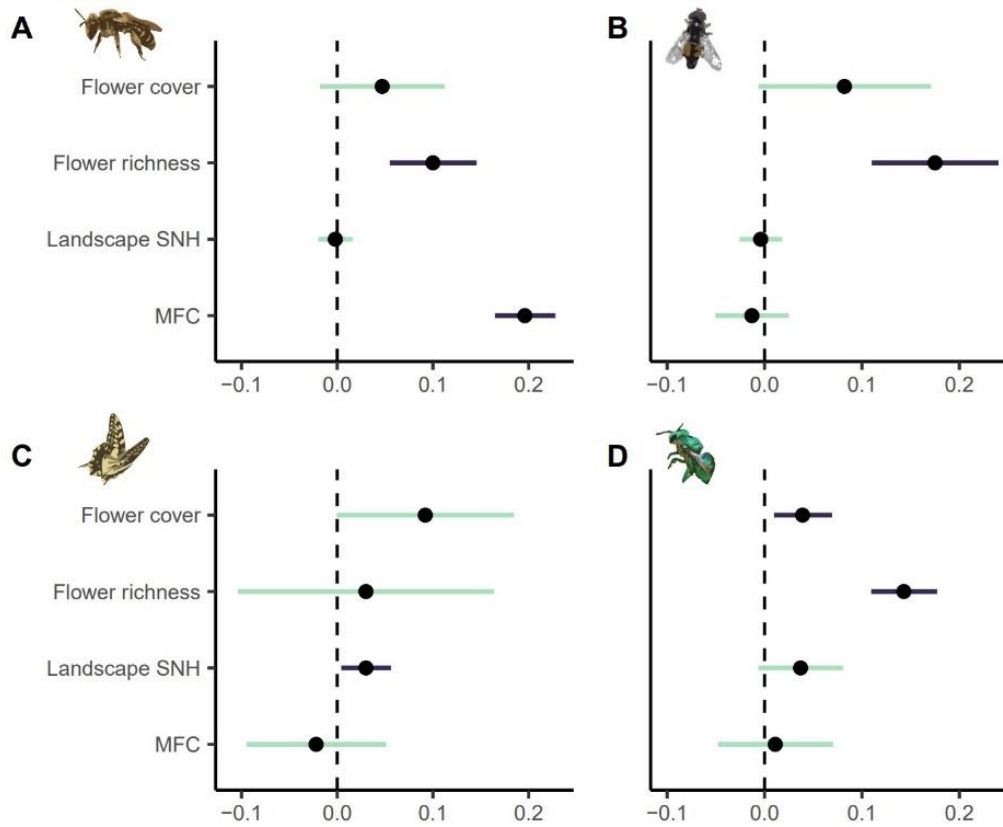


Fig. 4. Standardized beta coefficients and 95% confidence intervals for model main effects predicting local pollinator densities (log scale). (A) solitary bees, (B) hoverflies, (C) butterflies, and (D) tropical bees. See Fig. 5 for bumble bee model main and interaction effects. Dark confidence intervals do not overlap zero ($p < 0.05$). MFC, mass-flowering crop presence. SNH, semi-natural habitat. For effects visualizations, see figs. S4-S7, and for coefficient evaluations see tables S4-S7.

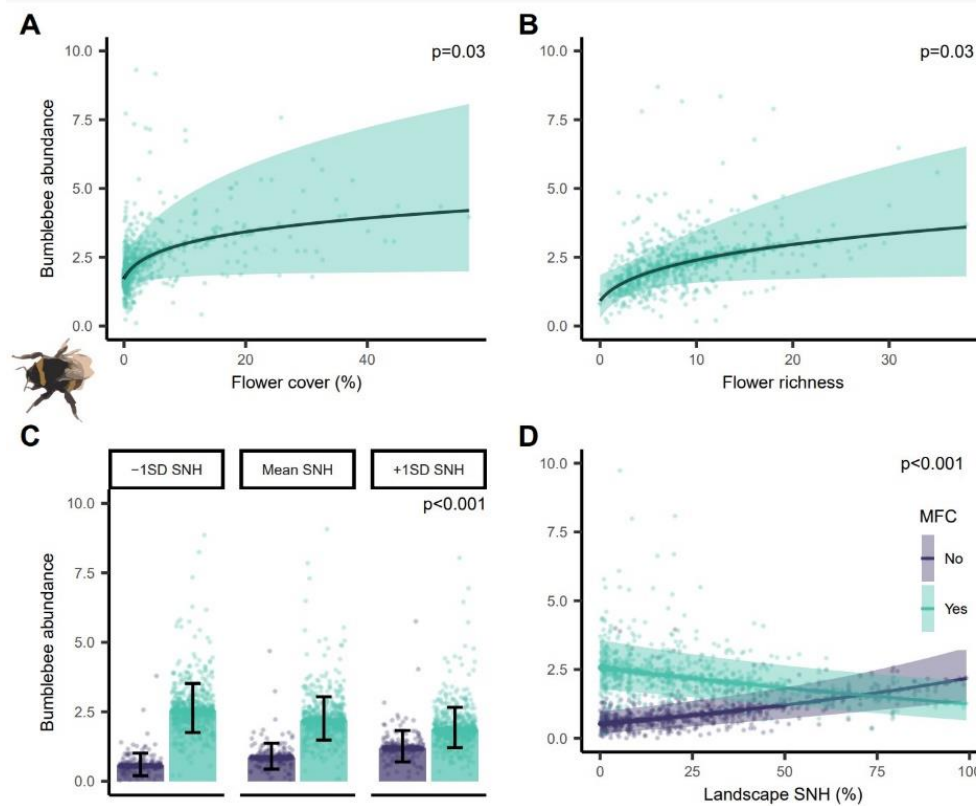


Fig. 5. Conditional effects of local and landscape habitat parameters on local bumble bee densities. (A) flower cover, (B) flower richness, (C) mass-flowering crop (MFC) presence, and (D) landscape semi-natural habitat (SNH). Panels (C) and (D) illustrate the significant interaction between SNH and MFC presence. Abundances are expressed per 150 m² and 15 min sampling. Points represent back-transformed partial residuals. SD, standard deviation. For model coefficients, see table S3.

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Supplementary Materials for

Current policies fall short of effective pollinator conservation in agricultural landscapes

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Materials and Methods

Criteria definition

We predefined a list of criteria for the inclusion of datasets based on our research objective, which was to synthesize the effects of habitat quantity and quality variables on local pollinator densities and landscape pollinator abundances. We defined four main topic-based criteria (Box 1 “Criteria”) to ensure studies measured wild pollinators and flowers in semi-natural habitats within agricultural areas. We focused on bees, hoverflies, and butterflies (including burnet moths) because they are best studied in agricultural landscapes due to their contributions to crop pollination (31) and their conservation concern (32). We considered all natural and semi-natural herbaceous and woody habitats, including extensive grasslands and perennial (older than one year) wildflower strips but excluding rotational or otherwise intensively managed areas, as semi-natural habitats. While nesting and oviposition resources can also be considered habitat quality indicators because they are important for pollinator reproduction, we chose to focus on floral resources because these are more easily and commonly measured and because resources for reproduction are generally captured by the amount of non-productive habitat in a given landscape (27). We defined seven specific criteria related to sampling methods and sample size for standardization and data quality purposes. We required studies to have sampled pollinators in a defined surface area and for a defined time duration to be able to calculate a standardized density of pollinators per area and sampling time, which was necessary for upscaling pollinator densities to the landscape scale. Butterfly sampling was not required to have a defined sampling duration because the standard accepted method in the field for sampling this group (“Pollard walks”; (51)) is not timed. We furthermore required studies to have sampled both flower richness and flower cover, since we use these variables as habitat quality proxies. We required flower cover to be measured quantitatively, such as flower counts or area coverage, so that flower cover for all studies could be uniformly calculated in units of percentage cover. Studies had to have measured pollinators in different landscapes (i.e., sufficient spatial replication; minimum 500 m radius), with at least ten landscapes and 20 total data points (sampling events). This allowed us to evaluate the effect of landscape context (% semi-natural habitat cover) and have a base level of replication to do so. If datasets met these requirements, we asked data owners to confirm two additional criteria. We required site coordinates for calculating surrounding landscape characteristics and spatial autocorrelation. We also required that studies covered a minimum gradient of 10% in semi-natural habitat cover, that is, that the study sampled a variety of landscape contexts, since evaluating the effects of habitat quantity and quality across a range of landscape contexts was a primary research objective.

Box 1. Criteria

Title-abstract screening

- a. Species groups: wild bees, wild bumble bees, hoverflies, or butterflies (including burnet moths)
- b. Locations: agricultural landscapes
- c. Habitat types: semi-natural habitats (not crop fields)
- d. Environmental variables: flowers

Full-text screening

- a. Sampling method: defined area (not e.g. pan traps)
- b. Sampling method: defined time per unit area (excl. butterflies)
- c. Environmental variables: floral richness and floral cover at the time of pollinator sampling
- d. Sampling method: quantitative* measure of floral cover
- e. Locations: different landscapes (buffer min. 500 m)**
- f. Sample size: at least 10 landscapes
- g. Sample size: at least 20 data points

Additional screening

- a. Data: coordinate availability
- b. Locations: range in landscape semi-natural habitat cover > 10%

*We accepted studies that counted flowers or that measured flower area or percentage cover. We only accepted studies using qualitative scales if the scale could be readily and accurately translated into percentage cover (e.g., Domin scale; (52)).

**The study might not have organized its sampling locations into landscapes, but we required enough spatial replication to do so.

Literature search and screening

We followed guidelines from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (53) in conducting our literature screening. We utilized two literature databases to evaluate published literature, and additionally solicited research networks for unpublished datasets. We first created a “naïve” search string based on our four main topic criteria. This search string of 19 terms (Box 2 “Search strings”) was expanded to a string of 87 terms using litsearchr, an R package that performs quasi-automatic search string development for systematic reviews (54), according to the approach of Grames et al. (55). We retrieved articles in English from Web of Science and Scopus on 19/09/22. We first screened titles and abstracts based on our first four criteria. When relevant review or synthesis papers were encountered, we retained these (17 in total) for reference “snowballing”, i.e., adding the studies that those papers cited and/or synthesized to the overall group of studies for screening. Studies that met our criteria at the title and abstract stage were evaluated based on the full text for our seven additional criteria. All screening was performed by one author using the online tool CADIMA (56). When a study met all of our full-text criteria, we contacted the corresponding author to request the

dataset and to evaluate our two additional criteria, which could not always be deduced from the text. We additionally gathered eight datasets external to our literature screen that met our criteria. The PRISMA flow diagram representing our study screening is presented in fig. S1.

Box 2. Search strings

“Naïve” search string

("pollinator*" OR "bee*" OR "bumblebee*" OR "hoverfl*" OR "hover fl*" OR "butterfl*") AND ("floral resource*" OR "flower*" OR "forb*") AND ("landscape*" OR "semi-natural habitat*" OR "natural habitat*") AND ("agricultur*" OR "agroeco*" OR "farm*")

Final Scopus search string

("floral* visitor*" OR "flower-visit* insect*" OR "flower* visitor*" OR "hover* flies" OR "pollin* insect*" OR apida* OR apoidea* OR bee OR bombus* OR butterfly* OR hoverfl* OR lasioglossum* OR lepidoptera* OR osmia* OR pollin* OR syrphid* OR bumble bee*) AND ("forag* avail*" OR "forag* plant*" OR "forag* resourc*" OR "habitat* qualit*" OR "resourc* abund*" OR "resourc* avail*" OR "resourc* provis*" OR floral* OR flower* OR forb* OR nectar* OR pollen*) AND ("adjac* habitat*" OR "buffer* strip*" OR "field* border*" OR "field* boundar*" OR "field* margin*" OR "flower-rich* habitat*" OR "flower* field*" OR "flower* patch*" OR "flower* strip*" OR "forag* habitat*" OR "habitat* featur*" OR "habitat* patch*" OR "habitat* type*" OR "landscap* element*" OR "landscap* featur*" OR "natur* area*" OR "natur* habitat*" OR "non-crop* habitat*" OR "pollin* habitat*" OR "suitabl* habitat*" OR "wood* habitat*" OR "field* edge" OR "forest* edge" OR grassland* OR hedg* OR pastur* OR "road* verg*" OR semi-natur* OR "wildflow* plant*") AND ("agricultur* area*" OR "agricultur* ecosystem*" OR "agricultur* environ*" OR "agricultur* field*" OR "agricultur* habitat*" OR "agricultur* manag*" OR "agricultur* practic*" OR "agricultur* product*" OR "agricultur* region*" OR "agricultur* site*" OR "agricultur* system*" OR "arabl* field*" OR "cultiv* field*" OR "cultiv* land*" OR "manag* agricultur*" OR "manag* field*" OR "manag* grassland*" OR "manag* landscap*" OR "rural* landscap*" OR agri-environ* OR "agricultur* land*" OR agricultur* OR agro-ecosystem* OR agroecosystem* OR "arabl* land*" OR crop* OR cultiv* OR farm* OR "adjac* field*")

(cont. below)

Box 2 (cont.). Search strings

Final Web of Science search string (variation in formatting)

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((TI=(“floral* visitor*” OR “flower-visit* insect*” OR “flower* visitor*” OR “hover* flies” OR “pollin* insect*” OR apida* OR apoidea* OR bee OR bombus* OR butterfly* OR hoverfl* OR lasioglossum* OR lepidoptera* OR osmia* OR pollin* OR syrphid* OR bumblebee*)) OR (AB=(“floral* visitor*” OR “flower-visit* insect*” OR “flower* visitor*” OR “hover* flies” OR “pollin* insect*” OR apida* OR apoidea* OR bee OR bombus* OR butterfly* OR hoverfl* OR lasioglossum* OR lepidoptera* OR osmia* OR pollin* OR syrphid* OR bumblebee*)) OR (AK=(“floral* visitor*” OR “flower-visit* insect*” OR “flower* visitor*” OR “hover* flies” OR “pollin* insect*” OR apida* OR apoidea* OR bee OR bombus* OR butterfly* OR hoverfl* OR lasioglossum* OR lepidoptera* OR osmia* OR pollin* OR syrphid* OR bumblebee*))) AND ((TI=(“forag* avail*” OR “forag* plant*” OR “forag* resourc*” OR “habitat* qualit*” OR “resourc* abund*” OR “resourc* avail*” OR “resourc* provis*” OR floral* OR flower* OR forb* OR nectar* OR pollen*)) OR (AB=(“forag* avail*” OR “forag* plant*” OR “forag* resourc*” OR “habitat* qualit*” OR “resourc* abund*” OR “resourc* avail*” OR “resourc* provis*” OR floral* OR flower* OR forb* OR nectar* OR pollen*)) OR (AK=(“forag* avail*” OR “forag* plant*” OR “forag* resourc*” OR “habitat* qualit*” OR “resourc* abund*” OR “resourc* avail*” OR “resourc* provis*” OR floral* OR flower* OR forb* OR nectar* OR pollen*))) AND ((TI=(“adjac* habitat*” OR “buffer* strip*” OR “field* border*” OR “field* boundar*” OR “field* margin*” OR “flower-rich* habitat*” OR “flower* field*” OR “flower* patch*” OR “flower* strip*” OR “forag* habitat*” OR “habitat* featur*” OR “habitat* patch*” OR “habitat* type*” OR “landscap* element*” OR “landscap* featur*” OR “natur* area*” OR “natur* habitat*” OR “non-crop* habitat*” OR “pollin* habitat*” OR “suitabl* habitat*” OR “wood* habitat*” OR “field* edge” OR “forest* edge” OR grassland* OR hedg* OR pastur* OR “road* verg*” OR semi-natur* OR “wildflow* plant*”)) OR (AB=(“adjac* habitat*” OR “buffer* strip*” OR “field* border*” OR “field* boundar*” OR “field* margin*” OR “flower-rich* habitat*” OR “flower* field*” OR “flower* patch*” OR “flower* strip*” OR “forag* habitat*” OR “habitat* featur*” OR “habitat* patch*” OR “habitat* type*” OR “landscap* element*” OR “landscap* featur*” OR “natur* area*” OR “natur* habitat*” OR “non-crop* habitat*” OR “pollin* habitat*” OR “suitabl* habitat*” OR “wood* habitat*” OR “field* edge” OR “forest* edge” OR grassland* OR hedg* OR pastur* OR “road* verg*” OR semi-natur* OR “wildflow* plant*”))) AND ((TI=(“agricultur* area*” OR “agricultur* ecosystem*” OR “agricultur* environ*” OR “agricultur* field*” OR “agricultur* habitat*” OR “agricultur* manag*” OR “agricultur* practic*” OR “agricultur* product*” OR “agricultur* region*” OR “agricultur* site*” OR “agricultur* system*” OR “arabl* field*” OR “cultiv* field*” OR “cultiv* land*” OR “manag* agricultur*” OR “manag* field*” OR “manag* grassland*” OR “manag* landscap*” OR “rural* landscap*” OR agri-environ* OR “agricultur* land*” OR agricultur* OR agro-ecosystem* OR agroecosystem* OR “arabl* land*” OR crop* OR cultiv* OR farm* OR “adjac* field*”)) OR (AB=(“agricultur* area*” OR “agricultur* ecosystem*” OR “agricultur* environ*” OR “agricultur* field*” OR “agricultur* habitat*” OR “agricultur* manag*” OR “agricultur* practic*” OR “agricultur* product*” OR “agricultur* region*” OR “agricultur* site*” OR “agricultur* system*” OR “arabl* field*” OR “cultiv* field*” OR “cultiv* land*” OR “manag* agricultur*” OR “manag* field*” OR “manag* grassland*” OR “manag* landscap*” OR “rural* landscap*” OR agri-environ* OR “agricultur* land*” OR agricultur* OR agro-ecosystem* OR agroecosystem* OR “arabl* land*” OR crop* OR cultiv* OR farm* OR “adjac* field*”)))
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Data preparation

We extracted data on three local-scale and two landscape-scale variables from each dataset. The three local-scale variables were pollinator (bumble bee, solitary bee, hoverfly, butterfly) densities, flower cover, and flower richness. We separated bumble bees and solitary bees due to their differences in life history and different geographic distributions (57). While Halictidae do exhibit social behaviors (58), here we separate truly eusocial bees (*Bombus*) from other bees and for simplicity refer to all non-*Bombus* bees in temperate regions as solitary. We separately analyzed datasets from the tropics, and we had enough data to include bees from tropical regions as a pollinator group, but not enough data for other species groups. In the tropics social bees (e.g., wild *Apis spp.*) can make up a majority of the bee community (57), so these were combined with other wild bees. *Apis mellifera* counts were excluded from all datasets because they were always managed, and our study focused on the conservation of wild pollinators. The landscape-scale variables were the percentage cover of semi-natural habitat and the presence of a blooming mass-flowering crop in the surrounding landscape (500 m radius) during the sampling period.

Local variables

Pollinator densities and floral resources (flower cover and richness of plants in bloom) were first calculated on the lowest sampling unit per study (e.g., quadrat or transect). If flower data were provided as counts, the flower area was calculated according to the methods of Scheper et al. (59) by multiplying the number of flowers per species (in some cases approximate, if flowers were recorded in umbels, heads, or stems) by an average flower area based on direct measurements and key botanical resources (60–69) and summing the area across species to yield total flower area. This area was divided by the sampling area to result in percentage flower cover. When flowers were sub-sampled (e.g., in sub-quadrats) within the sampling area, flower cover was first calculated per sub-sample and then averaged across sub-samples, while flower richness was calculated as the total number of unique species across sub-samples. To combine studies into one model, data were aggregated to the lowest nesting level across studies, which was landscapes within studies. This allowed us to model general relationships between habitat variables and pollinator densities regardless of differences across studies in sampling periods or number of surveys. We furthermore aggregated data across sampled habitat types to generalize these aforementioned relationships, which themselves capture inherent quality differences among habitats. Floral resource variables were averaged across samples within landscapes. Bee and hoverfly densities were standardized per landscape according to the following equation:

$$D = \frac{\sum_{i=1}^n P_i}{\sqrt{\frac{\sum_{i=1}^n A_i \times \sum_{i=1}^n T_i}{150 \times 15}}}$$

with D being the average pollinator density per 150 m² and 15 min sampling effort, P_i being the abundance of pollinators recorded in a sample within a landscape, and A_i and T_i being the area and time surveyed per sample within a landscape, in m² and min, respectively. We chose to standardize to densities per 150 m² and 15 min because these were the median survey efforts used for bees and hoverflies. For butterflies, the equation was slightly different, because surveys were not necessarily timed. In addition, the median survey area was larger (300 m²), so we divided the sum of butterflies by the sum of area surveyed over 300, per landscape. If a study had

$\geq 50\%$ of landscapes with zero pollinators recorded for a given species group, we excluded that species group from the study for data quality purposes.

Landscape composition

While landscape composition can be represented by several variables, we chose total pollinator habitat quantity as a landscape habitat indicator so that we could model pollinator density responses to landscape habitat availability and to extrapolate local densities to landscape abundances (see subsection Analysis). We calculated the % semi-natural habitat in a 500 m radius surrounding the center of each study landscape. We chose this radius because it captured a landscape habitat resources scale relevant to all pollinator groups included in our study (23–26), in particular because it represents the upper end of average foraging distances for the central-place foraging pollinators in our study (23). For studies that did not have sampling locations already grouped into landscapes, individual sampling sites were manually assigned to groups to create landscapes of minimum 500 m radius (i.e., minimum 1 km apart). The center of a landscape was defined as the geodesic centroid between grouped sampling locations, when applicable. Using these points, the semi-natural habitat cover was calculated in a 500 m buffer based on available land use/land cover GIS data relevant to the study area and period (70–87) using the *sf* (88) and *raster* (89) R packages. Semi-natural habitat was defined as forests (plantations were not distinguishable), shrublands, heath, (semi-)natural grasslands, wetlands, and (semi-)natural vegetation elements within the agricultural matrix. The only exception to this was Study G (table S1), for which we only included the habitat type in which sampling occurred (grasslands), because otherwise nearly the entire study area was estimated to be semi-natural habitat by the available data source (87) due to the high classification of tree cover. If no GIS data were available, or if zeroes were produced due to the coarseness of GIS data layers, we either a) used the semi-natural habitat cover in a 500 m radius provided by the dataset, b) estimated road verge semi-natural habitat cover, often the only remnant pollinator habitat in nearly cleared agricultural landscapes (90), by applying a 1 m buffer around roads in the study landscapes (70, 91–94), or c) estimated semi-natural habitat cover manually by tracing habitat patches using satellite images in GoogleEarth. We furthermore estimated the presence or absence of a blooming mass-flowering crop (Yes/No) in study landscapes (at any point in the study period, since samples were averaged within landscapes) based on available cropland GIS layers (95–101) and information provided by the data owners.

Analysis

All statistical analyses were conducted in R version 4.1.2 (102). We constructed linear mixed models using *glmmTMB* (103) for the four separate pollinator groups (bumble bees, solitary bees, hoverflies, and butterflies) from temperate regions, and an additional model for bees from tropical regions. These models tested the effects of local and landscape variables on the local densities of pollinators in semi-natural habitats. The $\log_{10}(+1)$ -transformed densities of pollinators were used as response variables, and flower richness, flower cover, % semi-natural habitat, and blooming mass-flowering crop presence were predictor variables. We included an interaction between blooming mass-flowering crop presence and % semi-natural habitat to test if the effect of crop floral resources on pollinator densities depended on the amount of alternative habitat available in the landscape (and therefore alternative floral resources). We did not include

an interaction between flower variables and % semi-natural habitat (habitat quality and habitat quantity interaction) since here these variables represent effects on the local scale only. While a plausible interaction, it did not represent our research objective, which was to explore the combined effects of habitat quantity and quality on pollinator abundance at the landscape scale instead (see below). We did however check that we were not missing this interaction (see below). We furthermore included the average survey area and average survey minutes per landscape as covariates to control for the effect of actual survey effort on our calculated densities. Because they were right-skewed, average survey area, average survey minutes, flower cover, and flower richness were all log-transformed to improve the linearity of the modelled relationship. All continuous predictor variables were standardized (i.e., z-scores) across all studies to aid model convergence and to compare effect sizes. We additionally added weights to each datapoint using the number of observations per landscape (on which the standardized pollinator densities were based) to control for variation in sample sizes, and therefore robustness of the relationships, both within and across studies.

Following the methods of Dainese et al. (3), we used study-year combinations as the highest hierarchical unit because the majority of studies ($n=40$) only had one year of data collection and studies with multiple years often varied site locations across years. Furthermore, interannual variability in pollinator abundances (104) can allow different years of data collection within the same study to be regarded separately. Study-year was thus fit as a random intercept to capture differences between studies, and random slopes were fit for each study-year for both of the floral resource variables. This allowed us to control for differences among studies in flower abundance sampling methods and in the total area of the flower survey, which would influence floral richness. We did not include a random slope for semi-natural habitat cover because it was calculated uniformly for all datasets, and because we aimed to model the effect of this variable across its entire range instead of only within the ranges in each individual study. Because random slopes caused model convergence issues in the tropical bees model (due to the small number of studies), we instead centered floral resource variables within studies before standardizing across studies, which approximates within-study relationships between floral resources and pollinator density (105). However, this prevents floral resource variables from being expressed on an absolute scale in landscape-scale extrapolations (see below). Due to the presence of spatial autocorrelation in the four temperate region models, which was evaluated with the DHARMA package (106) and by comparing semivariograms to expected semivariances (107), we included a Matern correlation structure using the spatial coordinates of each study landscape. We inspected residual plots to evaluate model assumptions, and we confirmed that all variance inflation factors were below 4 (108) using the performance package (109). Partial residual plots were inspected using the effects package (110) to ensure the linearity of relationships and the absence of unmodelled interactions (111). We used log-likelihood ratio tests to evaluate model fixed effects and dropped the interaction term from the model if it was not significant.

Since mass-flowering crop presence was not necessarily a within-study factor for every study (i.e., some studies had all landscapes with mass-flowering crops, or all landscapes without), we checked the robustness of our results for this fixed effect by repeating our models with only the subset of studies that had mass-flowering crop presence as a within-study factor. This check revealed that effects for this factor were consistent (Table S8).

As a secondary analysis step, we extrapolated pollinator densities to the landscape scale to evaluate the relative impact of improving habitat quantity or quality in different landscape contexts. Following the method of Fijen et al. (30), we separated both habitat quantity (% landscape semi-natural habitat) and habitat quality (both floral resource variables) into 20 quantiles (i.e., steps representing 5% of the range) along the entire range observed in the included studies. For the tropics model, this was a relative range for the floral resource variables, since we centered these variables within studies and thus the values were not comparable across studies. We then created a matrix made up of predicted pollinator densities based on our models at each of the combinations between the 20 quantity and quality quantiles, while holding crop flowering and sampling effort constant (mass-flowering crop = no; area surveyed = 150 m² [or, for butterflies, 300 m²]; time surveyed = 15 min). For the bumble bee model, which had a significant interaction between mass-flowering crop flowering and landscape semi-natural habitat (figure 4D; table S3), we predicted at an “average” level of mass-flowering crop flowering to more accurately model the effect of habitat quantity (112). Next we extrapolated these pollinator densities to the landscape scale by multiplying the (back-transformed) density per m² (predicted density / 150 or 300) by the coverage in m² of semi-natural habitat in the landscape (% semi-natural habitat of the given quantile / 100 * π * 500²) (29, 45), assuming a linear abundance-area relationship (22). Using these results we calculated the quality:quantity population response ratio by dividing the population increase with one quantile increase in habitat quality by the population increase with one quantile increase in habitat quantity for each quality-quantity combination in the matrix. This ratio assumes equal feasibility of enhancing either quality or quantity by one quantile. We defined the habitat quantity level at which the ratio = 1 for the lowest quality quantile as the minimum recommended landscape habitat coverage for application of habitat conservation measures for pollinator community size. All plots were constructed using the ggplot2 (113), viridis (114), ggeffects (112), and gridExtra (115) packages.

Supplementary Text

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Conservation Innovation Grant CIG-68-9104-6-101 (CK, LAM)

Cornwall Area of Outstanding Natural Beauty Unit (BBP)

Council of Scientific & Industrial Research sanction no. 09/028(0882)/2012-EMR-I, date 21.08.2012 (PB, SL)

Darwin Initiative project 19-024 (PB, SL)

De Vlinderstichting (MFWdV)

Deutsche Forschungsgemeinschaft grant no. BA 4438/2-1 “Biodiversity and associated ecosystem services in small- vs. large-scale agriculture”, (JIP, ALH)

Deutsche Forschungsgemeinschaft grant no. 279374797 (IG, TT, GM)

Deutsche Forschungsgemeinschaft grant nos. 493487387, 405945293, 289781364 (IG, CW)

Deutsche Forschungsgemeinschaft Priority Program 1374 ‘Infrastructure - Biodiversity Exploratories’ grant nos. LI 150/20-1 and BL 960/2-1 (N Blüthgen)

Deutsche Forschungsgemeinschaft-Collaborative Research Center 1047 “Insect Timing” (AH, ISD)

‘DRUID project: Drivers and Repercussions of UK Insect Declines’, funded by the Natural Environment Research Council, grant no. NE/V006916/1 (WEK)

EU Seventh Framework Programme project BeeFun grant no. 631653 (I Bartomeus)

EU Seventh Framework Programme project SCALES (“Securing the Conservation of biodiversity across Administrative Levels and spatial, temporal and Ecological Scales”) grant no. 226852 (BJ, JK, ISD)

EU-funded project EASY grant no. QLK5-CT-2002-01495 (AH, ISD, TT)

EU-funded project QUESSA grant no. 311879 (LS, MA)

EU Seventh Framework Programme project LIBERATION (www.fp7liberation.eu) grant no. 311781 (DK)

EU Seventh Framework Programme (FP7/2007–2013) project STEP grant no. 244090 (AH, SH, JS, DK, ISD, HGS, JE, MR, JPGV, SGP, SPMR, JBW, VJW, SMS, AV, MV, AM, RB, TT)

European Regional Development Fund (ERDF) (JM, JLGA, JI)

EU Sixth Framework Programme integrated project ALARM (Assessing Large scale environmental Risks for biodiversity with tested Methods), Pollinator Module, grant no. GOCE-CT-2003-506675 (BJ, JK, ISD)

EU Horizon 2020 research and innovation programme project SAFEGUARD grant no. 101003476 (AH, JK, ISD)

FOCA Banco Galicia – Fundación Williams 2015 award (MM, MD)

Foundation for Food and Agriculture grant no. CA18-SS-0000000009 (LCP, HC)

Foundation of the University of Marburg grant no. VB1.2-5.45.26 (J Albrecht, IG)

Grassland Heritage Foundation (BLF, KRD)

Helmholtz Association grant no. VH-NG-247 (AH, ISD, TT)

Ikerbasque research fellowship (AM)

Iowa Science Foundation grant no. 19-17 (AW)

Irish Department of Agriculture, Fisheries and Food Research Stimulus Fund (RSF), funded under the National Development Plan (2007–2013) grant no. 07512 (EFP, JCS)

Juan de la Cierva program grant no. IJCI-2014-22558 (AM)

Kansas Native Plant Society (BLF, KRD)

Kansas University Field Station (BLF, KRD)

Keren Kayemeth LeIsrael-Jewish National Fund Appelby program (YM, TR)

Koret Foundation (BJB)

‘Lendület’ program of the Hungarian Academy of Sciences (A Báldi, AKH)

Moore Family Foundation (BJB)

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National Science Foundation grant no. DEB-0919128 (CK, LAM)

National Science Foundation grant nos. DEB-1021158 and DEB-0950100 (BLF, KRD)

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Natural Environment Research Council grant no. NE/L002434/1 (BBP)

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Netherlands Organization for Scientific Research, NWO-ALW Biodiversity Works Program, grant no. 841.11.001 (JS, DK)

Norwegian Environment Agency grant no. 2012/16642 (EPK, J Åström)

Natural Sciences and Engineering Research Council of Canada Postdoctoral Fellowship (LAM)

Operation Pollinator (TJW, RI)

Peter and Helen Bing (BJB)

Prairie Biotic Research, Inc. (BLF, KRD)

Ramon y Cajal fellowship RYC2021-032251-I (AM)

Research Council of Norway, BIOSMART project no. 244608/050 (EPK, J Åström)

Research Council of Norway, NINA – Strategic Institute Program 208434/F40 (EPK, J Åström)

Research Council of Norway, PolliClover project no. 225019 (EPK, J Åström)

Research programme NWO-Green, which is jointly funded by the Netherlands Organization for Scientific Research (NWO) and Nunhems Netherlands BV (BASF) under project number 870.15.030 (TPMF)

Roy J. Carver Charitable Trust (AW)

Royal Society for the Protection of Birds (NIW)

Rural and Environment Science and Analytical Services Division (RESAS) of the Scottish Government, Theme C - 2022-2027 (LLC, DIM)

Scottish Government Rural Affairs and the Environment Strategic Research Programme 2016–2021, Theme 2: Productive and Sustainable Land Management and Rural Economies (LLC, DIM)

Scottish Government's Strategic Research Programme 2011–2016, Programme 1: Environment (LLC, DIM)

Sherwood Foundation (BJB)

SIMBIOSYS Project (<http://www.tcd.ie/research/simbiosys/>, 2007-B-CD-1-S1) as part of the Science, Technology, Research and Innovation for the Environment (STRIVE) Programme, financed by the Irish Government under the National Development Plan 2007–2013, administered on behalf of the Department of the Environment, Heritage and Local Government by the Irish Environmental Protection Agency (DAS, JCS)

SITA Environmental Trust (JO, ST)

Spanish Ministry of Economy and Competitiveness project FLORMAS no. CGL 2012-33801 (JPGV, MV)

Spanish Ministry of Economy and Competitiveness projects AGL2012-33736 and AGL2015-64130-R (JM, JLGA, JI)

Spanish Severo Ochoa Program SEV-2012-0262 (JPGV, AM)

Spanish State Research Agency María de Maeztu Excellence Unit accreditation (MDM-2017-0714 and CEX2021-001201-M) funded by MCIN/AEI /10.13039/501100011033 (AM)

Stanford University Field Studies and Human Biology Research Experiences for Undergraduates Programs (BJB)

Swedish Government Strategic Research Initiative Biodiversity and Ecosystem Services in a Changing Climate BECC (JE, HGS, MR)

Swedish Research Council FORMAS grant no. 2005-788 (HGS, JE, MR)

Swedish Research Council FORMAS grant no. 2016-00361 (A Berggren, LGAR)

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Syngenta (JS, DK)

Syngenta-CONICET grant no. RD298/14 (MM, MD)

Teresa Heinz Scholarship for Environmental Research (BJB)

The Leverhulme Trust (DG)

The Nature Conservancy (BLF, KRD)

UK Insect Pollinator Initiative project ‘AgriLand: Linking agriculture and land use change to pollinator populations’, funded under the Living with Environmental change programme, a collaboration between Biotechnology and Biological Sciences Research Council (BBSRC), the Wellcome Trust, Scottish Government, Department of Environment, Food and Rural Affairs (DEFRA) and Natural Environment Research Council (NERC): grant BB/H014934/1 (MAKG, SGP, DS, WEK, SPMR)

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University Fund Wageningen (TPMF)

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University of Northern Iowa Biology Department, College of Humanities, Arts and Sciences, and Tallgrass Prairie Center (AW)

USDA Farm Service Agency grant no. AG-3151-C-17-0013 (AW)

USDA Farm Service Agency Inter-agency Agreement 16IAMRECRPHBTA1 (GMQ)

USDA-NIFA Specialty Crop Research Initiative award 2012-51181-20105 (Developing Sustainable Pollination Strategies for U.S. Specialty Crops) (TJW, RI)

Winslow Foundation (BJB)

Women's League for Israel (YM, TR)

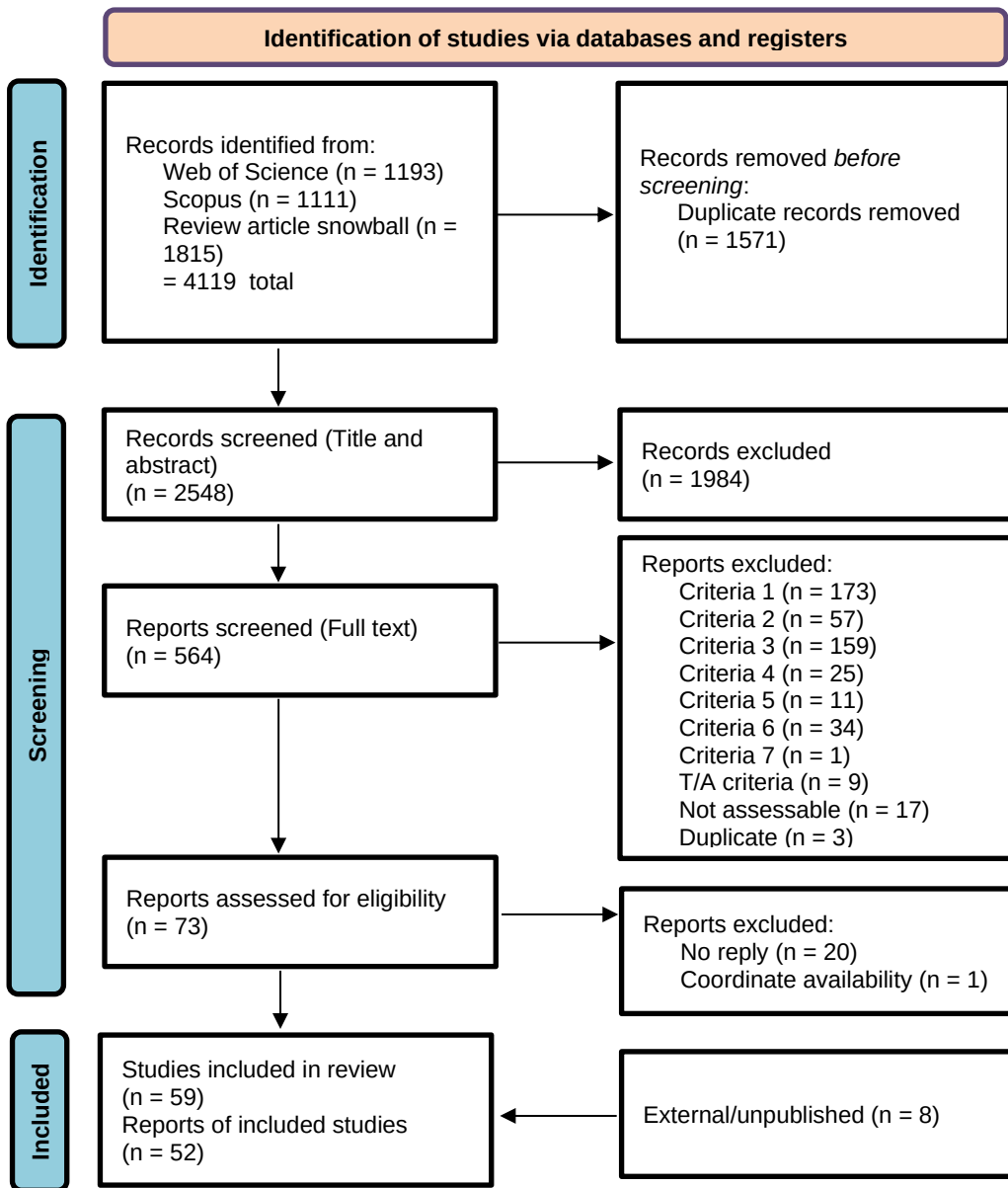


Fig. S1.

PRISMA flow diagram of study selection. T/A = Title / abstract. The total tally of included studies does not align with the total tally of reports (published articles) because some datasets are reported in multiple publications, and some publications report on multiple datasets.

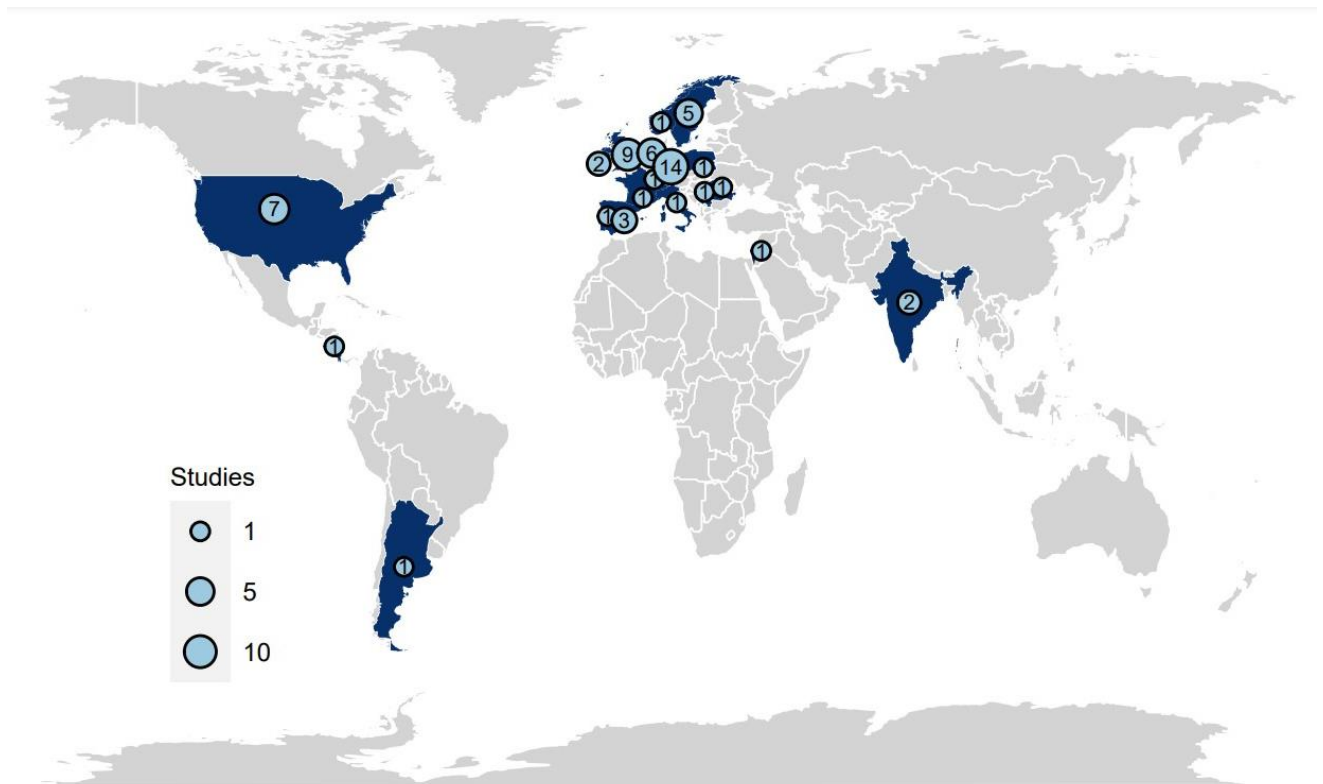


Fig. S2.
Countries from which datasets were collected.

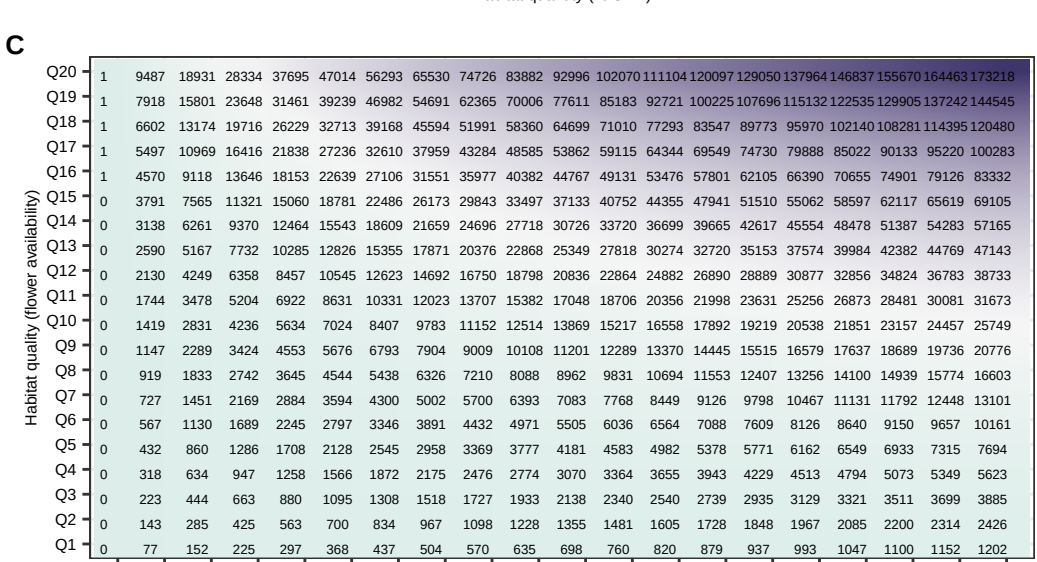
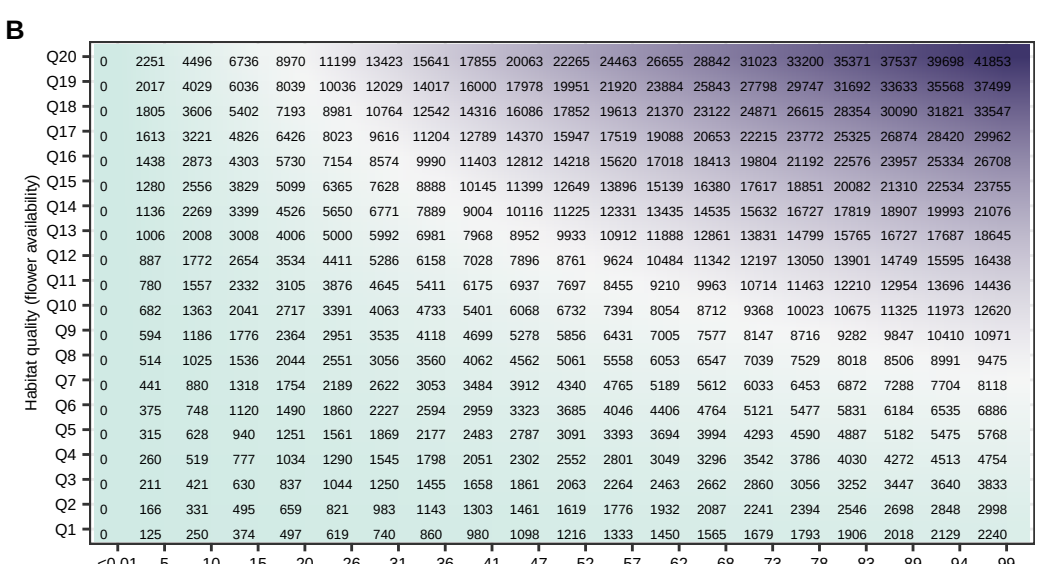
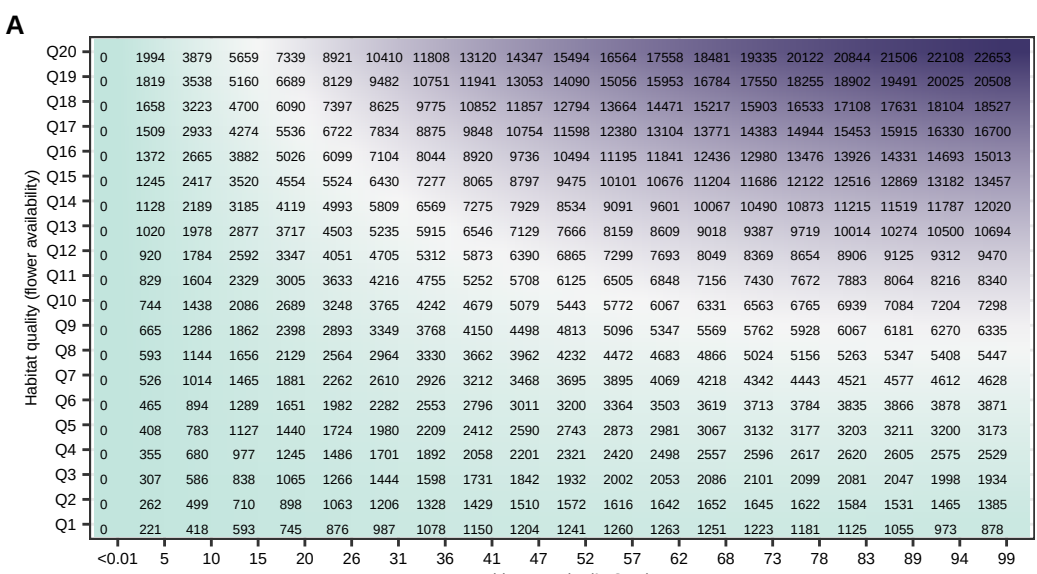


Fig. S3.

The relative gain in landscape-level pollinator abundances from increasing habitat quantity and quality. (A) bumble bees, (B) solitary bees, (C) hoverflies, (D) butterflies, and (E) tropical bees. Quantity and quality are expressed across the 20 quantiles of the ranges observed in the datasets. Matrix values represent back-transformed predicted abundances, rounded to the nearest integer. Q1-Q20 indicate quantiles of flower availability (flower cover and richness). SNH, semi-natural habitat.

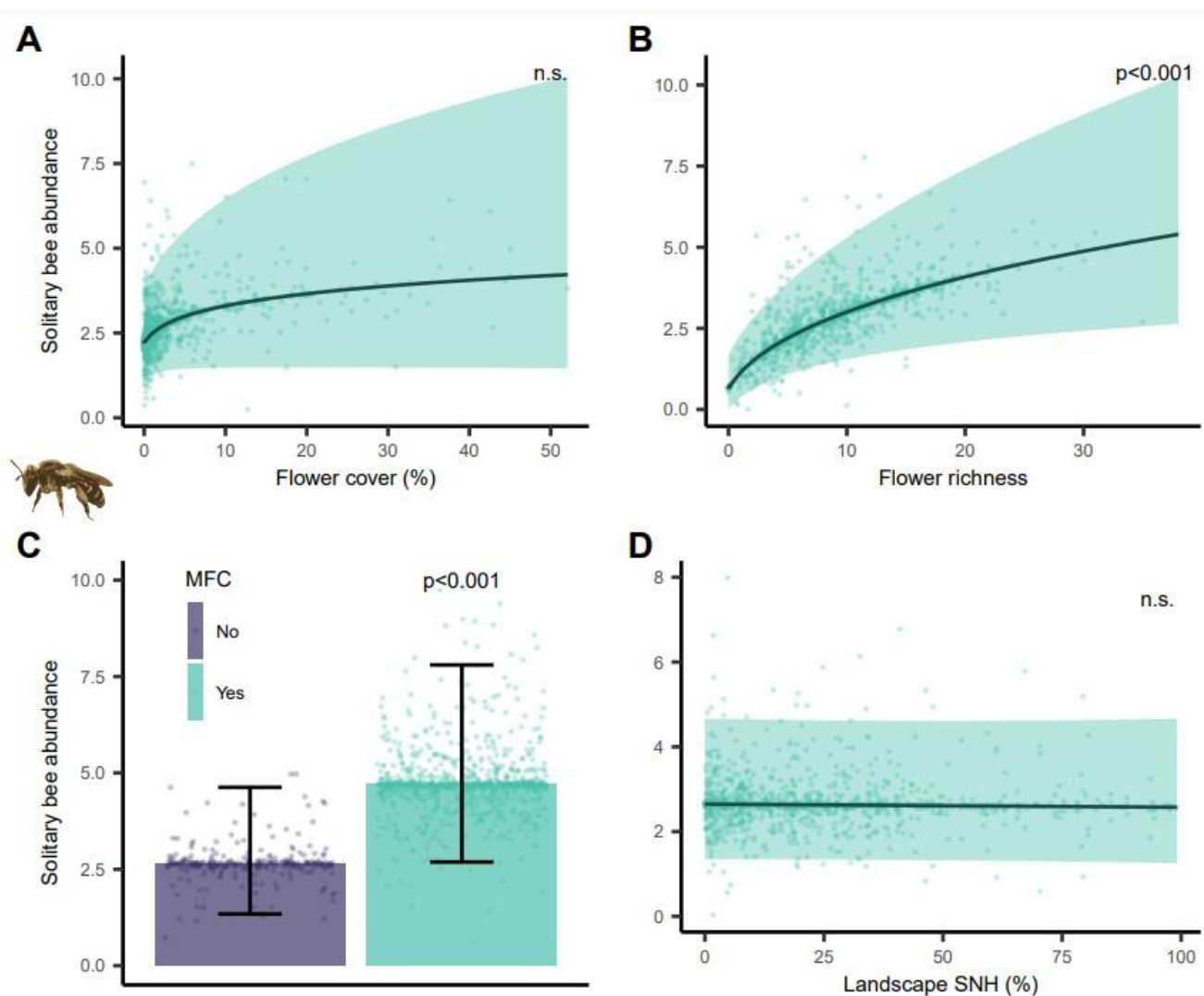


Fig. S4.

Conditional effects of local and landscape habitat parameters on local solitary bee densities. (A) flower cover, (B) flower richness, (C) mass-flowering crop (MFC) presence, and (D) landscape semi-natural habitat (SNH). Abundances are expressed per 150 m² and 15 min sampling. Points represent back-transformed partial residuals. SD, standard deviation. For model coefficients, see table S4.

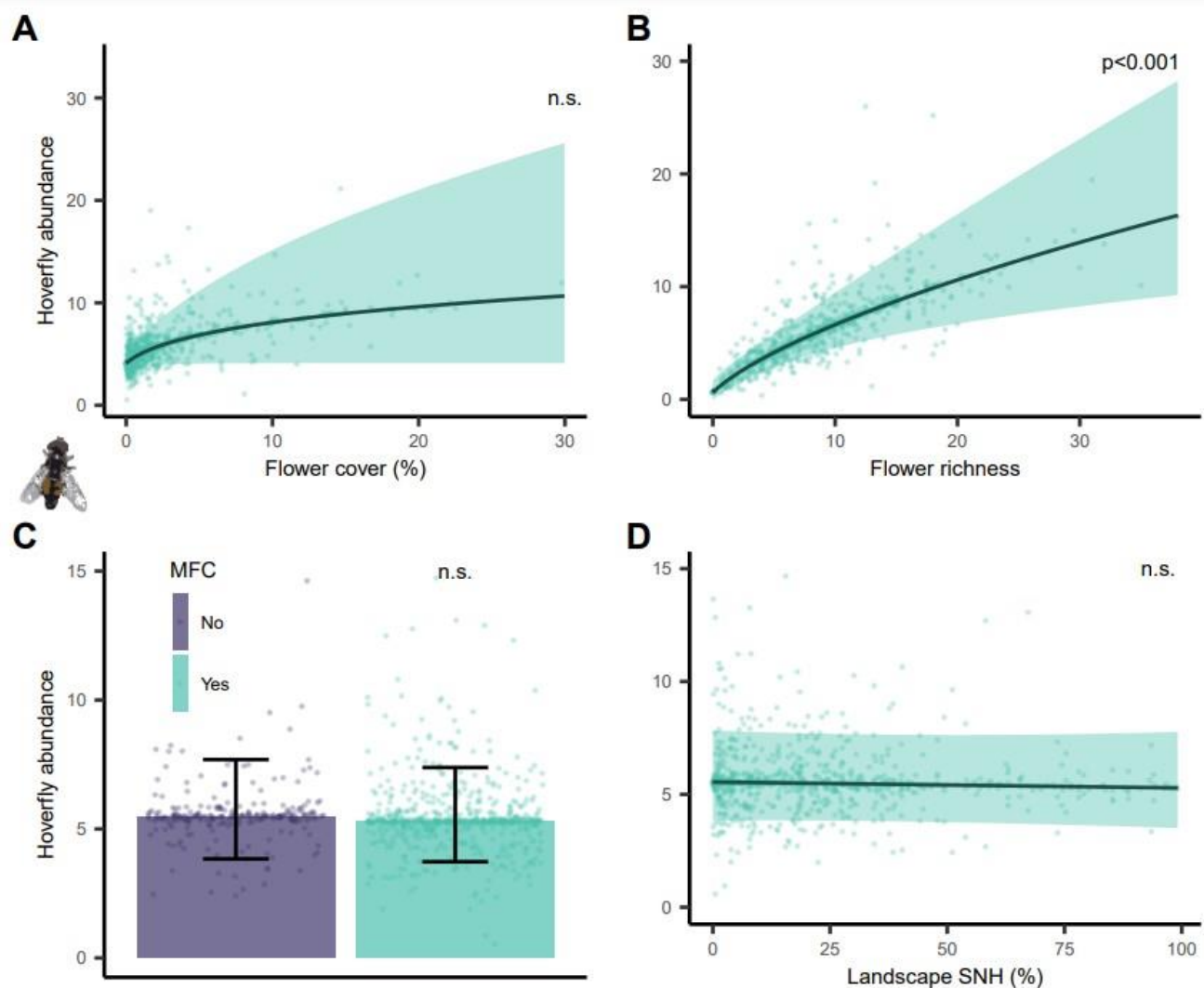


Fig. S5.

Conditional effects of local and landscape habitat parameters on local hoverfly densities. (A) flower cover, (B) flower richness, (C) mass-flowering crop (MFC) presence, and (D) landscape semi-natural habitat (SNH). Abundances are expressed per 150 m² and 15 min sampling. Points represent back-transformed partial residuals. SD, standard deviation. For model coefficients, see table S5.

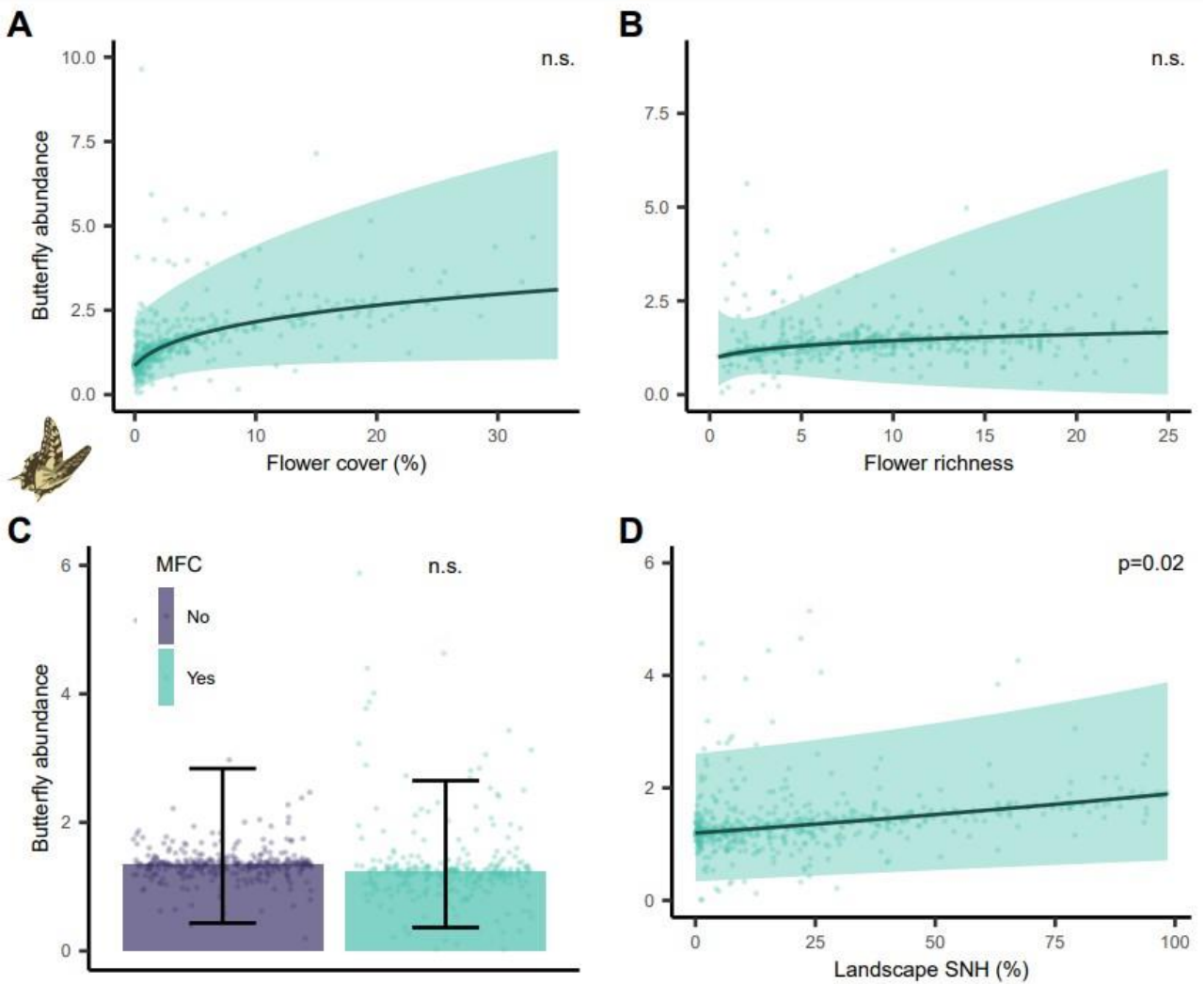


Fig. S6.

Conditional effects of local and landscape habitat parameters on local butterfly densities. (A) flower cover, (B) flower richness, (C) mass-flowering crop (MFC) presence, and (D) landscape semi-natural habitat (SNH). Abundances are expressed per 300 m². Points represent back-transformed partial residuals. SD, standard deviation. For model coefficients, see table S6.

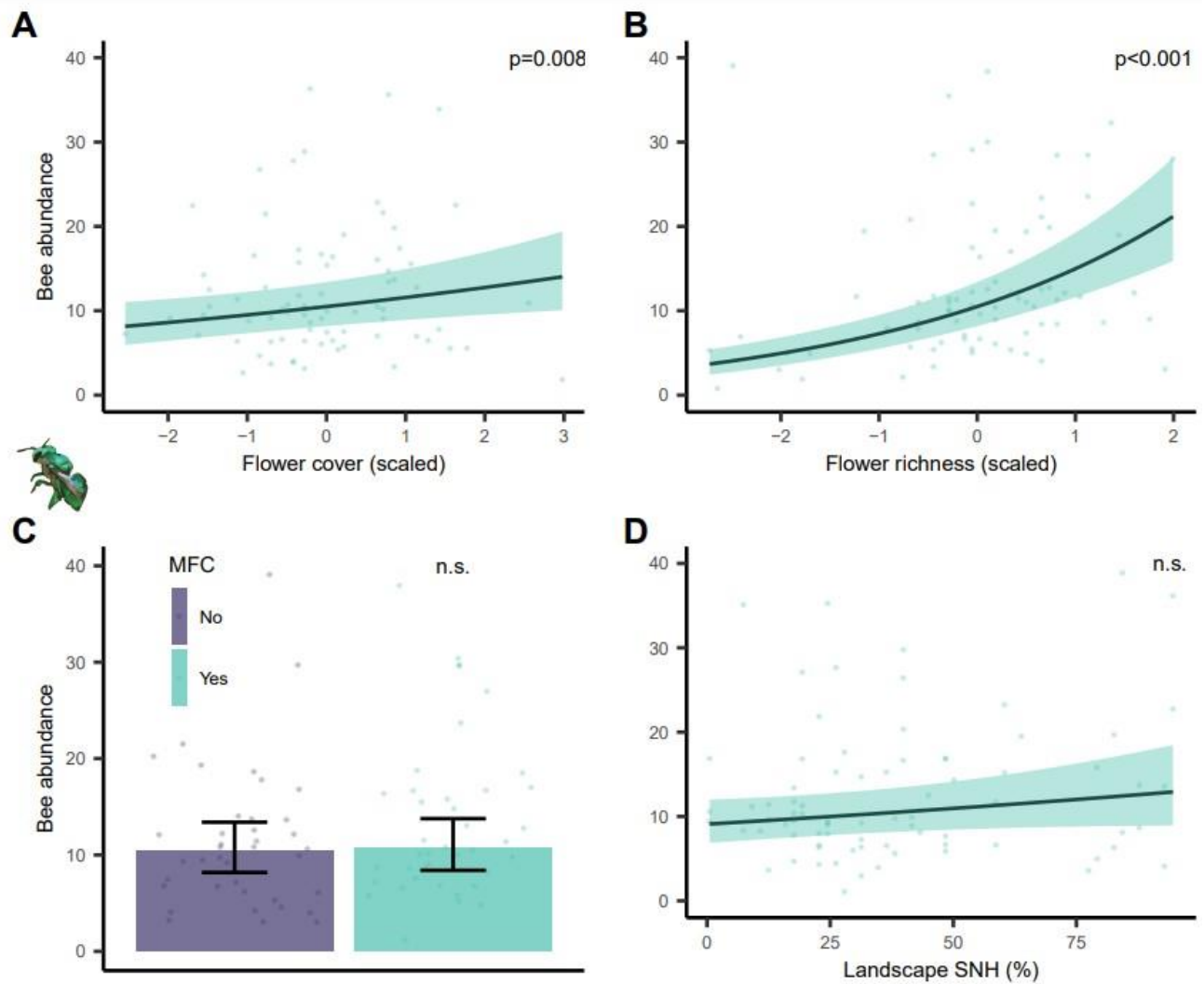


Fig. S7.

Conditional effects of local and landscape habitat parameters on local tropical bee densities. (A) flower cover, (B) flower richness, (C) mass-flowering crop (MFC) presence, and (D) landscape semi-natural habitat (SNH). Abundances are expressed per 150 m² and 15 min sampling. Points represent back-transformed partial residuals. SD, standard deviation. For model coefficients, see table S7.

Table S1.

Studies included in the synthesis. Landscapes are counted within year, and samples within landscapes.

Study	Country	Bumble bees	Solitary bees	Hoverflies	Butterflies	Tropical bees	Sampling effort		Habitat type	N Years	N Landscapes	N Samples	Publication
							m ²	min					
A	UK				X		Various	NA	Various	1	95	4173	Unpublished
B	Spain	X	X	X			200	30	Forest	1	16	112	(116)**
C	India					X	9	90	Various	1	20	60	(117)
D	Germany	X	X	X			400	10	Field margins	1	30	630	(118)
E	Germany	X	X	X			250	5	Various	1	30	540	(119)
F	Sweden	X					50	20	Various	1	17	152	(120)
G	Costa Rica					X	400	15	Grasslands	3	49	95	(121, 122)
H	USA	X	X				200	60	Various	1	12	71	(123)
I	UK				X		400	NA	Riparian margins	2	19	366	(124)
J	UK				X		400	NA	Various	2	31	343	(125)
K	USA	X	X	X	X		10000	60	Grasslands	3	30	98	(126, 127)
L	France	X	X	X			150	15	Various	1	25	206	(128)**
M	Sweden	X		X	X		150	15	Various	1	12	72	(129)
N	Netherlands	X	X	X	X		150	15	Various	1	16	131	Unpublished
O	Italy	X	X	X			150	15	Various	1	26	587	(130, 131)
P	Netherlands	X	X	X	X		450 [†]	45	Various	1	41	165	(19)**
Q	Germany	X	X	X			2	15	Grasslands	1	17	459	(132)
R	Poland	X					31416	60	Various	1	32	32	(133)
S	UK	X					31416	60	Various	1	41	46	(134)
T	Germany	X	X	X			200	240	Wildflower strips	1	14	28	(135)
U	Portugal		X				150	15	Various	1	29	79	Unpublished
V	Germany	X	X				100	15	Grasslands	1	32	32	(136)
W	Germany	X	X				Various	15	Field margins	1	27	198	(137)
X	Germany	X	X				100	45	Grasslands	1	23	115	(138)
Y	Germany	X	X	X			Various		Grasslands	1	27	192	(35, 139)
Z	Norway	X					200	5	Various	2	52	3676	(140)
AA	Netherlands	X	X	X			20	10	Various	2	40	606	(29)
AB	Romania	X	X	X	X		300	20	Various	1	28	217	(141)
AC	Germany	X	X	X			Various		Wildflower strips	1	19	37	(142)
AD	Germany	X	X	X	X		1800	360	Grasslands	1	28	143	(143)
AE	Israel		X				800	60	Various	2	30	30	(144)**
AF	India					X	100	10	Various	1	12	117	(145)
AG	Argentina		X	X	X		Various	240	Road verges	2	40	40	(146)
AH	USA		X	X			1	4	Various	1	16	455	(147)
AI	Spain		X	X			10	5	Field margins	1	17	340	(148)
AJ	Sweden	X					100	10	Various	1	12	363	(149)
AK	UK	X		X	X		100	10	Road verges	1	19	285	(90)
AL	Germany	X					100	10	Various	1	11	20	(150)
AM	Ireland				X		200	NA	Hedges	1	20	120	(151)
AN	USA	X	X				40	5	Various	1	12	964	(152)***
AO	Sweden	X	X	X	X		100	10	Various	1	20	235	(153)
AP	Netherlands	X	X	X	X		250	25	Various	1	10	40	(154)
AQ	USA		X				40	5	Grasslands	2	35	48	(155)
AR	Ireland				X		Various	NA	Grasslands	1	25	150	(156, 157)
AS	Spain		X	X			150	15	Various	2	30	226	(28, 158)
AT	UK	X	X	X			150	15	Various	3	47	550	(28, 59, 159)
AU	Sweden	X	X	X			150	15	Various	2	32	635	(28, 59, 159)
AV	Serbia	X	X	X			150	15	Various	2	31	218	(28)
AW	Netherlands	X	X	X			150	15	Various	3	50	799	(28, 59)
AX	Germany	X	X	X			150	15	Various	2	32	666	(28, 59, 159)
AY	Switzerland	X	X	X	X		150	20	Various	2	34	552	(47)
AZ	Netherlands				X		1000	NA	Grasslands	1	11	64	(160)
BA	UK	X		X			200	30	Grasslands	1	18	71	(161)
BB	UK			X			200	10	Forest	1	10	22	(162)
BC	Germany	X	X	X	X		1	5	Various	3	43	2340	(163, 164)

BD	Germany	X	X	X	X		1800	360	Grasslands	1	70	160	(165)
BE	USA		X				10000	60	Wildflower strips	1	11	33	(166)
BF	UK				X		Various	NA	Grasslands	2	31	654	(167)
BG	USA	X	X				Various	Various	Various	3	56	320	(168)

**Unpublished at the time of literature screen.

***Not gathered from literature screen.

†For bees and hoverflies only. Butterfly surveys varied in area and were untimed.

Table S2.

Sample sizes per species group. Landscapes are counted within study-year, and samples are sampling events within landscapes.

Species group	Studies	Study-years	Landscapes	Samples
Bumble bees	37	55	1107	16675
Solitary bees	37	58	1124	13294
Hoverflies	31	47	885	11156
Butterflies	19	29	613	9994
Tropical bees	3	5	81	272

Table S3.

Bumble bee model terms evaluated by log-likelihood ratio tests. SNH = semi-natural habitat; MFC = mass-flowering crop. The “no” level of MFC Bloom is captured in the intercept, meaning that the coefficients for landscape SNH and MFC Bloom here are representative of the “yes” level, as well as the slope of the interaction between landscape SNH and MFC Bloom. The single terms of landscape SNH and MFC Bloom are not evaluated with log-likelihood ratio tests because the interaction term is retained in the model. Coefficients are represented on the log scale.

Variable	Coefficient	SE	Chisq	P
Flower cover	0.062	0.028	4.683	0.030
Flower richness	0.060	0.027	4.726	0.030
Landscape SNH	0.075	0.012	-	-
MFC Bloom	0.235	0.018	-	-
SNH:MFC Bloom	-0.122	0.016	58.839	<0.001

Table S4.

Solitary bee model terms evaluated by log-likelihood ratio tests. SNH = semi-natural habitat; MFC = mass-flowering crop. The “no” level of MFC Bloom is captured in the intercept, meaning that the coefficient for MFC Bloom here is representative of the “yes” level. The interaction term is not included in the final model. Coefficients are represented on the log scale.

Variable	Coefficient	SE	Chisq	P
Flower cover	0.047	0.033	2.014	0.156
Flower richness	0.100	0.023	16.186	<0.001
Landscape SNH	-0.002	0.009	0.046	0.830
MFC Bloom	0.196	0.016	158.043	<0.001
SNH:MFC Bloom	-	-	0.869	0.351

Table S5.

Hoverfly model terms evaluated by log-likelihood ratio tests. SNH = semi-natural habitat; MFC = mass-flowering crop. The “no” level of MFC Bloom is captured in the intercept, meaning that the coefficient for MFC Bloom here is representative of the “yes” level. The interaction term is not included in the final model. Coefficients are represented on the log scale.

Variable	Coefficient	SE	Chisq	P
Flower cover	0.082	0.045	3.257	0.071
Flower richness	0.175	0.033	22.235	<0.001
Landscape SNH	-0.004	0.011	0.132	0.716
MFC Bloom	-0.013	0.019	0.470	0.493
SNH:MFC Bloom	-	-	0.374	0.541

Table S6.

Butterfly model terms evaluated by log-likelihood ratio tests. SNH = semi-natural habitat; MFC = mass-flowering crop. The “no” level of MFC Bloom is captured in the intercept, meaning that the coefficient for MFC Bloom here is representative of the “yes” level. The interaction term is not included in the final model. Coefficients are represented on the log scale.

Variable	Coefficient	SE	Chisq	P
Flower cover	0.092	0.047	3.570	0.059
Flower richness	0.030	0.068	0.195	0.659
Landscape SNH	0.030	0.013	5.230	0.022
MFC Bloom	-0.022	0.037	0.338	0.561
SNH:MFC Bloom	-	-	0.062	0.803

Table S7.

Tropical bee model terms evaluated by log-likelihood ratio tests. SNH = semi-natural habitat; MFC = mass-flowering crop. The “no” level of MFC Bloom is captured in the intercept, meaning that the coefficient for MFC Bloom here is representative of the “yes” level. The interaction term is not included in the final model. Coefficients are represented on the log scale.

Variable	Coefficient	SE	Chisq	P
Flower cover	0.039	0.015	7.029	0.008
Flower richness	0.143	0.017	59.749	<0.001
Landscape SNH	0.037	0.022	2.888	0.089
MFC Bloom	0.011	0.030	0.131	0.718
SNH:MFC Bloom	-	-	0.109	0.741

Table S8.

The effect of mass-flowering crop (MFC) presence evaluated by log-likelihood ratio tests on models with a subset of the datasets that had this variable as a within-study factor. SNH = semi-natural habitat.

Model	SNH:MFC Bloom		MFC Bloom	
	Chisq	P	Chisq	P
Bumble bees	109.694	<0.001	-	-
Solitary bees	0.293	0.588	379.260	<0.001
Hoverflies	2.431	0.119	0.270	0.604
Butterflies	0.306	0.580	0.360	0.549
Tropical bees	0.288	0.592	0.448	0.503