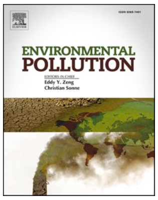
Environmental Pollution 402 (2026) 128348

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol



High temporal resolution pollen analysis: New insights into current-use pesticides distribution in agricultural landscapes

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ARTICLE INFO

Keywords:
Current-use pesticides
Bee pollen
Agricultural landscapes
Pollinators
Spray drift

ABSTRACT

Current-use pesticides (CUPs) disperse beyond treated areas, leading to unintended exposure of pollinators and other non-target organisms. Although this issue has received increasing attention, understanding how CUPs behave in agricultural landscapes remains challenging due to complex transport processes and limited field-based evidence on their movement over space and time. To address this gap, we used weekly pollen samples collected from five honeybee colonies over two growing seasons (2023–2024) in an intensively managed agricultural area to investigate the distribution of CUP residues in agricultural landscapes. Pollen was separated by plant species, allowing contamination patterns to be interpreted in relation to crop phenology, application timing, and weather conditions. Multiple CUPs were detected in pollen from both treated crops and untreated off-crop plants such as wildflowers, demonstrating substantial off-target drift. CUP residues persisted beyond intended application periods, with the neonicotinoid insecticide acetamiprid detected weeks after application. The fungicide cyprodinil reached up to 1025 $\mu g/kg_{dw}$ and was detected at distances exceeding 800 m from treated fields, suggesting contributions from spray drift, volatilisation, and atmospheric transport. By integrating pollen residue data with detailed spatial application records, crop maps, and meteorological information, this study moves beyond simple residue detection to infer the environmental processes that influence pesticide distribution. Our findings highlight the importance of weather conditions and the spatial distribution of agricultural and surrounding non-crop areas in shaping exposure pathways. These findings provide a strong evidence base for refining pesticide risk assessments and demonstrate that current mitigation measures may be insufficient to prevent widespread off-target exposure.

1. Introduction

Global pesticide use has increased substantially in recent decades, driven by population growth, the intensification of agricultural practices (Godfray et al., 2010; Popp et al., 2013; Schneider et al., 2023; Sharma et al., 2019; Tudi et al., 2021), and climate change, which alters precipitation patterns and shifts pest pressures (C. C. Chen & Mccarl, 2001; Delcour et al., 2015; Matzrafi, 2019; Pérez-Lucas et al., 2024). Current-use pesticides (CUPs), including insecticides, fungicides, and herbicides, are projected to remain crucial in modern agriculture to ensure stable yields (Lazarević-Pašti et al., 2025; Tudi et al., 2021). Studying CUPs is therefore central to assessing current exposure risks to non-target organisms in agricultural landscapes. Their increasing production and use pose serious risks to non-target organisms, biodiversity, ecosystem health, and long-term sustainability (Pretty, 2018; Pretty & Bharucha, 2014).

Current-use pesticides enter the environment through application to agricultural fields and can subsequently be transported via spray drift, runoff, volatilisation and deposition, distributing residues beyond treated areas (C. Chen et al., 2019; Singh et al., 2023). Once released, residues of CUPs can be detected in soil, water, and plant tissue, causing exposure for non-target species (Bondareva & Fedorova, 2021). Even at low environmental concentrations, they can impair survival and disrupt growth, reproduction, other physiological functions, and behaviour in exposed species (Nicholson et al., 2024; Wan et al., 2025). Pollinators such as honey bees, butterflies, and other insects are particularly

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https://doi.org/10.1016/j.envpol.2026.128348
Received 16 January 2026; Received in revised form 13 April 2026; Accepted 12 May 2026

vulnerable to CUP exposure, as these compounds can interfere with foraging, navigation, and learning abilities, reducing pollination efficiency and increasing mortality (Lu et al., 2020; Serrão et al., 2022). Herbicides and fungicides may also indirectly affect pollinators. For example, herbicides can reduce floral resources and alter plant community composition, while fungicides may interfere with plant–microbe interactions and affect nectar and pollen quality (Goulson et al., 2015; Schaeffer et al., 2017; Voβ et al., 2023). Together with habitat loss, climate extremes, and emerging diseases, CUPs contribute to global biodiversity loss and weaken ecological networks and services (Chagnon et al., 2015; Nicholson et al., 2024; Vanbergen and the Insect Pollinators Initiative, 2013; Wan et al., 2025).

Despite growing concern, research on CUPs in terrestrial ecosystems often remains short-term and limited in temporal resolution compared to the comprehensive monitoring and process-oriented studies in aquatic environments (Chiaia-Hernandez et al., 2017; Riedo et al., 2023; Silva et al., 2019). Although water monitoring can identify problematic compounds and approximate overall pesticide usage, it does not capture the complex dynamics of CUPs on land (Fabre et al., 2023; Stalder et al., 2025). Agricultural landscapes are highly variable in space and time, as fields differ in size, topography, soil type, crop composition, pesticide use, and phenology, influencing pesticide transport (Doppler et al., 2012; Flury, 1996). Pesticide application records, including timing and dosage, are often unavailable, leading to substantial knowledge gaps about the exposure of non-target organisms (Commelin et al., 2022; Mesnage et al., 2021; Riedo et al., 2023). Moreover, collecting spatially representative samples for terrestrial pesticide surveillance is logistically complex due to sequential pesticide applications and mixed-cropping systems (Chiaia-Hernandez et al., 2017; Kim Tiam et al., 2016; Kodešová et al., 2011; Mangold et al., 2024; Taylor et al., 2020; Vagi & Petsas, 2021).

To overcome these limitations, biomonitoring using pollinators has emerged as a practical approach, with honey bees representing a widely used model system (Cunningham et al., 2022; Mair et al., 2023; Schaad et al., 2023; Stalder et al., 2025). Honey bees typically forage within a distance up to 2 km from the hive (Couvillon et al., 2014), encountering pesticides in floral resources through contact and ingestion, and subsequently transporting contaminated pollen back to the hive, thus integrating exposure across multiple agricultural and non-agricultural habitats (Schaad et al., 2023). In agricultural landscapes, honey bees commonly forage on wildflowers and insect-pollinated crops, such as rapeseed, sunflowers, and a range of fruit crops, including vine, bush, and tree fruits (Lau et al., 2023; Requier et al., 2015). As prolific pollen collectors, honey bees provide near-real-time snapshots of pesticide contamination in the environment, offering a relatively high temporal resolution compared to traditional monitoring approaches (Kast et al., 2024). However, this signal is influenced by foraging behaviour and may not fully represent all parts of the landscape. Most biomonitoring studies also lack contextual information on pesticide applications and meteorological conditions, making the interpretation of residue patterns difficult (Averill et al., 2024; Simon-Delso et al., 2017).

The present study aims to (i) investigate how specific pesticide treatments, crop phenology, and meteorological conditions influence contamination in bee-collected pollen; (ii) examine how pesticide residues in pollen increase or decrease over time following applications; and (iii) evaluate how bee-collected pollen can be used to infer environmental processes influencing the distribution of CUPs across agricultural landscapes. To address these aims, we used honey bee colonies as bioindicators within an agricultural area where detailed pesticide application records were available for selected fields over two growing seasons (2023–2024). Weekly bee pollen sampling was combined with records of pesticide applications, meteorological conditions, crop distribution, and pollen botanical origin determined by pollen separation. By resolving contamination patterns within a well-characterised agricultural setting, this study provides new insights into the distribution of CUPs and pollinator exposure, contributing to a better understanding of pesticide fate in terrestrial ecosystems.

2. Materials and methods

2.1. Study area

This study was conducted at Agroscope Reckenholz in Zurich-Affoltern, Switzerland (coordinates WGS84: 47.428829°N, 8.516646°E). The hive placement site on the Agroscope grounds served as the centre point for defining the study area as illustrated in Fig. 1. As honey bees typically forage, on average, at distances of up to two km from the hive (Couvillon et al., 2014; Kendall et al., 2022), we delineated a two-km radius (~12.6 km^2) around this point to characterise the landscape from which most of the collected pollen was expected to originate.

Within this area, land-use composition consisted of approximately 42% agriculture (~5.3 km^2), 16% forest, 2% natural or semi-natural herbaceous vegetation, 21% urban built-up areas, and 16% urban green spaces (parks, gardens, and roadside vegetation). The landscape also contained major transport infrastructure, including a highway crossing the study area (Fig. 1), as well as several urban settlements located in the southern part of the radius. Agricultural land included a variety of arable crops, including cereals, maize, rapeseed, potatoes, sunflowers, and grass–clover leys, providing diverse floral resources whose distribution varied from year to year.

Of the total agricultural area, approximately 0.5 km^2 was managed by Agroscope, representing ~9% of the agricultural land and ~3.8% of the total study area. These fields included all major crop types present in the landscape (e.g., cereals, maize, oilseed crops, and root crops), thereby capturing the dominant crop categories relevant for pesticide use. Overall, the crop composition of Agroscope-managed fields was broadly comparable to that of the total agricultural area, indicating good representativeness of the study landscape. Differences were mainly observed for certain categories, with a higher proportion of grassland and forage systems, maize, and oilseed and protein crops, and a lower representation of root crops, vegetables, and fruit crops. A detailed quantitative comparison of crop composition is provided in Table S1 in the Supporting Information (SI).

In total, 58 agricultural fields were managed by Agroscope (highlighted in red in Fig. 1). These fields were cultivated according to standard agricultural practices by Agroscope staff or external farmers under Agroscope's coordination. Agroscope maintains a long-term archive documenting crop management activity, including CUP applications, fertilisation, and mechanical interventions. For the present study, detailed pesticide application records were compiled specifically for the 2023 and 2024 growing seasons. In 2023, 39 CUPs were applied in the study area, including 24 herbicides, 9 fungicides, 3 insecticides, and 2 plant growth regulators. In 2024, 47 CUPs were applied, comprising 29 herbicides, 12 fungicides, 3 insecticides, 2 plant growth regulators, and 1 molluscicide. Detailed records of pesticide applications, including total amounts applied per field, product concentrations, application dates, crop phenological stages, and locations of treated fields, are provided in the SI, Sections S1 and S3. For 2023, spatially resolved application data were available for all monitored fields. For 2024, spatially resolved application data were available only for rapeseed fields, while for other crops, applications were reported at the crop level without precise spatial allocation. Consequently, detailed spatial analyses of crop distribution and representativeness (Table S1) are based only on 2023 data. Pesticide application data were only available for Agroscope-managed fields, with no data available for other agricultural fields within the study area.

Meteorological parameters, including atmospheric pressure, air humidity, air temperature, precipitation, wind speed, and wind direction, were recorded for the years 2023 and 2024 at a 10-min temporal resolution by a MeteoSwiss meteorological station (station ID: REH) located within the study area (coordinates WGS84: 47.427694°N, 8.517953°E,

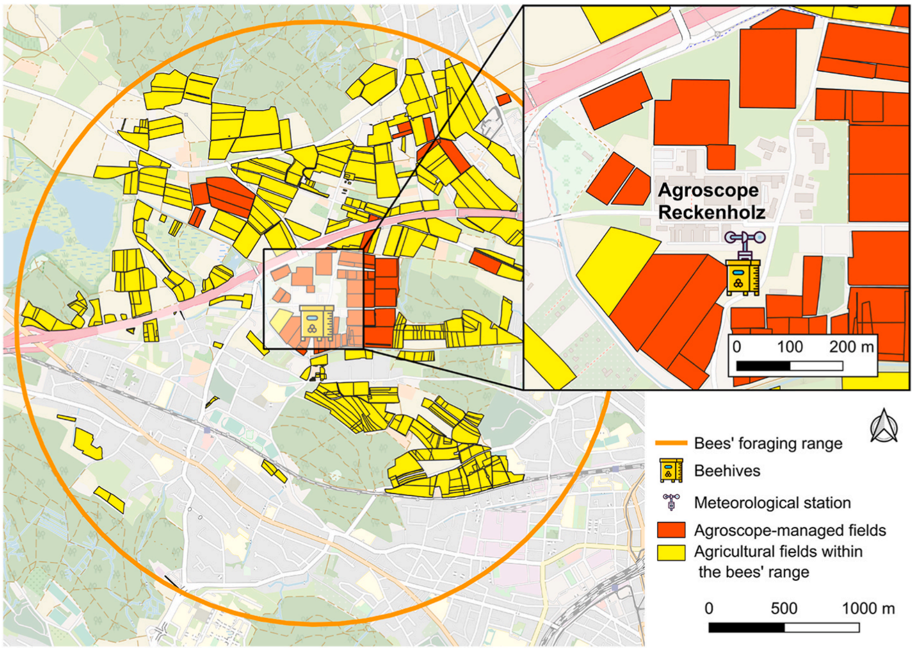

Fig. 1. Map of the area surrounding the study site (based on OpenStreetMap), showing the location of the honey bee colonies (1-5) and the meteorological station. The orange circle indicates the 2 km foraging range of honey bees from the hives located within the study site. Red areas indicate agricultural fields controlled and managed by Agroscope staff or collaborating farmers under Agroscope's coordination. Yellow areas show other agricultural fields within the foraging range of the honey bees. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

see Fig. 1). The full dataset was accessed through the Open Data portal of MeteoSwiss (MeteoSwiss).

2.2. Crop mapping and Sentinel-2 imagery

To identify additional fields and their crops within our study area that were not managed by Agroscope, agricultural land-use data for 2023 and 2024 were retrieved from the geoportal of the Canton of Zürich. Spatial analyses were conducted in QGIS (version 3.40.4), integrating crop maps, hive locations, and sampling data to identify potential foraging zones and overlaps between bee flight radius and pesticide applications.

Sentinel-2 satellite imagery from the Copernicus program was visually inspected to identify the flowering period of rapeseed fields. Rapeseed was the only crop for which flowering could be reliably identified, as its bright yellow bloom allows for straightforward visual identification on cloud-free images. Flowering periods of other crops in the study area could not be identified from Sentinel-2 imagery due to the absence of a consistent spectral signal (e.g., colour or reflectance pattern) at the available spatial or spectral resolution. Additionally, periods of high cloud cover resulted in data gaps, introducing some uncertainty in determining the exact timing of the peak bloom. Details on the imagery used to assess rapeseed flowering periods are presented in Section S4 in the SI.

2.3. Honey bee colonies setup

Five beehives (12-frame Dadant Blatt hives) with honey bee (*Apis mellifera carnica*) colonies (colony IDs: 1-5) were installed on April 10, 2023, as fully established colonies containing brood, workers, and a queen. The use of a limited number of colonies is consistent with previous biomonitoring studies, where typically 3–5 hives per site were used to characterise pesticide exposure at the landscape scale (Cilia et al., 2022; Ostiguy et al., 2019). The hives were strategically placed south of the meteorological station, centrally within the Agroscope-managed fields (see Fig. 1 for the layout), ensuring that honey bees primarily foraged on nearby crops within the study site. From August 14 to 29, 2023, no pollen samples were collected due to the application of formic acid (Nassenheider Pro, 290 ml Formivar 60%) to control *Varroa destructor*, a significant external parasitic threat to honey bees.

2.4. Bee pollen sampling

A custom-made pollen trap was installed on each hive, consisting of a wooden frame surrounding the hive entrance and a removable grid with 5 mm diameter holes (Kast et al., 2024). As bees pass through the grid, pollen pellets are removed from their legs and collected in a drawer underneath. The trap was activated only once per week (24 h) to minimise stress on the colonies and ensure a sufficient pollen supply.

Bee pollen was sampled weekly on Friday or Saturday, depending on the meteorological conditions, during two agricultural seasons. In 2023, sampling occurred from April 28 to October 13, covering the main bee foraging season and most of the CUP applications. In 2024, sampling focused on the early season, from March 15 to May 3, to capture initial pesticide applications missed in 2023. Two samples (March 29 and April 19) couldn't be collected due to pollen scarcity caused by poor weather conditions. In 2024, sampling was limited to four colonies (IDs 1–4), as colony 5 showed weak development and was excluded to protect its health. The pollen was collected in single-use LDPE bags and immediately stored at -20 °C until analysis.

2.5. Detection and quantification of CUP residues in bee pollen

Solvents, reagents, reference standards, and deuterated internal standards were used according to established protocols. The extraction method is described in detail in a previous study (Kast et al., 2024). In short, 2 g of pollen from each colony sample collected on the same day were combined to create a single pooled sample per week. This approach provides an integrated perspective on CUP exposure across the bees' entire foraging area and is consistent with previous studies that aggregate data across colonies to obtain a site-level signal of contamination (Ostiguy et al., 2019). The resulting 10 g of pooled bee pollen was homogenised and freeze-dried to remove water. CUP extraction was performed with 1 g of freeze-dried pooled pollen using the QuEChERS method (Quick, Easy, Cheap, Efficient, Rugged, Safe), employing primary secondary amine (PSA) and C18 sorbents as cleanup agents.

The analytical method covered 50 target pesticides (see Table S4 in the SI), including a broad range of commonly used insecticides, fungicides, herbicides, and acaricides. The method targets a predefined set of compounds and does not cover all pesticide classes; certain compound classes, such as highly polar pesticides (e.g., glyphosate), were not included due to analytical limitations.

Acetonitrile was used for the extraction and contained the following internal standards: azoxystrobin-D4, clothianidin-D3, cyproconazole-D3, fluopyram-D4, terbuthylazine-D5, and thiacloprid-D4. After extraction, the supernatant was filtered through a 0.45 μm polyamide filter into 1.5 mL autosampler vials and analysed by high-performance liquid chromatography-tandem mass spectrometry (HPLC-MS/MS). The analysis was performed using an Agilent 1290 Infinity II UHPLC system coupled to an Agilent 6495C MS/MS using a C18 reversed-phase column (Acquity UPLC HSS T3 column, 100 Å, 1.8 μm, 2.1 × 100 mm) at 40 °C, following previously published conditions (Kast et al., 2024).

A commercial pollen (Bienen Roth GmbH, Wila, Switzerland) containing low background levels of several CUPs (see Section S5 of the SI) was used to prepare blank extracts. These background levels were incorporated into the calculation of compound-specific limits of detection (LOD) and limits of quantification (LOQ), and no blank subtraction was applied to the sample results. External matrix-matched calibration curves (0.1-1000 μg/L) were prepared by spiking the commercial blank pollen extract with known pesticide concentrations (Kast et al., 2024). For the six pesticides with available deuterated internal standards, calibration was performed in acetonitrile, and quantification was corrected using the corresponding internal standards. Calibration, data acquisition, and quantification were performed using MassHunter software (Agilent, Basel, Switzerland). LODs and LOQs are listed in Table S4 of the SI. All CUP residue concentrations in pollen are reported on a dry weight (dw) basis.

All 2023 pooled pollen samples were analysed in duplicate. Due to good agreement between duplicate samples (differences <20%), duplicate analysis was limited to 20% of samples in 2024 to reduce analytical workload.

In this study, approximately 28% of the CUPs applied within Agroscope's managed fields were included in the analytical target list and could therefore be detected and quantified. This limitation reflects analytical and logistical constraints. The additional pesticides covered by the method but not applied in the Agroscope-managed fields are known to be relevant to bee toxicity or are commonly found in high concentrations in bee matrices (Kast et al., 2024; Schaad et al., 2023).

2.6. Pollen separation by plant species

We separated selected pollen samples with high CUP concentrations to identify the botanical origin of the pollen containing CUP residues, following previously described procedures (Kast et al., 2019). Briefly, 6 g of non-dried pollen from an individual colony sample (or the entire available sample if less than 6 g) was visually separated by colour as a preliminary step to group pollen into distinct fractions prior to microscopic identification. Non-dried pollen was used to preserve the integrity of individual pellets, allowing accurate colour-based separation. Sorting was performed manually under consistent lighting by one trained operator. A few pollen pellets of each colour fraction were prepared on microscope slides using a preheated Kaiser's glycerol gelatine (Merck, Art. 1.09242.0100) (Von Der Ohe et al., 2004). Palynological characteristics were then used to determine the botanical origin of each pollen fraction, typically at the genus level and, where possible, at the species level. When multiple pollen types were present within a fraction, these were recorded as mixed. Fractions identified as the same botanical type were pooled. Each pooled fraction was weighed and processed individually for CUP residue analysis. For simplification, CUP concentrations were normalised to dry weight using the water content measured in the pooled bee pollen sample, assuming a similar moisture content across all fractions.

3. Results and discussion

Overall, the analysis of bee pollen revealed a diverse range of CUPs across both sampling campaigns. A total of 15 of the 50 target CUPs (30%) were identified, encompassing 8 fungicides, 2 herbicides, 3 insecticides, 1 fungicide metabolite, and 1 synergist, with concentrations ranging from 0.4 to over 1025 μg/kgdw, as detailed in Section S6 of the SI.

In 2023, 10 CUPs were detected, with concentrations ranging from 0.2 to 29 $\mu g/kg_{dw}$, with the fungicide difenoconazole peaking on July 28. The CUPs' contamination showed peak values from April to June, isolated detections at the end of July, and a substantial decline from August to October, consistent with pesticide application patterns in Swiss arable cropping systems. In 2024, 11 CUPs were detected, with concentrations ranging from 0.5 to 1025 $\mu g/kg_{dw}$. These ranges reflect the wide variability across different pesticide classes and compounds. Among the 15 CUPs detected across the two sampling seasons, 6 were present in both 2023 and 2024. Despite a shorter sampling period compared to 2023, the 2024 sampling campaign showed substantially higher contamination levels for the same targeted compounds, with the fungicide cyprodinil peaking at 1025 $\mu g/kg_{dw}$. The difference in CUP contamination between inter-annual seasons may be attributed to the earlier start of sampling in 2024 and variations in environmental conditions. For example, March 2024 was more humid than the same period in 2023, as indicated by higher cumulative precipitation and relative humidity (see Section S7 in the SI). These conditions may have promoted fungal growth and accelerated insect development, as humid weather is known to increase pest and disease pressure and can lead to more frequent fungicide and insecticide applications (Skendžić et al., 2021). At the same time, honey bee foraging is constrained by short-term weather, with reduced activity under unfavourable conditions, potentially concentrating foraging closer to the colony. This may increase exposure to contaminated pollen from nearby treated fields (Vincze et al., 2025). In addition, weather conditions can influence pesticide persistence and residue levels in crops, further affecting exposure risk (Averill et al., 2024; Karbassioon et al., 2023).

3.1. Applied CUPs

Applied and detected CUPs. During the 2023 season, we detected five of the eleven (~45%) applied and detectable compounds in the Agroscope-managed fields (red fields in Fig. 1), including the insecticide acetamiprid, the herbicides prosulfocarb and terbuthylazine, and the fungicides difenoconazole and mandipropamid. In 2024, during the sampled period, only the insecticide acetamiprid and the herbicide prosulfocarb were detected. Contamination time series for all detected and applied compounds are presented for 2023 and 2024 in Section S8 in the SI. The field numbers referenced in the following discussion correspond to individual agricultural fields, as shown in Fig. S1 in the SI.

Acetamiprid (insecticide) was detected in bee pollen samples after applications to rapeseed fields in 2023 (fields 109 S and 112 W) and 2024. In 2023, it was applied on April 5 and detected in the sample taken on April 28. However, no pollen contamination was detected after later applications to potato fields (fields 109 N, 206, and 210) on June 27 and August 17. This is consistent with the low attractiveness of potato as a pollen source for honey bees, which cannot effectively access pollen due to the absence of buzz pollination (Buchanan et al., 2017). In 2024, acetamiprid was applied to rapeseed fields on March 15, with contamination detected in bee pollen samples from early April to early May. A detailed analysis of acetamiprid contamination patterns is presented later in Section 3.3.

Prosulfocarb (herbicide) was applied twice to potato fields in 2023 on May 27 (fields 206 and 210) and June 7 (field 109 N). The pollen sample collected on May 26, one day before the first documented application, already contained 2.3 $\mu g/kg_{dw}$ of prosulfocarb, indicating exposure from sources outside the Agroscope-managed fields. Residue levels below the LOQ were present in samples collected before the first application and in one sample collected after the second application. In 2024, prosulfocarb was applied to potato fields on May 4, yet contamination was detected in the pollen sample taken on May 3. Moreover, prosulfocarb was also detected in the sample from April 12, more than two weeks prior to the documented application, further indicating exposure from sources outside the Agroscope-managed fields. The absence of a clear increase in contamination following applications to potato fields likely reflects their low importance as a pollen source for honey bees, suggesting that these applications contributed only minimally to the observed pollen contamination.

Terbuthylazine (herbicide) was applied twice in 2023: first on May 26 to corn silage (fields 117 and 118), and then on June 17 to corn silage and sorghum (fields 306 and 307). Following the first application, low residue levels (<LOQ) were detected in pollen samples. However, higher terbuthylazine levels were detected in the June 16 sample, prior to the second documented application. This pattern suggests that the observed exposure cannot be explained by the recorded applications in Agroscope-managed fields and may reflect additional sources not captured in the available data.

Difenoconazole and **mandipropamid** (fungicides) were consistently applied together, mainly on nearby potato fields on July 23, 2023 (fields 109 N and 206), and on September 2, 2023 (field 206). Difenoconazole contamination in the sample from July 28 coincided with the first application. However, no contamination was detected following the second application. In contrast, mandipropamid showed a different contamination pattern. Although the contamination levels were lower than those of difenoconazole, the residues prevailed over a longer period. Mandipropamid was also detected before the first application on July 23, peaking on July 7 and then falling below the LOQ. Additionally, mandipropamid contamination was detected in the pollen sample from September 8, which appeared shortly after the second application.

Applied but non-detected CUPs encompass six compounds. Their absence in bee pollen is likely due to a combination of four possible factors. First, some compounds, such as the insecticides indoxacarb and lambda-cyhalothrin, were applied before the pollen sampling began in March, which may explain why they were not detected. Second, the herbicide flufenacet, applied at low concentrations to silage maize on May 26, was likely not detected due to dilution caused by pooling samples from several colonies. While pooling improved the representativeness of the overall study area, it also resulted in a lower concentration of individual compounds in the combined sample, potentially falling below the method's LOD. Third, certain compounds, including the fungicide boscalid and the herbicide flufenacet, have physicochemical properties that may limit their accumulation in pollen. For example, compounds with high GUS (Groundwater Ubiquity Score) values are more mobile and tend to leach, which has been shown to decrease their likelihood of being detected in bee matrices (Stalder et al., 2025) (see Section S9 in the SI for the relevant physical-chemical properties of the applied and detected CUPs). Fourth, some compounds were applied to crops likely before flowering, which may limit their uptake into pollen. For example, the herbicide aclonifen was applied to sunflowers on May 27, prior to their typical flowering period, and it was not detected in pollen.

The observed relationships between bee pollen contamination and pesticide applications highlight the complex interplay of factors influencing the results. Variables such as application rate, crop type, flowering stage at the time of application, distance from treated fields to the hives, and undocumented applications in nearby areas can affect the presence and concentration of pesticide residues in pollen. In addition, seasonal foraging behaviour, weather conditions, and the physicochemical properties of the compounds can also influence the likelihood and extent of pesticide transfer into pollen. For example, bees rarely collect pollen from potato plants; therefore, applications on potato fields are unlikely to contribute to pollen contamination through direct foraging, and any observed residues likely result from indirect exposure (e.g. drift, environmental deposition, contact with contaminated plant surfaces or bee-mediated transfer during foraging).

3.2. *Not applied CUPs*

Ten additional CUPs were detected, although they were not applied within the Agroscope-managed fields. These included 2 insecticides (spirodiclofen and chlorpyrifos), 6 fungicides (azoxystrobin, mepanipyrim, cyprodinil, trifloxystrobin, fluopyram, and fludioxonil), 1 fungicide metabolite (desthio-prothioconazole), and 1 synergist (piperonyl butoxide). While bees typically forage near their hives when pollen is readily available, environmental factors such as meteorological conditions or pollen scarcity may drive them to explore further areas (Karbassioon et al., 2023; Visscher & Seeley, 1982), which could explain the presence of CUPs originating from fields outside the Agroscope-managed area. Except for the fungicide cyprodinil, concentrations of pesticides applied outside the Agroscope-managed fields were generally low and often below the LOQ, as reported in Section S6 of the SI. Some detected compounds, such as the insecticides spirodiclofen and chlorpyrifos, have been banned for agricultural use in Switzerland since 2020. Therefore, their presence in pollen samples could be due to residual environmental contamination, which has been reported in agricultural soils years after their last application (Barmettler et al., 2025; Riedo et al., 2023). Alternatively, non-agricultural uses (e.g., urban or landscaping applications) or misuse may contribute to the observed contamination, particularly given the proximity of urban and agricultural areas surrounding the Agroscope-managed fields (red fields in Fig. 1).

No miticides were detected in the pollen samples, which is consistent with the absence of miticide treatments in the study hives during the sampling period.

3.3. *Distribution of key CUPs in agricultural landscapes*

We selected two compounds, the neonicotinoid insecticide acetamiprid (applied) and the anilinopyrimidine fungicide cyprodinil (not applied), to further investigate the spatial and temporal occurrences of CUPs in agricultural landscapes.

Acetamiprid was selected because it exhibited high contamination levels in bee pollen in 2023 and 2024 and was consistently detected following applications within the Agroscope-managed fields, as illustrated in Fig. 2. This insecticide is commonly applied to rapeseed, a crop that is highly attractive to bees due to its rich nectar and pollen. In Switzerland, acetamiprid is also approved for a wide range of other crops, including fruit trees (e.g., cherries, apples), vegetables (e.g., cabbage, tomatoes), and field crops such as potatoes and wheat (Federal Food Safety and Veterinary Office, 2026). It is primarily used to control pests such as aphids and whiteflies and is considered moderately systemic, meaning it can be absorbed and translocated within plant tissues (Buchholz & Nauen, 2002). Its relatively low acute toxicity to non-target insects has contributed to its popularity as an alternative to other neonicotinoids. However, concerns remain about its potential sub-lethal effects on pollinators and other beneficial insects (Lewis et al., 2016).

In 2023, acetamiprid was applied to rapeseed fields in the managed area on April 5. However, pollen sampling did not begin until April 28, resulting in a data gap immediately after the application. Acetamiprid concentrations in pollen ranged from 0.5 to 3.0 $\mu g/kg_{dw}$, with the highest levels observed in the first available sample after application, followed by a gradual decline. This decline likely reflects decreasing residue availability over time due to degradation and reduced concentrations in flowering plant tissues. Together, these patterns suggest a direct link between the insecticide application and subsequent pollen

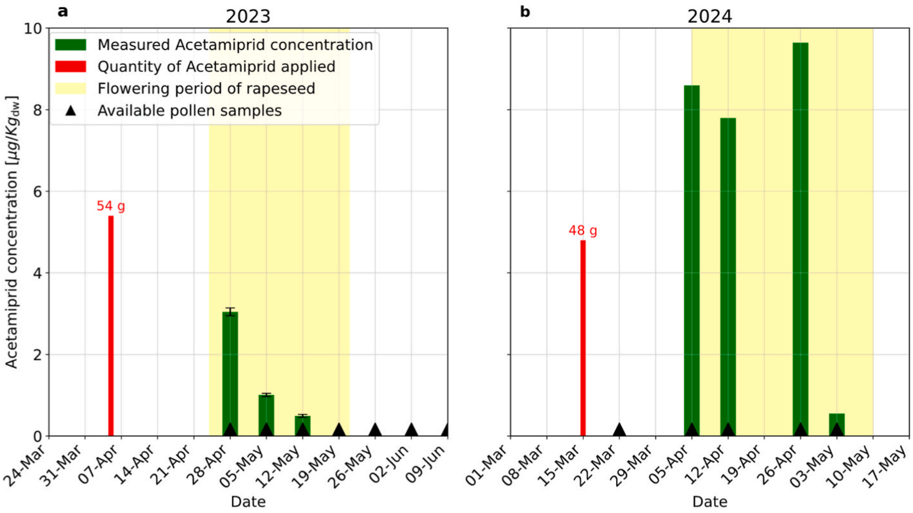

Fig. 2. Temporal trends of acetamiprid concentrations in pooled pollen samples during (a) the 2023 and (b) 2024 sampling campaign. Green bars represent acetamiprid concentrations (μg/kg$_{dw}$), with error bars indicating the variability between duplicate samples. Red bars indicate the absolute amount of acetamiprid applied in managed fields (expressed as total mass rather than per unit area to reflect landscape-scale bee foraging). Yellow-shaded areas denote the rapeseed blooming period, as determined from satellite imagery. Black triangles on the x-axis mark the pollen collection days. Note: All 2023 samples were analysed in duplicate. In 2024, only 20% of samples were analysed in duplicate, as good agreement was observed in the previous year. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

contamination, as illustrated in Fig. 2a.

In 2024, acetamiprid residue levels in pollen were notably higher, with concentrations ranging from 0.6 to 9.6 μg/kg$_{dw}$. Acetamiprid was applied on March 15. Although sampling was planned before this application to capture pollen collected before acetamiprid treatment, cold weather limited bee foraging. Therefore, the first sample was collected on March 22, prior to rapeseed flowering, and showed no detectable residues. However, on April 5, a high concentration of acetamiprid (8.6 μg/kg$_{dw}$) was measured. Contamination levels then remained high throughout April, with the highest concentration of the season detected on April 26, as shown in Fig. 2b.

The contamination pattern coincided with the flowering periods in both years, as identified using satellite imagery (see Section S3.1 and S3.2 in the SI), suggesting that honey bees likely collected contaminated pollen directly from treated rapeseed fields once flowering began. Given the timing of the acetamiprid detections in late March–April and its common use on specific crops, two potential sources are early-flowering rapeseed fields and/or early-season fruit tree sprays (e.g., cherries, peaches, apricots, apples, pears, etc.) (Federal Food Safety and Veterinary Office, 2026). However, since acetamiprid was applied to rapeseed within the managed fields on April 5, 2023, and March 15, 2024, the rapeseed treatments appear to be the most probable source of the observed contamination.

Cyprodinil was selected because it showed the highest contamination levels of all CUPs detected in bee pollen, with particularly high concentrations in early April 2024. Cyprodinil was not applied within the managed fields in the two seasons, suggesting that the elevated contamination originated from external sources. Previous research has also identified cyprodinil as a key compound in studies on pollinator exposure, reflecting its relevance and consistent occurrence in bee matrices (Schaad et al., 2023).

In 2023, cyprodinil was detected (<LOQ) in only one sample collected on April 28. No other 2023 samples showed detectable cyprodinil contamination. In contrast, all 2024 pollen samples contained cyprodinil, with concentrations ranging from 13 to 1025 μg/kg$_{dw}$. Due to pollen scarcity caused by poor weather conditions, no samples were available on March 29 and April 19, 2024. However, as illustrated in Section S10 in the SI, the available data indicate a drastic increase in cyprodinil contamination from March 22 until April 12, followed by an equally drastic decrease by late April.

Cyprodinil is commonly applied to cereals, fruit crops (e.g., pome and stone fruits, berries, grapevines), vegetables (e.g., asparagus, cucumbers, onions, peas, leafy greens), and ornamental or recreational plants, including flowering plants, lawns, and sports fields (Federal Food Safety and Veterinary Office, 2026). Given that most of the contamination occurred in April, we identified winter wheat, orchards, and perennial berries as the most likely sources based on their recommended application periods (e.g., specific growth stages according to the BBCH scale – Biologische Bundesanstalt, Bundessortenamt and CHemical industry (Lancashire et al., 1991)).

3.3.1. *Pollen separation: identifying the source*

To trace the floral origin of the pollen contaminated by **acetamiprid** residues, we selected the earliest date from each season (April 28, 2023, and April 5, 2024; see Fig. 2) for which the pooled samples contained acetamiprid. Pollen collected on the same day from individual colonies was analysed to avoid the dilution effects and accurately track contamination sources (see Section S11 in the SI for individual colony residue levels). Pollen collected by colony 3 was selected for separation, as it consistently showed the highest residue levels, providing the clearest signal for source identification. This pattern indicates variability in residue levels between colonies, likely reflecting differences in foraging range and resource use within the same landscape (Schmolke et al., 2018). However, as pooled samples showed consistent temporal patterns, this variability does not affect the overall interpretation at the landscape scale. Rapeseed pollen was the most contaminated fraction in both years, with peak concentrations of 10 μg/kg$_{dw}$ (2023) and 96 μg/kg$_{dw}$ (2024), while other plant species contributed minimally, as detailed in Section S12 in the SI.

For **cyprodinil**, we focused on the pooled bee pollen sample collected on April 12, 2024, which showed the highest overall contamination level. On this day, pollen was collected only from colonies 2, 3, and 4, as colony 1 did not produce any sample. All three individual colony samples showed high cyprodinil concentrations and were selected for pollen separation, in contrast to acetamiprid, where a single colony provided a clearly dominant contamination signal. Cyprodinil residues were detected across multiple pollen types, including target and non-target plant species, as illustrated in Fig. 3, indicating widespread contamination beyond treated crops. In colony 2, the highest residue level was detected in the apple tree pollen fraction

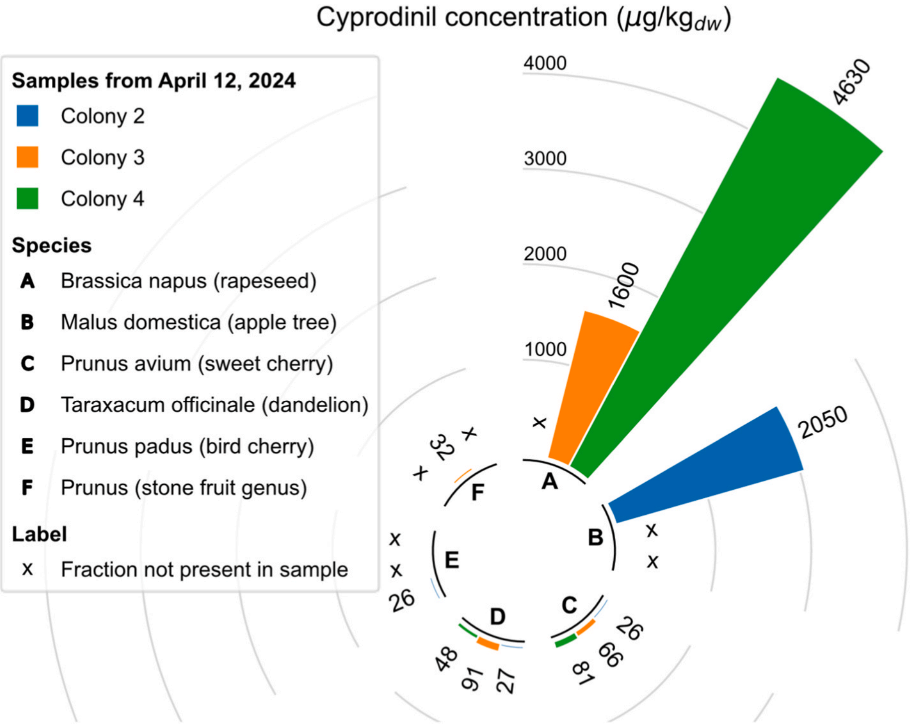

Fig. 3. Circular bar plot showing cyprodinil contamination levels (black numbers, concentrations in µg/kg$_{dw}$) in pollen fractions from the most contaminated individual colony samples collected on April 12, 2024: colony 2 (blue), colony 3 (orange), and colony 4 (green). Each segment of the circle represents a different plant species, labelled A–F as defined in the legend. An “x” in place of a numerical value indicates that the corresponding pollen fraction was not present in the sample from that hive. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(2050 µg/kg$_{dw}$), with additional residues found in other orchard-associated species such as sweet cherry (26 µg/kg$_{dw}$). Cyprodinil residues were also detected in off-crop plant species, including bird cherry (16 µg/kg$_{dw}$) and wildflowers, specifically dandelion (27 µg/kg$_{dw}$). These species are not subject to direct cyprodinil application, and although they may occur adjacent to or within treated fields, their contamination is most likely explained by off-target deposition or environmental transport processes. In colony 3, the highest residue level was detected in rapeseed pollen fraction (1600 µg/kg$_{dw}$), a crop for which no cyprodinil applications were recorded in the Agroscope-managed fields and for which this fungicide is not approved for use, along with moderate residue levels in sweet cherry (66 µg/kg$_{dw}$) and dandelion (91 µg/kg$_{dw}$) fractions. Similarly, in colony 4, the rapeseed fraction showed the highest concentration (4630 µg/kg$_{dw}$), with lower levels in sweet cherry (81 µg/kg$_{dw}$) and dandelion (48 µg/kg$_{dw}$) fractions. Detailed information on fraction quantities and corresponding contamination is provided in Section S12.2 of the SI.

The detection of cyprodinil in orchard-related pollen (e.g., apple trees, sweet cherry) indicates a direct exposure from fungicide applications in managed orchards. However, cyprodinil is not applied to crops such as rapeseed or wildflower species, and therefore, residues detected in their pollen cannot originate from direct application. The frequent and substantial detection of cyprodinil in these pollen types indicates off-target transfer processes such as spray drift or secondary deposition. Here, secondary deposition refers to volatilisation from treated surfaces followed by atmospheric transport and re-deposition onto surrounding vegetation.

As part of the pollen separation procedure (see Section 2.6), samples were visually divided into colour-based fractions. Therefore, a slight cross-contamination of the rapeseed fraction, particularly with apple pollen due to its similar colour, can't be ruled out. However, the cyprodinil concentration observed in the rapeseed pollen fraction from colony 4 (Fig. 3, Species A) exceeded that found in the apple pollen fraction from colony 2 (Fig. 3, Species B), supporting the validity of the observed contamination patterns.

3.3.2. *Identifying key CUPs contamination pathways*

Acetamiprid: the flowering period of rapeseed varies annually due to factors such as weather and crop management practices. Despite these variations, both seasons in our study showed a similar pattern. Farmers typically apply acetamiprid to rapeseed before the flowering begins (BBCH stage 59). Residues were detected in bee pollen only after flowering had begun and rapeseed pollen was available (BBCH stage 61). This timing, along with the pollen separation results, suggests that bees collected contaminated pollen directly from treated rapeseed crops rather than from other crops or wildflowers affected by spray drift.

However, detailed application data were only available for Agroscope-managed fields. Because rapeseed within a region is typically treated and flowers synchronously, we cannot distinguish between contributions from Agroscope-managed fields and other fields within the foraging range. Therefore, we cannot attribute residues exclusively to the monitored fields. Nevertheless, the temporal alignment between application, flowering, and contamination, combined with the pollen source, strongly supports rapeseed treatments as the primary source of acetamiprid in bee pollen. This pattern further indicates that acetamiprid persists on rapeseed plants for several weeks following application. Additional details on rapeseed growth stages are provided in Section S13 in the SI.

Cyprodinil: the interpretation of the pollen separation by plant species results, as described in Section 3.3.1, is challenging and requires further consideration of meteorological conditions, crop types, and CUP applications.

Fig. 4 shows a few orchards northeast of the beehives, approximately 800 to 1000 m away and separated by a highway. In contrast, winter wheat fields are evenly distributed across the surrounding landscape. A broader overview of the full 2 km foraging radius and surrounding fields is provided in Fig. S15 in the SI. A previous study has shown that urban infrastructure, such as buildings or highways, can restrict bee movement

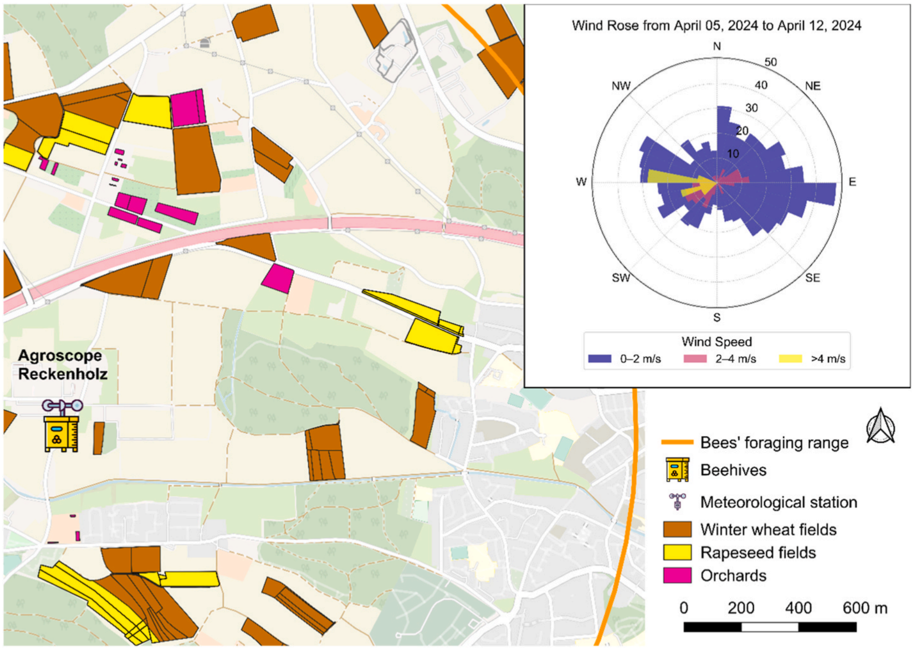

Fig. 4. Map of the area around the beehives (2024 season) based on OpenStreetMap, showing the location of the five honey bee colonies, the meteorological station, and surrounding crop fields within the bees' foraging range of 2 km. The wind rose (top right) shows wind direction and speed recorded between April 5 and April 12, 2024. Wind speeds are categorised as low (0–2 m/s, blue), medium (2–4 m/s, pink), and high (>4 m/s, yellow), illustrating prevailing wind conditions during the key period of cyprodinil contamination. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(Andersson et al., 2017). Under this condition, bees may have preferentially collected contaminated rapeseed pollen from fields east and south of the hives, rather than from fields north of the highway. Based on this spatial configuration, we hypothesise that the contamination was caused by winter wheat treatments and/or by pesticide drift originating from more distant orchards and perennial berries.

While pesticides in winter wheat cultivation are usually applied at ground level or near the soil surface, which generally reduces drift (Wolters et al., 2008), wind or improper application techniques can still transport pesticide droplets to nearby fields (Graham et al., 2025). Bees foraging on these contaminated blooms could then carry cyprodinil back to their hives. Although winter wheat is not attractive to pollinators because it is a wind-pollinated crop that provides no nectar and only limited accessible pollen, the resulting cross-contamination of neighbouring rapeseed fields can lead to significant exposure of pollinators and nearby off-crop untreated plant species. Drift is more likely during orchard treatments because fungicides are applied at the height of the tree canopy, often several meters above the ground, where air currents can more easily transport the droplets (Blanco et al., 2019). Even moderate winds can carry these droplets beyond the target area, especially when trees are tall, or airblast sprayers are used (Zivan et al., 2017). Cyprodinil may have drifted to fields east of the orchards, as suggested by the wind conditions between April 5 and 12, 2024, as shown in Fig. 4, when cyprodinil residues peaked (see Fig. S11 in the SI). During this period, winds were predominantly weak (0–2 m/s) and variable in direction, but stronger gusts (up to 9.5 m/s) also came from west-northwest (270–315°). This direction aligns the orchards with the rapeseed fields to the northeast, creating a plausible pathway for spray drift. Fig. S16 in Section S15 in the SI shows minimal rainfall during this period, with only a small precipitation event of approximately 3.5 mm on April 9, 2024, allowing residues to remain on plant surfaces rather than being washed off. Under these meteorological conditions, fungicide droplets sprayed at canopy height in orchards could have dispersed widely. An alternative contamination pathway, such as residue transfer from winter wheat applications, could explain some of the observed cyprodinil dispersal. However, the substantial cyprodinil contamination detected in non-target plant species remains a considerable concern, regardless of the specific source.

3.3.3. *Ecological implications*

Our data show that pesticides can persist on target and non-target crops after application, especially for the neonicotinoid insecticide acetamiprid, which was detected in pollen for several weeks following application and poses a risk to pollinators once rapeseed fields are in bloom. These observations challenge the assumption that pre-flowering insecticide applications minimise pollinators' exposure (Averill et al., 2024). In our study, we detected up to 95 $\mu g/kg_{dw}$ of acetamiprid in bee pollen. Although the detected concentration is well below levels expected to cause acute toxicity, acetamiprid could still impair the lifespan and foraging behaviour of bees (Shi et al., 2020). Our findings are consistent with previous research, showing that acetamiprid can persist on plants for more than 20 days, depending on weather conditions (Petrova et al., 2021; Tong et al., 2018). While prolonged residue presence may provide extended pest control, it can also negatively impact beneficial insects and soil microbes (Liu et al., 2011). Even low, sub-lethal pesticide exposure can alter the behaviour, development, and physiology of many insect species, thereby threatening their long-term survival and ecological function (Gandara et al., 2024).

Our findings reveal significant off-site contamination by the fungicide cyprodinil, with residues most plausibly originating from orchards located up to ~800 m from the contaminated rapeseed fields. Concentrations of up to 4600 $\mu g/kg_{dw}$ were found in pollen identified as originating from rapeseed, a crop for which cyprodinil is not applied. This suggests that multiple transport mechanisms likely contributed to the observed distribution. A previous study reported cyprodinil residues not only in treated orchards but also in adjacent soil, which the authors interpreted as resulting from spray drift during application (Piechowicz et al., 2022). Volatilisation may also have contributed to the observed distribution, as cyprodinil fractions up to 42% have been reported to volatilise from plant surfaces under warm, windy conditions (Lewis et al., 2016). Airborne cyprodinil can then be deposited on vegetation outside the treatment area, including wildflowers at field margins and on uncultivated areas, increasing exposure risks for pollinators and other beneficial insects. Moreover, the persistence of cyprodinil on aerosol particles for several days (Socorro et al., 2016) further aggravates its potential for long-range transport under favourable environmental conditions (Mayer et al., 2024).

4. Conclusions

Recent studies have demonstrated the value of bee matrices, such as bee bread and pollen, as biomarkers for monitoring CUPs in complex ecosystems (Kast et al., 2024; Schaad et al., 2023; Stalder et al., 2025). This study builds upon these works by evaluating the potential of bee pollen to understand the environmental processes governing the behaviour of contaminants under real-world conditions. Our findings show that meteorological conditions and the extended presence and dispersal of CUPs must be considered when assessing their environmental impacts. These insights also emphasise the need to investigate exposure pathways and the species-specific sensitivity of non-target organisms to CUPs.

Bee pollen proved to be crucial for uncovering these complexities, providing direct, temporally resolved evidence of when, where, and how CUPs are transported through agroecosystems. Despite the value of this method, several limitations need to be considered. The availability and quality of bee pollen samples depend on bees' foraging behaviour and cannot be controlled experimentally. As foraging locations were not directly monitored, spatial attribution remains inferential and reflects landscape-level exposure rather than field-specific sources. In addition, pesticide application data were available only for Agroscope-managed fields; therefore, the observed exposure patterns likely also reflect contributions from surrounding fields not covered by the dataset, as well as indirect exposure pathways, limiting source attribution and generalisability beyond the study area. Honey bees may prefer certain flowers over others, which can lead to sampling bias in favour of specific crops or plants. This variability, including differences in pesticide profiles between colonies, may limit the comprehensiveness of the data. Furthermore, meteorological conditions and differences in crop management can influence flowering patterns and CUP occurrences, complicating interpretation and potentially reducing the temporal resolution of the findings.

A combined methodological approach that includes sampling from multiple environmental matrices, such as air, soil, water, and vegetation, could enhance our ability to track the distribution and persistence of CUPs. Integrating data across these compartments would improve our understanding of the processes driving their environmental behaviour and provide a context for site-specific contamination and distribution of CUPs in terrestrial environments.

Unlike standard residue analysis, such as standalone measurement of different environmental matrices, this study adopts a process-based approach by interpreting pollen residues in relation to pesticide application practices, weather conditions, and crop phenology. By linking these factors, we move beyond detection to identify CUP's dispersal patterns in agricultural landscapes. These insights highlight the need for more effective strategies to mitigate risks to pollinators and broader ecosystems. Further research in this direction can help improve regulations and farming practices that protect ecological integrity while maintaining agricultural productivity.

CRediT authorship contribution statement

Sergio Cirelli: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christina Kast:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Marion Fracheboud:** Writing – review & editing, Investigation. **Benoît Droz:** Investigation. **Karel Hornak:** Writing – review & editing, Resources, Methodology. **Thomas D. Bucheli:** Writing – review & editing, Supervision, Resources, Conceptualization. **Aurea C. Chiaia-Hernández R:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used ChatGPT (OpenAI) and Gemini (Google) to assist with language editing and to improve the clarity of the manuscript. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Funding

Swiss National Science Foundation (SNSF) PRIMA grant (Grant No. 201583).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

We would like to express our sincere gratitude to the Micropollutants group and the Paleolimnology Unit at the Institute of Geography, University of Bern, for their collaboration, enthusiasm, and insightful advice throughout this research. We also thank Emmanuel Schaad, Cornel Stutz, and Esther Jung for their assistance in collecting bee pollen samples. We are grateful to Agroscope for granting access to the managed fields and providing essential laboratory facilities for chemical analyses. We thank Katharina Bieri of the Biologisches Institut für Pollenanalyse (BIP) for identifying the plant species in the pollen samples using microscopy. We further acknowledge MeteoSwiss for providing open access to meteorological data. Finally, we gratefully acknowledge the financial support provided by the SNSF PRIMA grant (Grant No. 201583), which made this research possible.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2026.128348.

Data availability

Data will be made available on request.

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