Received: 19 August 2024 | Accepted: 17 September 2024

DOI: 10.1111/1365-2664.14808

Journal of Applied Ecology BRITISH ECOLOGICAL SOCIETY

RESEARCH ARTICLE

Landscape and local factors drive pesticide distribution in perennial agroecosystems

Radek Michalko[1] | Luboš Purchart[1] | Ondřej Košulič[2]

[1]Department of Forest Ecology, Faculty of Forestry and Wood Technology, Mendel University in Brno, Brno, Czech Republic

[2]Department of Forest Protection and Wildlife Management, Faculty of Forestry and Wood Technology, Mendel University in Brno, Brno, Czech Republic

Correspondence
Ondřej Košulič
Email: ondra.kosulic@seznam.cz

Funding information
Technology Agency of the Czech Republic, Grant/Award Number: TITSMZP833

Handling Editor: Nubia Marques

Abstract

1. Pesticides constitute a major threat to biodiversity, but our understanding of the complex interactions between local and landscape factors influencing their distribution in agroecosystems remains limited.
2. We conducted a pioneering study where we screened spiders, rodents, plants and soils for multiple pesticide residues in perennial crops (orchards and vineyards) managed under organic ($N=8$) and integrated pest management ($N=8$) systems. We then quantified the proportional representation of major habitat types in surrounding landscapes. Additionally, we conducted interviews with farmers to gain precise insights into pesticide applications. We expected that landscape factors would be more important for mobile entities (i.e. spiders and rodents), while management type would be relatively more important for the sedentary entities (i.e. soils and plants).
3. We detected various pesticides within studied crop types, including several forbidden in the European Union. We found that pesticide distribution in spiders was influenced by the proportion of semi-natural habitats in the landscape, with pesticide concentration decreasing as the proportion of semi-natural habitats increased. Additionally, we observed that the spectrum of pesticides in spiders increased with the dominance of web-building spiders. In contrast, pesticide levels in rodents were not affected by either landscape composition or local management type. For plants, pesticide distribution was affected by the proportion of forests and shrublands and, to some extent, by local management practices. In the case of soil, pesticide distribution was primarily determined by local management.
4. This study marks an effort in demonstrating that both local and landscape factors play crucial roles in shaping pesticide distribution within perennial crops. Importantly, the relative importance of these factors varied across the four matrices investigated.
5. *Synthesis and applications*: To comprehend the factors that determine pesticide distribution in crops, it is crucial to monitor diverse ecosystem components rather than focusing on a few model species. This approach underscores the necessity for ecologically sensitive management at landscape scale. Such management

should involve the preservation and enhancement of (semi)natural habitats around crops. These combined insights can form the foundation for conservation and management initiatives aimed at mitigating the impact of pesticides on biodiversity within crops.

KEYWORDS
fungicide, herbicide, insecticide, pesticide residues, plant, rodent, soil, spider

1 | INTRODUCTION

Pesticides are among the major threats to biodiversity and seriously threaten also human health (Bernhardt et al., 2017; Goulson, 2013; Kimmel et al., 2022; Shelton et al., 2014), yet we know very little about relative importance of local (e.g. management type) and landscape factors (e.g. land-use composition) that can interactively determine the distribution of pesticides (i.e. pesticides concentration, composition and number) in local terrestrial ecosystems, including agroecosystems. This is primarily because those studies investigating how local and landscape factors affect the distribution of multiple pesticides have been limited mostly to pollinators (e.g. Knapp et al., 2023; Medici et al., 2022) while information about other nontarget beneficial organisms such as natural enemies of pests is currently lacking. To disentangle the direct and indirect effects of pesticides on nontarget organisms, it is necessary to study the relative importance of local and landscape factors influencing the distribution of pesticides in local crop fields (Desneux et al., 2007).

The most important local factor that can affect pesticide distribution in a local crop field is likely management (Karasali et al., 2016; Pelosi et al., 2021). Higher concentrations and larger numbers of pesticides can be expected in crops under integrated pest management (IPM), where synthetic pesticides are applied, than in organic farms, where synthetic pesticide use is prohibited (Pelosi et al., 2021). Another local factor may be the trait composition of a focal community (Knapp et al., 2023). For example, bee species that are extensive foragers are exposed to higher pesticide risk than are limited foragers because extensive foragers have larger foraging range and therefore more contact with pesticides (Knapp et al., 2023). Similarly to bees, spiders can be divided into two broader categories according to hunting strategies: sedentary web-building and more mobile cursorial spiders that hunt prey without web (Cardoso et al., 2011). Cursorial spiders are likely to have a more diverse range of pesticide residues compared with web-building spiders, as they are exposed to a broader variety of pesticides (Drouillard, 2008; Knapp et al., 2023).

Beside local factors, landscape factors are also likely to affect the distribution of pesticides in local crop fields as there are several routes through which pesticides can enter a local crop field from a surrounding landscape (e.g. drift, spillage and leaching; Cessna et al., 2005). Several studies show that growing proportion of crop fields in a landscape increases the risk of pesticide exposure (Knapp et al., 2023; Medici et al., 2022) but no specific relationship has yet been documented (Urbanowicz et al., 2019). Theoretically, not only a proportion of crop fields within a given landscape but also a proportional representation of the different and specific types of seminatural habitats (SNH: forests, grasslands, shrublands) within that landscape may influence any flow of pesticides from the broader landscape into the local crop fields (Fritsch et al., 2022). This is because different habitats vary in several factors that are known to affect bioaccumulation and biodegradation processes, such as plant species composition (Main et al., 2015), organic matter in soil (Svobodová et al., 2018) and environmental conditions (Li, 2020). Moreover, the drift of pesticides is also affected differently by shrubs and trees as they affect wind flow differently (Ucar & Hall, 2001).

To address the knowledge gaps, we investigated how local (management type, hunting strategy of spiders) and landscape (proportional representation of major habitat types) factors affect the distribution of multiple pesticide residues within perennial crops in four matrices: spiders, rodents, plants and soil (including inorganic matter and soil-dwelling organisms). We also investigated how the composition of spider-hunting strategies affects the distribution of pesticides in spider communities. For plants and soil, we hypothesized that (i) management will be the most important factor determining the distribution of pesticides because they are immobile entities. Specifically, we predicted that the concentration and number of pesticides will be greater in crops under IPM than under organic management. For spiders and rodents, we hypothesized that (ii) landscape factors will also determine the distribution of pesticides as spiders and rodents are relatively mobile. We specifically hypothesized that the concentration and number of pesticides in spiders and rodents will decrease with an increasing proportional representation of SNH in surrounding landscape. For spiders, we further hypothesized that (iii) concentration and number of pesticides will decrease with increasing dominance of web-building spiders as cursorial spiders are more mobile than web-building spiders.

2 | MATERIALS AND METHODS

2.1 | Study area and agroecosystems characterization

The study took place in Southern and Central Moravia, Czech Republic (Figure 1), regions known since the 1950s for their extensive cultivation of both annual and perennial crops, contributing

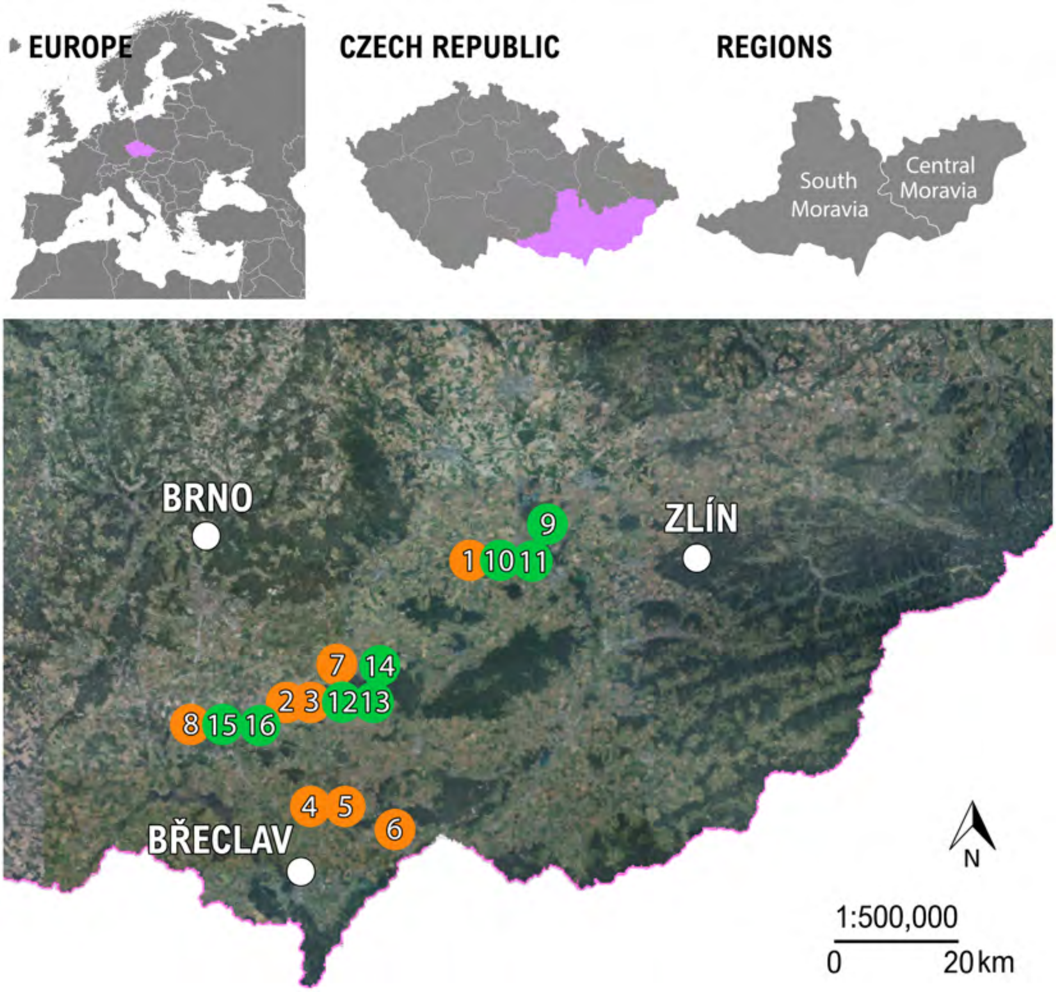


FIGURE 1 Distribution of the 16 study sites across two major agricultural areas of the Czech Republic. Green indicates perennial crops under organic management, while orange represents those under integrated pest management (IPM) management. The numbering of locations corresponds to the settings in Table 1. The map background was downloaded from Free Vector Maps (https://freevectormaps.com/) and the State Administration of Land Surveying and Cadastre (https://cuzk.cz/en), then modified in Adobe Photoshop CS6.

significantly to the country's agricultural production (Šarapatka & Niggli, 2008). Surrounding areas consist of nonproductive ecosystems, such as meadows, shrublands, forests and other SNH. Within these regions, we selected 16 perennial crop fields differing in management systems: (a) organic crop fields ($n=8$) with no pesticide inputs and (b) IPM-managed crop fields (n = 8) subject to varying pesticide applications. The minimum distance between locations was set at 1.5 km. Specific crop types and site details are found in Table 1.

Pesticide treatments in IPM-managed crop fields were applied based on the particular crop system, the farming companies involved and the specific years of application. These treatments included significant quantities especially of fungicides, followed by insecticides and herbicides. Pesticides were applied as early as March/April and as late as July/August, depending on the crop. To comprehensively assess pesticide residues, we surveyed the farmers managing these sites, gathering detailed information on pesticide applications from 2017 through the sampling Year 2020. A sample questionnaire form is provided in Table S1, and the complete dataset of applied and detected pesticide residues is available in the Zenodo repository (Michalko, Purchart, & Košulič, 2024).

2.2 | Sampling design

We examined four matrices: soil (primary resource), plants (primary producers), rodents (herbivores) and spiders (arthropod predators). Sampling was conducted in 2020 during the vegetation season. The periods and techniques varied by target groups. We coordinated with farmers to determine pesticide application dates in their crops and collected samples at least 10 days after the pesticide applications at all sites. We avoided sampling when pesticides were freshly applied, especially of spiders and rodents. Our goal was to avoid the deposition of freshly sprayed pesticides to ensure an unbiased interpretation of residue bioaccumulation in the target groups. Following each field collection, samples were transported to the laboratory and kept in a −20°C freezer until they were analysed for pesticide residues.

TABLE 1 Characteristics of individual study sites (perennial crops—orchards and vineyards) located across South and Central Moravia in the Czech Republic.

No. of location	Crop type	Management	Region	Cadaster	GPS	Altitude (m a.s.l)
1	Plum	IPM	Central Moravia	Litenčice	49°12′34.93″ N 17°11′55.40″ E	445
2	Apricot	IPM	South Moravia	Kobylí	48°55′48.80″ N 16°55′25.47″ E	281
3	Peach	IPM	South Moravia	Kobylí	48°56′38.55″ N 16°55′1.79″ E	198
4	Pear	IPM	South Moravia	Velké Bílovice	48°50′48.52″ N 16°56′6.40″ E	196
5	Pear	IPM	South Moravia	Velké Bílovice	48°51′32.70″ N 16°55′31.87″ E	225
6	Pear	IPM	South Moravia	Lužice	48°50′0.22″ N 17° 4′33.96″ E	164
7	Vineyard	IPM	South Moravia	Morkůvky	48°58′17.44″ N 16°51′9.68″ E	223
8	Vineyard	IPM	South Moravia	Hustopeče	48°55′51.33″ N 16°45′51.24″ E	198
9	Pear	Organic	Central Moravia	Netčice	49°14′36.88″ N 17°19′35.30″ E	237
10	Apple	Organic	Central Moravia	Litenčice	49°12′10.83″ N 17°13′55.20″ E	389
11	Pear	Organic	Central Moravia	Litenčice	49°12′24.86″ N 17°11′32.09″ E	401
12	Pear	Organic	South Moravia	Kobylí	48°56′39.46″ N 16°55′1.43″ E	195
13	Apricot	Organic	South Moravia	Kobylí	48°56′10.22″ N 16°54′36.28″ E	290
14	Pear	Organic	South Moravia	Brumovice	48°58′31.16″ N 16°52′58.23″ E	215
15	Apricot	Organic	South Moravia	Hustopeče	48°56′11.25″ N 16°45′20.81″ E	233
16	Vineyard	Organic	South Moravia	Hustopeče	48°55′56.64″ N 16°45′39.66″ E	227

Samples were collected according to the methods outlined by Michalko, Purchart, Hofman, et al. (2024) and Košulič et al. (2022). Soil samples were taken from the 0 to 25 cm layer using a steel spade, as this depth is most relevant for detecting pesticides (Pose-Juan et al., 2015). Five subsamples, each weighing approximately 1.5 kg, were randomly collected across each crop field and then combined. The soil sampling took place on 15–16 August 2020, shortly after the final pesticide applications of the season, determined by the type of crop.

For plant sampling, 15 subsamples of herbaceous vegetation were randomly gathered from each crop field, ensuring they were taken at least 100 m from the field edges and towards the centre to minimize edge effects from surrounding habitats. These subsamples were combined to produce a total of at least 1 kg of plant biomass. The plant samples were collected simultaneously with the soil samples across all fields. To maintain consistency in the residual analysis for different crop management types, only the above-ground parts of the plants—specifically, stems with leaves—were collected. The similarity in plant species between the vineyard and orchard agroecosystems was due to regular mowing and occasional mulching, which enhanced habitat uniformity. This similarity was also influenced by the fact that the study areas shared comparable environmental conditions, leading to similar vegetation compositions.

Small mammals (rodents) were snap-trapped in each crop field during May–June and November. These time frames correspond to when rodents are most active in agroecosystems (Suchomel et al., 2012). A maximum of 10 wood mice (*Apodemus sylvaticus*) and common voles (*Microtus arvalis*) were sampled at each site. Both species were categorized as herbivores for statistical analysis, reflecting their primarily herbivorous diets (Jacob et al., 2014). Sampling took place at least 100 m from the field edge, towards the centre of the pesticide-treated agroecosystem, to reduce edge effects from nearby habitats. This distance was selected based on the home range of the rodent species involved (Jacob et al., 2014). To analyse pesticide residues in small mammals, kidneys and livers were dissected from each rodent in the laboratory. The tissues were then combined to reach the minimum required weight for analysis—5 g for liver and 1.5 g for kidney—typically involving three to five specimens.

To meet the required sample weight of 3 g per location, spiders were sampled intensively during May–June and August–September

2020, which aligns with their peak activity period in European agroecosystems (Samu & Szinetár, 2002). Given the substantial arthropod biomass needed for residue analysis, three intensive sampling methods were employed simultaneously to gather enough spiders from various functional groups. Dry pitfall traps and sweep nets were used to collect ground-dwelling and vegetation-dwelling spiders, respectively. Additionally, foliage-dwelling spiders in perennial crops, such as fruit orchards, were collected by beating lower branches over a cloth tray. Spiders were transferred using an entomological aspirator from beating trays, pitfall traps and sweeping nets to dry, clean laboratory vials. This procedure ensured that small debris, leaves or pieces of vegetation were not collected, thus preventing contamination of the samples. The spider composition observed was notably consistent across the different sampling methods used within the studied crop fields, with a dominance of species common to both orchard and vineyard perennial systems. Consequently, specific methods were chosen to target various functional groups of spiders that could most accurately represent pesticide bioaccumulation. Spider sampling was carried out on the same spatial scale as that of small mammals within pesticide-treated crops. The collected spiders were kept alive in separate jars, transported to the laboratory and then stored in a freezer.

Rodent trapping was carried out in accordance with the ethical and capture permit issued by the Czech Ministry of the Environment (MZP/2020/630/2605). Ethics approval was not required for the sampling of soil, plants and spiders. Fieldwork permission was granted by the landowners. Since no company names were mentioned in the study, consent to use the data for research purposes was obtained through verbal agreements. This approach was deemed sufficient and was accepted by all participating farmers without the need for formal written agreements.

2.3 | Local and landscape factors

Management type (IPM, Organic) constituted the local factor for all matrices. For spiders, another local factor was spider community composition, specifically the proportion of web-building spiders in a spider community. We consider hunting strategy of spiders as a local factor as we sampled local spider community within the crop fields. The local spider community composition is a result of local and landscape processes (e.g. Picchi et al., 2016). The landscape factors represented the proportion of the main habitat types within the landscape, including arable land, perennial crops, forests and shrublands (e.g. open habitats with lines of shrubs and overgrown thickets), as well as grasslands (nonproductive meadows). In selected analyses, the last three categories were combined and referred to as SNH.

We used high-resolution land cover data from 3-m spatial resolution 4-Band PlanetScope images provided by Planet Labs (Planet Team, 2017). These data offer detailed and up-to-date information about the landscape. The PlanetScope images provide high spatial resolution, which allows for precise classification of habitat types. The 4-Band data include red, green, blue and near-infrared bands, which are useful for differentiating various land cover types. We calculated the landscape composition within a 750-m radius around each sampling site. We chose this radius because studies on spiders and other arthropods often use radii between 500 and 1000 m (e.g. Lami et al., 2021; Torma et al., 2014). For classification, we employed a pixel-based classification method with a maximum likelihood classifier (Foody et al., 1992). While we acknowledge that this method has been around since 1992, it remains a robust technique for land cover classification, especially when combined with high-resolution and high-quality land cover data such as the PlanetScope images. We used GIS tools to manage and analyse the spatial data (ESRI, 2021).

2.4 | Pesticide residue analysis

We analysed collected samples for the presence of pesticide residues, including their metabolites, using a method designed for 300 analytes. These analytes were selected based on preliminary sample screening, a farmer questionnaire survey, and data from the Registration Database of Plant Protection Products in the Czech Republic (eAGRI, 2024). Furthermore, a wide scope multi-residue screening method (e.g. Guo et al., 2020) was employed to quantify various chemical analytes, including older and currently banned pesticides along with their metabolites. The identified metabolites were categorized as insecticides, herbicides or fungicides for further examination, based on their frequent presence in food webs (Goutte et al., 2020). All samples, except those tested for glyphosate and its metabolite aminomethylphosphonic acid (AMPA), were processed using the QuEChERS method (Mei et al., 2011). The QuEChERS method is not suitable for glyphosate and AMPA due to their high polarity and lack of chromophores, which hampers effective extraction and detection (Ciasca et al., 2020). After extraction and purification using the QuEChERS method, the reconstituted samples were analysed by liquid chromatography–high-resolution mass spectrometry (LC/HRMS) using a Q Exactive Focus high-resolution mass spectrometer (Thermo Fisher Scientific). An UltiMate 3000 liquid chromatograph coupled with a Zorbax Eclipse XDB-C18 separation column (2.1 × 150 mm, 5 μm; Agilent) was employed for the separation of components. For the analysis of glyphosate and AMPA, a weighted amount of the sample was extracted with 0.6 M KOH to enhance the solubility of these highly polar compounds. An aliquot of the extract was then derivatized to increase detection sensitivity and improve chromatographic behaviour. Following derivatization, the sample was concentrated and further purified using solid-phase extraction (SPE) columns (Strata-X). The purified extract was subsequently analysed by liquid chromatography-mass spectrometry (LC/MS). The same LC/MS method was also used for the detection of pyrethroid insecticides. Liquid chromatography (Acquity UPLC I-Class, Waters, USA) was coupled to tandem mass spectrometry (Xevo TQ-XS, Waters, USA). Separation was achieved using an Acquity UPLC BEH C18 column (1.7 μm, 2.1 × 100 mm). Limits of quantification

(LOQs) for all analytes were ≤10 ng/g, except for glyphosate and its metabolite AMPA, which had LOQs of ≤50 ng/g.

The analytical process was customized according to the specific requirements of each entity or trophic group (Guo et al., 2020). Detailed methodologies for these procedures are provided in Methods S1. For information on the selection of analytes for chemical analyses and detailed residue analysis data, please refer to Košulič et al. (2022) and Michalko, Purchart, & Košulič (2024). All pesticide residue analyses were conducted in certified laboratories specializing in toxicological testing.

2.5 | Statistical analyses

All analyses were performed within the R environment (R Development Core Team, 2023). Depending on the data structure, we used general linear models (LM) or generalized linear models (GLM) to investigate the impact of landscape and local factors on the detected spectrum of agrochemicals, overall concentration of agrochemicals, and concentration of insecticides, herbicides and fungicides. For concentrations, we used LMs or GLMs with gamma error structure and inverse link function (GLM-g) if the data were heteroscedastic (Zuur et al., 2015). For the spectrum of agrochemicals, we used GLM with quasi-Poisson error structure with log link function as the data were counts and over- or under-dispersed (Zuur et al., 2015).

We used the theoretic information approach based on the Akaike information criterion for small sample sizes (AICc) to select the most influential measured variables. We built 15 (spiders) or 10 (rodents, plants and soil) competing models including the null model (Tables S1–S18). We compared models that included single effects and two-fold additive effects of local and landscape factors. We did not include more complex models due to the relatively small sample size ($N=16$ agroecosystems). We selected models based on the lowest value of AICc in combination with the rule of parsimony, considering ΔAICc >2.0 to be the reason to select a more complex model over a simpler model (Zuur et al., 2015). There was an influential outlier (Cook's distance >3.0; concentration = 2000 ng/g) when studying the local and landscape effect on the concentration of pesticides in spiders. We therefore ran the analyses also by excluding the outlier.

3 | RESULTS

3.1 | Overview

Between 2017 and 2020, farmers reported the use of 43 different pesticides in the IPM-managed perennial crops, while no pesticides were applied in the organically managed crops. Of the total pesticides detected, only 16 (including their metabolites) were directly applied by farmers. This means that a significant portion of the detected pesticides were not applied by the farmers, contributing to an overall total of 49 pesticide compounds, including metabolites such as AMPA and ketocarbofuran, across the sampled matrices (soil, plants, rodents and spiders) within the studied perennial crops. The detected pesticides were categorized into 21 fungicides, 15 insecticides and 13 herbicides. Of these, 14 insecticides were found in IPM fields and 12 in organic fields. Similarly, 20 fungicides were detected in IPM fields and 12 in organic fields. Herbicides were represented by 12 compounds in IPM fields and 6 in organic fields. The highest number of pesticides were found in spiders (28) and rodents (21), followed by plants (20) and soil (12). For a detailed list of the pesticides applied and detected, along with their metabolites, please see the dataset available in the Zenodo repository (Michalko, Purchart, & Košulič, 2024).

3.2 | Spiders

If the influential outlier was present, the best model predicted a negative relationship between proportional representation of grasslands in landscape and concentration of pesticides (Table S2, ΔAICc from the second-best model = 2.67, $R^2_{adj}=0.28$; Figure 2a). When the influential outlier was excluded, the best model predicted the concentration decrease with an increasing proportion of SNH in landscape (Table S3, ΔAICc from the second-best model = 3.90, $R^2_{adj}=0.44$; Figure 2b).

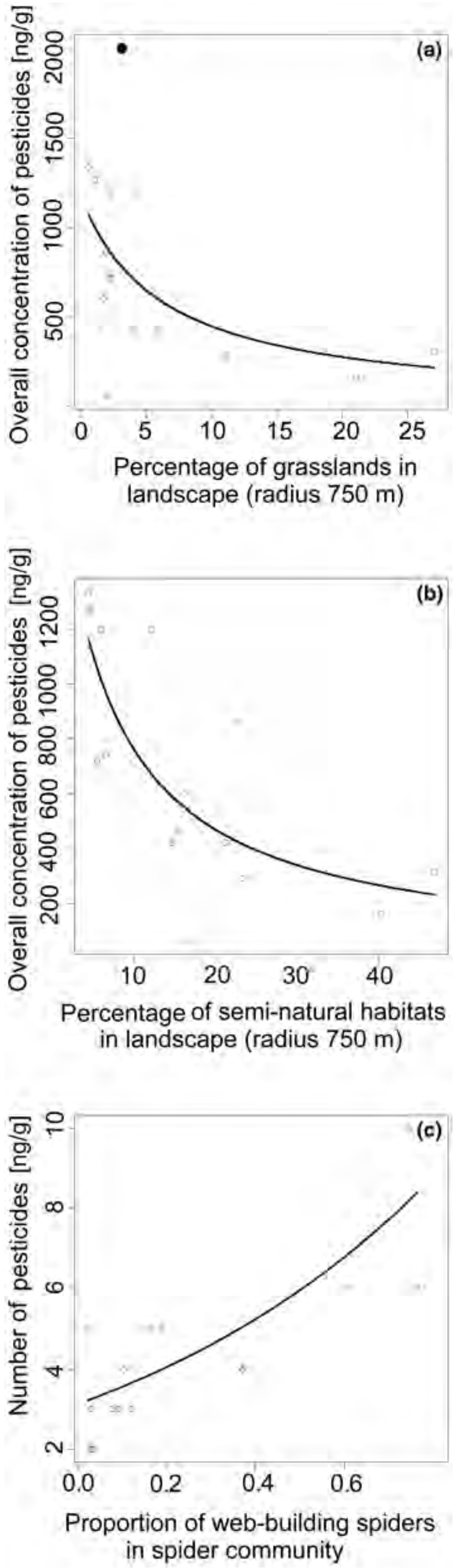
When studying the spectrum of pesticides, the best model predicted only the effect of spider community composition and the spectrum of pesticides increased with a growing proportion of web-building spiders in the community (Table S4, ΔAICc from the second-best model = 1.01, $R^2_{adj}=0.54$; Figure 2c).

When studying the pesticide types separately, the most optimal models were the null models (Tables S5–S7; ΔAICc from the second-best models >0.61).

3.3 | Rodents

With respect to the overall concentration and spectrum of pesticides, as well as concentrations of insecticides, herbicides and fungicides, the best models were the null models (Tables S8–S12, ΔAICc from the second-best models >0.01).

FIGURE 2 Pesticides in spiders. (a) Relationship between overall concentration of pesticides in spiders and proportional representation of grasslands in a landscape defined as 750 m radius around focal crop field. The significant outlier was retained in the model. (b) Relationship between overall concentration of pesticides and proportion of semi-natural habitats in a landscape defined as 750 m radius around focal crop field. Outlier was excluded from the analysis. (c) Relationship between number of pesticides detected in spiders and proportion of web-building spiders in spider community. In all panels, the lines are estimated relationship and the points are the individual measurements. The black point in panel (a) shows the significant outlier.



3.4 | Plants

The most optimal model predicted the decline in the overall concentration of pesticides with an increasing proportion of forests in landscape (Table S13, ΔAICc from the second-best models = 2.05, R^2_{adj} = 0.62; Figure 3a).

The most optimal model predicted that the spectrum of pesticides declined with an increasing proportion of shrubland in the landscape (Table S14, ΔAICc from the second-best model = 1.3, R^2_{adj} = 0.24; Figure 3b).

For insecticides, the optimal model was the null model (Table S15, ΔAICc from the second-best model = 2.19). However, the most optimal model predicted the decline in the herbicide concentration with increasing coverage of forest in landscape (Table S16, ΔAICc from the second-best model = 2.77, R^2_{adj} = 0.43; Figure 3c). Fungicides in plants were found only in agroecosystems under IPM (Figure 3d).

3.5 | Soil

The most optimal models predicted that overall concentration (Table S17, ΔAICc from the second-best model = 1.05, R^2_{adj} = 0.51; Figure 4a) and number of agrochemicals (Table S18, ΔAICc from the second-best model = 0.08, R^2_{adj} = 0.24; Figure 4b) were greater in agroecosystems under IPM than in those under organic management.

Insecticides in soil were detected in only one pear orchard under IPM. Fungicides were detected only in soil within agroecosystems under IPM (Figure 4c). The best model predicting the distribution of herbicides in soil was the null model (Table S19, ΔAICc from the second-best model = 1.46).

4 | DISCUSSION

We investigated how local management and landscape composition affect the pesticide distribution across four matrices: spiders, rodents, plants and soil. We found that both local and landscape factors determine the distribution of pesticides in local perennial agroecosystems, but their relative importance differed among the four studied matrices. In spiders, pesticide distribution in their bodies was mostly affected by landscape factors and functional composition of spider communities, supporting our hypothesis that these mobile organisms are more affected by pesticide application at broader landscape scale. However, in contrast to our hypothesis, the number of detected pesticides increased with increasing dominance of web-building spiders. Contrary to our expectations, we were unable to identify any significant factors influencing pesticide distribution in rodents. For plants, the distribution of pesticides was affected by both local management and landscape factors, though the latter did not align with our initial hypothesis. In soil, as expected, pesticide presence was determined solely by local management practices. The results therefore show that different compartments of agroecosystems are exposed to pesticides via different routes.

In general, the provided data reveal the unexpected presence of many pesticides represented mainly by fungicides, insecticides and herbicides in crops under organic management (Michalko, Purchart, & Košulič, 2024). This is surprising given that organic farming practices explicitly prohibit the use of many synthetic pesticides (Šarapatka & Niggli, 2008). Furthermore, the analyses

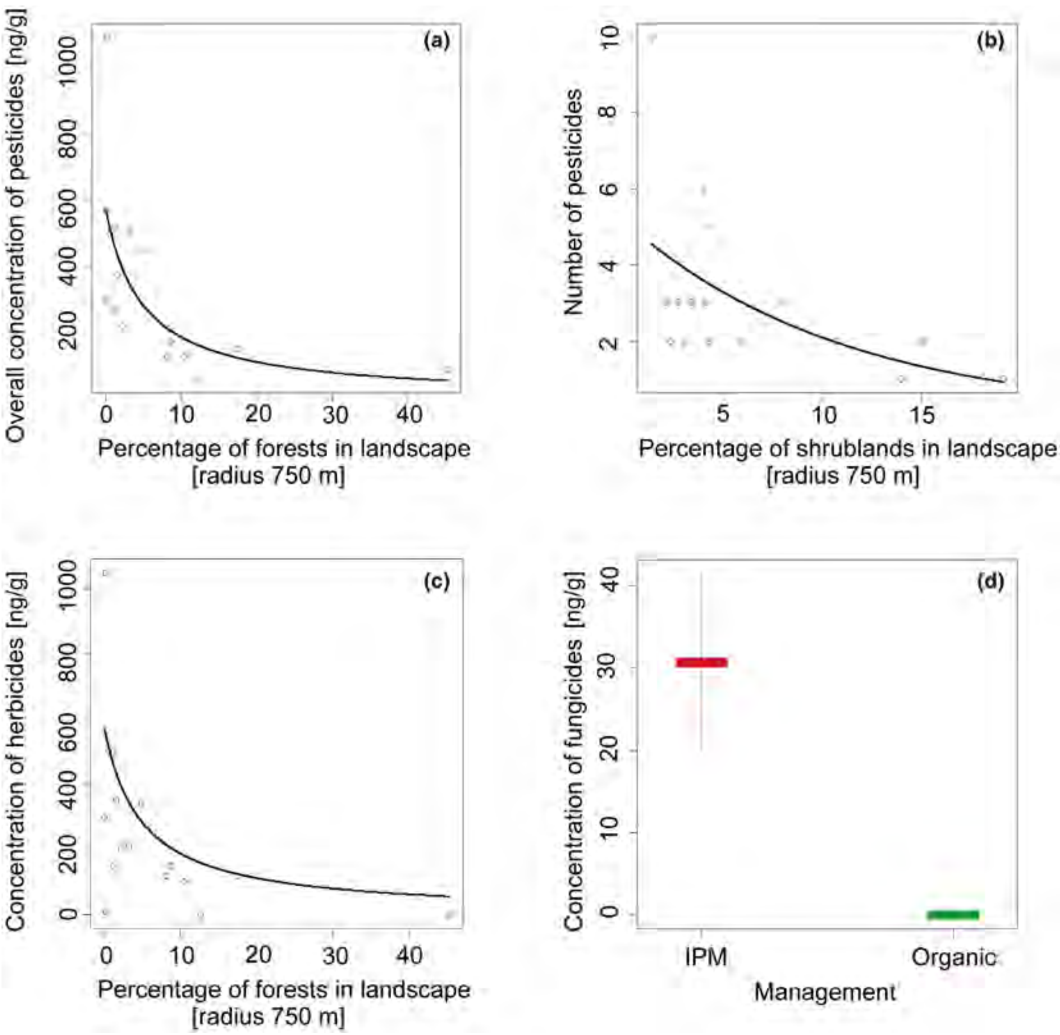


FIGURE 3 Pesticides in plants. (a) Relationship between overall concentration and proportional representation of forests in a landscape defined as 750 m radius around focal crop field. (b) Relationship between number of pesticides detected in plants and proportional representation of shrublands in a landscape defined as 750 m radius around focal crop field. (c) Relationship between concentration of herbicides and proportional representation of forest in landscape defined as 750 m radius around focal crop field. (d) Comparison of fungicide concentration detected in plants between two management types. The lines and points in the panels (a–c) are the estimated relationships and individual measurements, respectively. The thick horizontal lines in panel (d) are means and the vertical thin line is SE.

identified several legacy pesticides and some banned substances never approved in the European Union or Great Britain. Their presence likely results from illegal application, counterfeit pesticides and environmental persistence (Fritsch et al., 2022). The carbamate insecticide carbofuran and its metabolites, highly toxic to small mammals, birds and even humans (Sharma et al., 2012), were frequently detected in rodents, suggesting long-term persistence or ongoing illegal use. The detection of the organochloride insecticide methoxychlor, prohibited in Europe since 2002 and in the United States since 2003, is particularly alarming. Alongside this, the organophosphate insecticide malathion, restricted to greenhouse use in the EU, was also found. Both of these pesticides are infamous for their severe bioaccumulation, potential carcinogenicity and detrimental effects on insects, birds and humans (Qi et al., 2022). Even more concerning is the detection of fungicide pyrametostrobin and herbicide tripropindan, which are not registered in European, British or US markets. These substances are likely imported illegally from Asia, where they are commonly used (Huang et al., 2017). This finding highlights a significant breach in regulatory enforcement and raises serious concerns about the illegal trade and use of unapproved pesticides (Storck et al., 2017).

We did not assess the detected pesticide concentrations against national and EU standards because our analysis was focused on a different approach, specifically aimed at disentangling the effects of both local and landscape factors on pesticide uptake within various trophic groups. Nonetheless, certain findings are particularly concerning, including the detection of high levels of toxic insecticides that have been banned for years in European markets. These results underscore the serious risks these substances pose, even at lower concentrations, due to their extreme toxicity and detrimental effects on biodiversity (Beaumelle et al., 2023; Kaur et al., 2024).

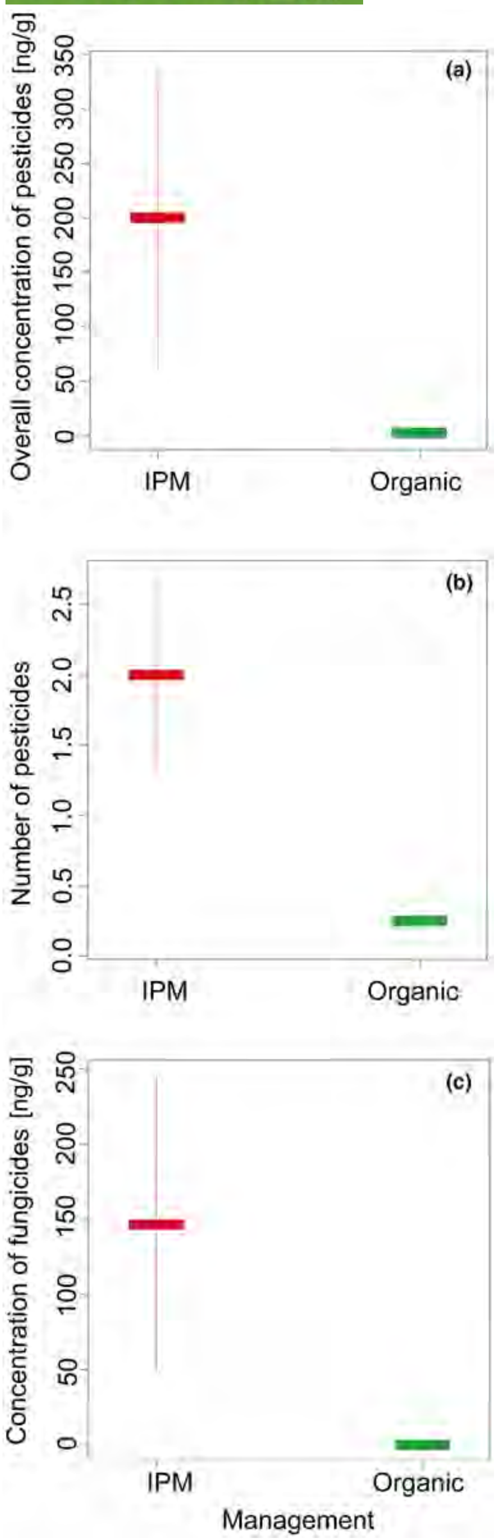


FIGURE 4 Pesticides in soil. Comparisons of overall concentration of pesticides (a), number of detected pesticides (b) and concentration of fungicides (c) in soil between IPM and organic management. The thick horizontal lines show means and the thin vertical lines are SE.

Michalko, Purchart, Hofman, et al. (2024) provided evidence of increasing pesticide concentrations and numbers across trophic levels within various agroecosystems, particularly in predatory spiders and herbivorous rodents. This bioaccumulation suggests that persistent organic pollutants can magnify within the food web, leading to greater exposure and potentially harmful effects on organisms at higher trophic levels. Our research, focused specifically on perennial crops such as orchards and vineyards, further supports this hypothesis. We observed a significantly higher number of pesticides in higher trophic levels, reinforcing the concept of bioaccumulation (e.g. Coat et al., 2011).

We found that, except for soils and fungicides in plants, the management within perennial crops had no significant effect on the distribution of pesticides. Although the concentration of pesticides in soil and herbicides in plants was lower in organic orchards than in orchards under IPM, the mean concentration was not zero. These results agree with recent studies on small mammals (Fritsch et al., 2022) and soils (Pelosi et al., 2021) showing the same pattern but in cereal fields. Our results and those of previous studies show that exposure to pesticides in agricultural landscapes is ubiquitous and ecologically sensitive pesticide management must be planned at the landscape level (Brühl & Zaller, 2019).

The overall concentrations of pesticides in spiders diminished with an increasing proportion of SNH in surrounding landscapes. The result agrees with those from studies on bee pollinators (Knapp et al., 2023; Medici et al., 2022) and indicates that increasing proportion of SNH habitats may reduce the pesticide burden in agricultural landscapes. On the contrary, local management had no significant effect on the distribution of pesticides in spiders and in rodents. The fact that the landscape factors overrode the effect of local management can be explained by the high mobility of spiders (Birkhofer et al., 2018) and rodents (Wang, 2013), which can move among agroecosystems under different management. The mobility of spider prey, which often consists in flying insects that move across habitats (Michalko & Pekár, 2016), may also be responsible for this pattern.

Contrary to our hypothesis, we found that the number of detected pesticides rose with an increasing proportion of web-building spiders in spider communities. This can be explained by several non-exclusive reasons. Web-building spiders capture proportionally more highly mobile flying insects while cursorial spiders tend to prey on more sedentary organisms, despite being more active hunters (Michalko & Pekár, 2016). The mobile prey that moves across agricultural landscape can be exposed to wider spectra of pesticides than is sedentary prey (Drouillard, 2008; Knapp et al., 2023). Additionally, pesticide droplets dispersed by wind or during pesticide applications may cling on webs, directly exposing web-building spiders to these chemicals. Overall, these findings indicate that the functional traits of local communities may play a key role in how pesticides are distributed through food webs.

The concentration of pesticides in plants decreased with a growing proportion of forests in landscape, which was primarily driven by decreasing concentration of herbicides. On the contrary, the number of pesticides in plants decreased with increasing shrublands in landscape. It is possible that these habitats influenced the composition of plants in local agroecosystems (Gallé et al., 2022). Forest and shrublands might harbour fewer weed species, which might lead to a lesser need for herbicides at the landscape scale. Also, different plant species affect biodegradation and bioaccumulation processes of pesticides differently (Koech et al., 2023; Main et al., 2015).

5 | CONCLUSIONS

In summary, this is the first study showing that both landscape and local factors influenced the distribution of pesticides in local agroecosystems even as their relative importance varied among spiders, rodents, plants and soil. This reveals that different ecosystem components are exposed to pesticides via different routes. The results therefore highlight the complex ways through which pesticides enter local food webs. While traditional monitoring often focuses on specific groups (Démares et al., 2022; Goulson, 2013; Sabzevari & Hofman, 2022), our findings strongly support a more holistic strategy. To understand pesticide distribution in agricultural landscapes, monitoring should encompass various agroecosystem components, extending beyond a few selected species to include a broader range of organisms. Moreover, the ubiquitous exposure to pesticides in agricultural landscapes and greater importance of the landscape factor than of local factors highlight that ecologically sensitive pesticide management must be at the landscape scale (Bakker et al., 2022). Consequently, management efforts should expand beyond individual species, adopting a broader landscape-level perspective to effectively address the widespread impacts of pesticide use. This can, for example, include the preservation of grasslands and other nonproductive habitats within intensively exploited agricultural landscapes. Such preservation may result in better conditions for biodiversity, as suggested by our results, due to the decrease in pesticide residue accumulation and their overall presence. To conclude, our study emphasizes the significance of adopting a comprehensive, landscape-scale approach to pesticide management in conservation. The results underscore the urgency of ensuring the health and sustainability of agroecosystems and their diverse organisms.

AUTHOR CONTRIBUTIONS

Radek Michalko, Ondřej Košulič and Luboš Purchart contributed to the conception and design of the study. Ondřej Košulič and Luboš Purchart were responsible for material sampling. Ondřej Košulič collected the landscape data. Radek Michalko performed the statistical analyses. The manuscript was written by Radek Michalko and Ondřej Košulič. All authors provided critical feedback on the drafts, assisted in revising the manuscript and gave final approval for publication.

ACKNOWLEDGEMENTS

We would like to thank Tomáš Hamřík, Martin Ernst and Petra Hulejová for their assistance during fieldwork and Šárka Mašová for her help in creating and editing the graphical abstract. We also greatly appreciate the insightful discussions on pesticide residue analysis with Jakub Hofman, Zuzana Bílková, Michal Bartoš, Eva Eiglová and Jiří Kwiecien. We want to express our sincere thanks to the farmers and stakeholders who generously allowed us to conduct research on their properties. Their cooperation, including sharing information about their pesticide use in recent years, was crucial to the success of this study. Additionally, we extend our gratitude to Gale A. Kirking for proofreading the manuscript to ensure English language accuracy. The study was financially supported by the Technology Agency of the Czech Republic, program BETA2 (TITSMZP833).

CONFLICT OF INTEREST STATEMENT

There are no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

Data are available from Zenodo Digital Repository https://doi.org/10.5281/zenodo.13840817 (Michalko, Purchart, & Košulič, 2024).

ORCID

Radek Michalko https://orcid.org/0000-0003-0831-0823
Luboš Purchart https://orcid.org/0000-0001-9958-2300
Ondřej Košulič https://orcid.org/0000-0003-2199-1694

REFERENCES

Bakker, L., van der Werf, W., & Bianchi, F. J. (2022). Sweep netting samples, but not sticky trap samples, indicate beneficial arthropod abundance is negatively associated with landscape wide insecticide use. *Journal of Applied Ecology*, *59*, 942–952. https://doi.org/10.1111/1365-2664.14106

Beaumelle, L., Tison, L., Eisenhauer, N., Hines, J., Malladi, S., Pelosi, C., Thouvenot, L., & Phillips, H. R. (2023). Pesticide effects on soil fauna communities—A meta-analysis. *Journal of Applied Ecology*, *60*(7), 1239–1253. https://doi.org/10.1111/1365-2664.14437

Bernhardt, E. S., Rosi, E. J., & Gessner, M. O. (2017). Synthetic chemicals as agents of global change. *Frontiers in Ecology and the Environment*, *15*, 84–90. https://doi.org/10.1002/fee.1450

Birkhofer, K., Fevrier, V., Heinrich, A. E., Rink, K., & Smith, H. G. (2018). The contribution of CAP greening measures to conservation biological control at two spatial scales. *Agriculture, Ecosystems and Environment*, *255*, 84–94. https://doi.org/10.1016/j.agee.2017.12.026

Brühl, C. A., & Zaller, J. G. (2019). Biodiversity decline as a consequence of an inappropriate environmental risk assessment of pesticides. *Frontiers in Environmental Science*, *7*, 177. https://doi.org/10.3389/fenvs.2019.00177

Cardoso, P., Pekár, S., Jocqué, R., & Coddington, J. A. (2011). Global patterns of guild composition and functional diversity of spiders. *PLoS One*, *6*, e21710. https://doi.org/10.1371/journal.pone.0021710

Cessna, A. J., Wolf, T. M., Stephenson, G. R., & Brown, R. B. (2005). Pesticide movement to field margins: Routes, impacts and mitigation. Field boundary habitats: Implications for weed. *Insect and Disease Management*, *1*, 69–112.

Ciasca, B., Pecorelli, I., Lepore, L., Paoloni, A., Catucci, L., Pascale, M., & Lattanzio, V. M. T. (2020). Rapid and reliable detection of glyphosate in pome fruits, berries, pulses and cereals by flow injection–mass spectrometry. *Food Chemistry*, *310*, 125813. https://doi.org/10.1016/j.foodchem.2019.125813

Coat, S., Monti, D., Legendre, P., Bouchon, C., Massat, F., & Lepoint, G. (2011). Organochlorine pollution in tropical rivers (Guadeloupe): Role of ecological factors in food web bioaccumulation. *Environmental Pollution*, *159*, 1692–1701. https://doi.org/10.1016/j.envpol.2011.02.036

Démares, F. J., Schmehl, D., Bloomquist, J. R., Cabrera, A. R., Huang, Z. Y., Lau, P., & Ellis, J. D. (2022). Honey bee (*Apis mellifera*) exposure to pesticide residues in nectar and pollen in urban and suburban environments from four regions of the United States. *Environmental Toxicology and Chemistry*, *41*(4), 991–1003. https://doi.org/10.1002/etc.5298

Desneux, N., Decourtye, A., & Delpuech, J. M. (2007). The sublethal effects of pesticides on beneficial arthropods. *Annual Review of Entomology*, *52*, 81–106. https://doi.org/10.1146/annurev.ento.52.110405.091440

Drouillard, K. G. (2008). Biomagnification. In S. E. Jorgensen & B. D. Fath (Eds.), *Encyclopaedia of ecology*. Elsevier.

eAGRI. (2024). *Portal of agricultural and rural development*. Ministry of Agriculture of the Czech Republic. https://mze.gov.cz/public/app/eagriapp/POR/

ESRI. (2021). *ArcGIS Pro 2.8.0*. ESRI. https://www.esri.com/en-us/home

Foody, G. M., Campbell, N. A., Trodd, N. M., & Wood, T. F. (1992). Derivation and applications of probabilistic measures of class membership from the maximum likelihood classification. *Photogrammetric Engineering & Remote Sensing*, *58*, 1335–1341.

Fritsch, C., Appenzeller, B., Burkart, L., Coeurdassier, M., Scheifler, R., Raoul, F., & Pelosi, C. (2022). Pervasive exposure of wild small mammals to legacy and currently used pesticide mixtures in arable landscapes. *Scientific Reports*, *12*, 15904. https://doi.org/10.1038/s41598-022-19959-y

Gallé, R., Tölgyesi, C., Császár, P., Bátori, Z., Gallé-Szpisjak, N., & Kaur, H. (2022). Landscape structure is a major driver of plant and arthropod diversity in natural European forest fragments. *Ecosphere*, *13*, e3905. https://doi.org/10.1002/ecs2.3905

Goulson, D. (2013). An overview of the environmental risks posed by neonicotinoid insecticides. *Journal of Applied Ecology*, *50*(4), 977–987. https://doi.org/10.1111/1365-2664.12111

Goutte, A., Alliot, F., Budzinski, H., Simonnet-Laprade, C., Santos, R., Lachaux, V., Maciejewski, K., le Menach, K., & Labadie, P. (2020). Trophic transfer of micropollutants and their metabolites in an urban riverine food web. *Environmental Science & Technology*, *54*, 8043–8050. https://doi.org/10.1021/acs.est.0c01411

Guo, Z., Zhu, Z., Huang, S., & Wang, J. (2020). Non-targeted screening of pesticides for food analysis using liquid chromatography high resolution mass spectrometry—A review. *Food Additives and Contaminants: Part A*, *37*, 1180–1201. https://doi.org/10.1080/19440049.2020.1753890

Huang, C., Zhu, H., Yu, Y., Ding, Q., Jia, F., Zhao, B., Wei, S., Gong, D., Xu, W., & Ji, M. (2017). Simultaneous determination of pyrametostrobin and its two metabolites in cucumber and soil using a quick, easy, cheap, effective, rugged, and safe method with HPLC–MS/MS. *Journal of Separation Science*, *40*(11), 2335–2343.

Jacob, J., Manson, P., Barfknecht, R., & Fredricks, T. (2014). Common vole (*Microtus arvalis*) ecology and management: Implications for risk assessment of plant protection products. *Pest Management Science*, *70*, 869–878. https://doi.org/10.1002/ps.3695

Karasali, H., Marousopoulou, A., & Machera, K. (2016). Pesticide residue concentration in soil following conventional and low-input crop management in a mediterranean agro-ecosystem, in Central Greece. *Science of the Total Environment*, *541*, 130–142. https://doi.org/10.1016/j.scitotenv.2015.09.016

Kaur, R., Choudhary, D., Bali, S., Bandral, S. S., Singh, V., Ahmad, M. A., Rani, N., Singh, T. G., & Chandrasekaran, B. (2024). Pesticides: An alarming detrimental to health and environment. *Science of the Total Environment*, *915*, 170113. https://doi.org/10.1016/j.scitotenv.2024.170113

Kimmel, K., Clark, M., & Tilman, D. (2022). Impact of multiple small and persistent threats on extinction risk. *Conservation Biology*, *36*(5), e13901. https://doi.org/10.1111/cobi.13901

Knapp, J. L., Nicholson, C. C., Jonsson, O., de Miranda, J. R., & Rundlöf, M. (2023). Ecological traits interact with landscape context to determine bees' pesticide risk. *Nature Ecology & Evolution*, *7*, 547–556. https://doi.org/10.1038/s41559-023-01990-5

Koech, S. J., Karanja, R. H., Kurgat, J. K., Mokaya, H. O., Dubois, T., & Lattorff, H. M. G. (2023). Pesticide contamination and their botanical sources in pollen loads collected by honeybees in Kenya: A spatio-temporal context. *Agriculture, Ecosystems and Environment*, *343*, 108264. https://doi.org/10.1016/j.agee.2022.108264

Košulič, O., Purchart, L., Hruška, J., Svobodová, K., Bartoš, M., Čermák, J., Kwiecien, J., Eiglová, E., Karanská, K., Vlková, Š., Chudobová, M., & Ernst, M. (2022). *Methodology for minimization of impact of plant production products on non-target organisms and regulation of the use of risk products in agriculture* (p. 52). Certified Methodology (Ministry of the Environment of the Czech Republic). https://www.mzp.cz/cz/rostliny_houby_nepuvodni_druhy

Lami, F., Bartomeus, I., Nardi, D., Beduschi, T., Boscutti, F., Pantini, P., Santoiemma, G., Scherber, C., Tscharntke, T., & Marini, L. (2021). Species–habitat networks elucidate landscape effects on habitat specialisation of natural enemies and pollinators. *Ecology Letters*, *24*, 288–297. https://doi.org/10.1111/ele.13642

Li, Z. (2020). Spatiotemporal pattern models for bioaccumulation of pesticides in common herbaceous and woody plants. *Journal of Environmental Management*, *276*, 111334. https://doi.org/10.1016/j.jenvman.2020.111334

Main, A. R., Michel, N. L., Headley, J. V., Peru, K. M., & Morrissey, C. A. (2015). Ecological and landscape drivers of neonicotinoid insecticide detections and concentrations in Canada's prairie wetlands. *Environmental Science and Technology*, *49*, 8367–8376. https://doi.org/10.1021/acs.est.5b01287

Medici, S. K., Maggi, M. D., Galetto, L., Iglesias, M. d. R., Sarlo, E. G., Recavarren, M. I., Salar, P. E., & Eguaras, M. J. (2022). Influence of the agricultural landscape surrounding *Apis mellifera* colonies on the presence of pesticides in honey. *Apidologie*, *53*, 21. https://doi.org/10.1007/s13592-022-00930-9

Mei, M., Du, Z. X., & Chen, Y. (2011). QuEChERS-ultra performance liquid chromatography-tandem mass spectrometry for determination of 5 currently used herbicides. *Chinese Journal of Analytical Chemistry*, *39*, 1659–1664. https://doi.org/10.1016/S1872-2040(10)60482-3

Michalko, R., & Pekár, S. (2016). Different hunting strategies of generalist predators result in functional differences. *Oecologia*, *181*, 1187–1197. https://doi.org/10.1007/s00442-016-3631-4

Michalko, R., Purchart, L., Hofman, J., & Košulič, O. (2024). Distribution of pesticides in agroecosystem food webs differ among trophic groups and between annual and perennial crops. *Agronomy for Sustainable Development*, *44*(1), 13. https://doi.org/10.1007/s13593-024-00950-y

Michalko, R., Purchart, L., & Košulič, O. (2024). Dataset for: Landscape and local factors drive pesticide distribution in perennial agroecosystems. *Journal of Applied Ecology. Zenodo*. https://doi.org/10.5281/zenodo.13840817

Pelosi, C., Bertrand, C., Daniele, G., Coeurdassier, M., Benoit, P., Nélieu, S., Lafay, F., Bretagnolle, V., Gaba, S., Vulliet, E., & Fritsch, C. (2021). Residues of currently used pesticides in soils and earthworms: A silent threat? *Agriculture, Ecosystems and Environment*, *305*, 107167. https://doi.org/10.1016/j.agee.2020.107167

Picchi, M. S., Bocci, G., Petacchi, R., & Entling, M. H. (2016). Effects of local and landscape factors on spiders and olive fruit flies. *Agriculture, Ecosystems & Environment*, *222*, 138–147. https://doi.org/10.1016/j.agee.2016.01.045

Planet Team. (2017). Planet application program interface. In *Space for life on earth*. Planet Labs Inc. https://api.planet.com

Pose-Juan, E., Sanchez-Martin, M. J., Soledad Andrades, M., Sonia Rodriguez-Cruz, M., & Herrero-Hernandez, E. (2015). Pesticide residues in vineyard soils from Spain: Spatial and temporal distributions. *The Science of the Total Environment*, *514*, 351–358. https://doi.org/10.1016/j.scitotenv.2015.01.076

Qi, S. Y., Xu, X. L., Ma, W. Z., Deng, S. L., Lian, Z. X., & Yu, K. (2022). Effects of organochlorine pesticide residues in maternal body on infants. *Frontiers in Endocrinology*, *13*, 890307. https://doi.org/10.3389/fendo.2022.890307

R Development Core Team. (2023). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. http://www.R-project.org/

Sabzevari, S., & Hofman, J. (2022). A worldwide review of currently used pesticides' monitoring in agricultural soils. *The Science of the Total Environment*, *812*, 152344. https://doi.org/10.1016/j.scitotenv.2021.152344

Samu, F., & Szinetár, C. (2002). On the nature of agrobionts spiders. *Journal of Arachnology*, *30*, 389–402. https://doi.org/10.1636/0161-8202

Šarapatka, B., & Niggli, U. (2008). Organic farming in The Czech Republic: Practice and policy. In U. Niggli, T. Alföldi, & H. Willer (Eds.), *Organic farming and biodiversity in Europe* (pp. 42–47). FiBL and IFOAM.

Sharma, R. K., Jaiswal, S. K., Siddiqi, N. J., & Sharma, B. (2012). Effect of carbofuran on some biochemical indices of human erythrocytes in vitro. *Cellular and Molecular Biology*, *58*(1), 103–109. https://doi.org/10.1170/T927

Shelton, J. F., Geraghty, E. M., Tancredi, D. J., Delwiche, L. D., Schmidt, R. J., Ritz, B., Hansen, R. L., & Hertz-Picciotto, I. (2014). Neurodevelopmental disorders and prenatal residential proximity to agricultural pesticides: The CHARGE study. *Environmental Health Perspectives*, *122*, 1103–1109. https://doi.org/10.1289/ehp.1307044

Storck, V., Karpouzas, D. G., & Martin-Laurent, F. (2017). Towards a better pesticide policy for the European Union. *Science of the Total Environment*, *575*, 1027–1033. https://doi.org/10.1016/j.scitotenv.2016.09.167

Suchomel, J., Purchart, L., & Čepelka, L. (2012). Structure and diversity of small-mammal communities of lowland forests in the rural central European landscape. *European Journal of Forest Research*, *131*, 1933–1941. https://doi.org/10.1007/s10342-012-0644-3

Svobodová, M., Šmídová, K., Hvězdová, M., & Hofman, J. (2018). Uptake kinetics of pesticides chlorpyrifos and tebuconazole in the earthworm *Eisenia andrei* in two different soils. *Environmental Pollution*, *236*, 257–264. https://doi.org/10.1016/j.envpol.2018.01.082

Torma, A., Gallé, R., & Bozsó, M. (2014). Effects of habitat and landscape characteristics on the arthropod assemblages (Araneae, Orthoptera, Heteroptera) of sand grassland remnants in southern Hungary. *Agriculture, Ecosystems & Environment*, *196*, 42–50. https://doi.org/10.1016/j.agee.2014.06.021

Ucar, T., & Hall, F. R. (2001). Windbreaks as a pesticide drift mitigation strategy: A review. *Pest Management Science*, *57*, 663–675. https://doi.org/10.1002/ps.341

Urbanowicz, C., Baert, N., Bluher, S. E., Böröczky, K., Ramos, M., & McArt, S. H. (2019). Low maize pollen collection and low pesticide risk to honey bees in heterogeneous agricultural landscapes. *Apidologie*, *50*, 379–390. https://doi.org/10.1007/s13592-019-00655-2

Wang, M. (2013). From home range dynamics to population cycles: Validation and realism of a common vole population model for pesticide risk assessment. *Integrated Environmental Assessment and Management*, *9*, 294–307. https://doi.org/10.1002/ieam.1377

Zuur, A. F., Hilbe, J. M., & Ieno, E. N. (2015). *A beginner's guide to GLM and GLMM with R. A frequentist and Bayesian perspective for ecologists*. Highland Statistics Ltd.

SUPPORTING INFORMATION

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

Method S1. Pesticide residue analysis.

Table S1. Questionnaire form used for collecting data from farmers on their agricultural practices.

Table S2. Comparison of AICc values of generalized linear models with gamma error structure and inverse link function investigating the effect of selected local (local management, proportional representation of web-building spiders in spider community) and landscape factors (proportion of semi-natural habitats [SNH], forests, grassland, and shrubland) on the overall concentration of agrochemicals in spider bodies.

Table S3. Comparison of AICc values of generalized linear models with gamma error structure and inverse link function investigating the effect of selected local (local management, proportional representation of web-building spiders in spider community) and landscape factors (proportion of semi-natural habitats [SNH], forests, grassland, and shrubland) on the overall concentration of agrochemicals in spider bodies.

Table S4. Comparison of AICc values of generalized linear models with quasipoisson error structure and log link function investigating the effect of selected local (local management, proportional representation of web-building spiders in spider community) and landscape factors (proportion of semi-natural habitats [SNH], forests, grassland, and shrubland) on the spectrum of agrochemicals detected in spider bodies.

Table S5. Comparison of AICc values of generalized linear models with gamma error structure and inverse link function investigating the effect of selected local (local management, proportional representation of web-building spiders in spider community) and landscape factors (proportion of semi-natural habitats [SNH], forests, grassland, and shrubland) on the concentration of insecticides in spider bodies.

Table S6. Comparison of AICc values of generalized linear models with gamma error structure and inverse link function investigating the effect of selected local (local management, proportional representation of web-building spiders in spider community) and landscape factors (proportion of semi-natural habitats [SNH], forests, grassland, and shrubland) on the concentration of herbicides in spider bodies.

Table S7. Comparison of AICc values of generalized linear models with gamma error structure and inverse link function investigating the effect of selected local (local management, proportional representation of web-building spiders in spider community) and landscape factors (proportion of semi-natural habitats [SNH], forests, grasslands, and shrublands) on the concentration of fungicides in spider bodies.

Table S8. Comparison of AICc values of generalized linear models with gamma error structure and inverse link function investigating the effect of local management and landscape factors (proportion of semi-natural habitats [SNH], forests, grasslands, and shrublands) on the overall concentration of agrochemicals in rodents.

Table S9. Comparison of AICc values of Generalized Linear Models with quasipoisson error structure and log link function investigating the effect of local management and landscape factors (proportion of semi-natural habitats [SNH], forests, grasslands, and shrublands) on the spectrum of agrochemicals in rodents.

Table S10. Comparison of AICc values of generalized linear models with gamma error structure and inverse link function investigating the effect of local management and landscape factors (proportion of semi-natural habitats [SNH], forests, grasslands, and shrublands) on the concentration of insecticides in rodents.

Table S11. Comparison of AICc values of generalized linear models with gamma error structure and inverse link function investigating the effect of local management and landscape factors (proportion of semi-natural habitats [SNH], forests, grasslands, and shrublands) on the concentration of herbicides in rodents.

Table S12. Comparison of AICc values of generalized linear models with gamma error structure and inverse link function investigating the effect of local management and landscape factors (proportion of semi-natural habitats [SNH], forests, grasslands, and shrublands) on the concentration of fungicides in rodents.

Table S13. Comparison of AICc values of generalized linear models with gamma error structure and inverse link function investigating the effect of local management and landscape factors (proportion of semi-natural habitats [SNH], forests, grasslands, and shrublands) on the overall concentration of agrochemicals in non-crop plants.

Table S14. Comparison of AICc values of generalized linear models with quasipoisson error structure and inverse link function investigating the effect of local management and landscape factors (proportion of semi-natural habitats [SNH], forests, grasslands, and shrublands) on the spectrum of pesticides in non-crop plants.

Table S15. Comparison of AICc values of general linear models investigating the effect of local management and landscape factors (proportion of semi-natural habitats [SNH], forests, grasslands, and shrublands) on the concentration of insecticides in non-crop plants.

Table S16. Comparison of AICc values of generalized linear models with gamma error structure and inverse link function investigating the effect of local management and landscape factors (proportion of semi-natural habitats [SNH], forests, grasslands, and shrublands) on the concentration of herbicides in non-crop plants.

Table S17. Comparison of AICc values of generalized linear models with gamma error structure and inverse link function investigating the effect of local management and landscape factors (proportion of semi-natural habitats [SNH], forests, grasslands, and shrublands) on the overall concentration of agrochemicals in soil.

Table S18. Comparison of AICc values of generalized linear models with quasipoisson error structure and log link function investigating the effect of local management and landscape factors (proportion of semi-natural habitats [SNH], forests, grasslands, and shrublands) on the spectrum of agrochemicals in soil.

Table S19. Comparison of AICc values of general linear models investigating the effect of local management and landscape factors (proportion of semi-natural habitats [SNH], forests, grasslands, and shrublands) on the concentration of herbicides in soil.

How to cite this article: Michalko, R., Purchart, L., & Košulič, O. (2024). Landscape and local factors drive pesticide distribution in perennial agroecosystems. *Journal of Applied Ecology*, *61*, 3066–3078. https://doi.org/10.1111/1365-2664.14808