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Effects of arsenic and selenium pollution on wild bee communities in the agricultural landscapes

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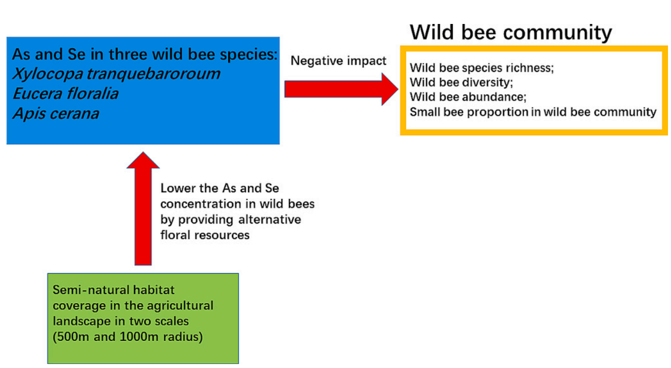
HIGHLIGHTS

- As and Se concentrations in carpenter bee was lower than that the other wild bee samples.
- Semi-natural habitat was negatively related to Se concentrations in wild bee bodies.
- As pollution negatively impacted wild bee diversity but not abundance.
- Future wild bee conservation schemes should take As and Se pollution into consideration.

GRAPHICAL ABSTRACT



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ABSTRACT

Wild bees play crucial roles in pollinating numerous crops and fruits worldwide. However, these essential insect pollinators are threatened with decline due to a variety of stressors. Among stressors, relatively little work has been done on metalloid pollution. Laboratory experiments have shown that arsenic (As) and selenium (Se) can negatively impact on bees, it is unknown if these effects translate in real-world environments. To address this

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Crop pollinator
Agroecosystem
Biodiversity
China

knowledge gap, wild bee communities were sampled from 18 smallholder farmlands in Kaihua County in Quzhou, Southeast China and As and Se concentrations in three bee species were measured (*Xylocopa tranquebarorum*, *Eucera floralia*, and *Apis cerana*). Analyses revealed that the large carpenter bee, *X. tranquebarorum*, exhibited significantly lower As and Se concentrations than the other two wild bee species. No significant correlations were found between As and Se concentrations in all three wild bee species. Interestingly, the proportion of semi-natural habitat was found to be significantly related to reduced Se concentration in wild bee bodies, though no such effect was observed for As. As pollution negatively impacted bee diversity but not abundance, whereas Se significantly impacted neither bee diversity nor abundance. Furthermore, both As and Se pollution had no significant effect on the abundance of small-bodied wild bees. Given the essential role of wild bees for pollination services, monitoring of As and Se pollution in wild bee bodies and their food resources (pollen and nectar) is recommended across agricultural and other potentially impacted systems.

1. Introduction

Wild bees are essential pollinators for many crops and plants globally (Pirk et al., 2017; Venturini et al., 2017; Liu et al., 2020). Worryingly, reported pollinator declines have raised significant concerns regarding their potential impacts on food security and wild plant biodiversity (Aizen et al., 2009; Warrit et al., 2023). Among the contributing factors to the decline of wild bees in agroecosystems, exposure to environmental pollutants, such as pesticides (Heard et al., 2017) and heavy metals (Moroń et al., 2012; Moroń et al., 2014) has emerged as a major issue.

Arsenic (As) and Selenium (Se) pollution have been recognized as serious environmental issues (Lemly, 2004; Huang et al., 2009b; Gong et al., 2020; Bundschuh et al., 2021) with documented negative impacts on insects (Hladun et al., 2012; Champeau et al., 2017; So et al., 2023). Studies have reported the negative impact of As and Se on both managed honeybee foragers (*Apis mellifera*) (Hladun et al., 2012; Burden et al., 2016; Monchanin et al., 2021). Monchanin et al. (2021) reported that As had a negative effect on honeybee cognition and disrupted their memory, while Hladun et al. (2012) found that Se can alter the food-collecting behavior of honeybee foragers and potentially reduce the amount of food successfully recovered for the hive. Additionally, Burden et al. (2016) found that Se can disrupt both the long-term and conditioning memory of honeybee foragers. However, compared with honeybees, the impacts of As and Se on wild bees is virtually unknown. Although Heard et al. (2017) explored As toxicity for both *Bombus terrestris* and *Osmia bicornis*, the former species is social and represents only a minority of total bee diversity (Danforth et al., 2019), which the latter is a cavity nester and possibly less impacted by soil contamination. In addition, while Moroń et al. (2012) found that heavy metal pollution (Cd, Pb, and Zn) can lower wild bee diversity as well as abundance, no study has thoroughly explored the impact of As and Se on wild bee communities.

Whether pollutants impact bees depends not just on physiological tolerance, but also exposure. Bees may face contamination through their consumption of food (nectar and pollen) and water intake (Whitehorn et al., 2012; Dinkov and Stratev, 2016). Several studies have detected significant heavy metal concentrations in both honeybee foragers and honeybee products (van der Steen et al., 2012; van der Steen et al., 2016; Giglio et al., 2017) as well as in bumblebees (Lindqvist, 1993; Szentgyoergyi et al., 2011). Similarly, some studies have assessed the presence of As and Se, two harmful elements, in honeybee foragers' bodies and honeybee products (Roman, 2010; Matin et al., 2016; Altunatmaz et al., 2017). However, no previous study has measured the concentrations of As and Se in wild bees, despite their significance as important crop pollinators. The traits of wild bees likely influence their susceptibility, as the body sizes of wild bee species have been found to be positively linked to their flight ability (Zurbuchen et al., 2010). Smaller bees, with limited foraging distances, may face challenges in accessing suitable floral resources and could be more vulnerable to As and Se pollution (Gathmann and Tscharntke, 2002).

The impacts of heavy metal pollution on wild bees might also depend on the landscape. It may be that semi-natural or natural environments in agroecosystems present better conditions where contamination is less likely (Holland et al., 2016; Garibaldi et al., 2021). These habitats not only provide essential nesting sites and materials for wild bees, but also offer diverse floral resources (Cole et al., 2017; Rodríguez et al., 2021). Polluted monoculture farmlands offer little alternative food source, and if the crop accumulates metals well then contamination is a given, but diverse floral resources would enable greater choice for wild bees. Despite this, studies are lacking on the influences of landscape on heavy metal contamination in wild bees.

In light of these concerns, we conducted a study across 18 research sites located in Kaihua County in Quzhou, Southeast China. As and Se pollution are now serious environmental issues in the lower reaches of Yangtze River in China (Xie et al., 2006; Huang et al., 2009a; Li et al., 2012; Chen et al., 2018; Zhuang et al., 2020). The potential sources for As and Se pollution include industrial and agricultural production, mining, and coal combustion (Jiang et al., 2015; Ullah et al., 2023). To explore the impact of As and Se pollution on wild bee communities in smallholder agroecosystems, we measured As and Se concentrations in three local bee species (*Xylocopa tranquebarorum*, *Eucera floralia*, and *Apis cerana*) at each site. We formulated the following research questions and corresponding hypotheses: 1. What are the differences in As and Se concentrations in the bodies of wild bee species? It was hypothesized that the carpenter bee, *Xylocopa tranquebarorum*, would exhibit lower As and Se concentrations due to their larger body size and higher foraging potential. 2. What is the impact of the agricultural landscape on As and Se concentrations in the wild bees' bodies? It was hypothesized that, for all three wild bee species, As and Se concentrations would be negatively correlated with the proportion of semi-natural habitat in these agricultural landscapes. 3. What are the impacts of As and Se pollution on wild bee diversity and abundance? It was hypothesized that both As and Se pollution would lead to a lower abundance and diversity of wild bees. Understanding these potential impacts is crucial for implementing effective conservation strategies to safeguard wild bees and the vital pollination services that they provide.

2. Methods

2.1. Study site and land use analysis

This study was conducted in Kaihua County in Quzhou, Southeast China in the spring of 2022, encompassing 18 locations. These sites were characterized by smallholder fields, each covering <2 ha, with heterogeneous landscapes. The local farmers in these areas practiced a crop rotation system, cultivating oilseed rape from October to April and rice from May to October. Oilseed rape is a pollinator-dependent crop that relies on insect pollination for high yields (Perrot et al., 2018). Fig. 1 illustrates the study sites, including hilly terrain among the sample locations, with the shortest distance between the two sites being 1.9 km. This distance is greater than the expected foraging distances of most wild bee species (Chifflet et al., 2011). To quantify the extent of semi-natural habitat, which includes forest, shrubland, and grassland, within a 1000-meter radius around each research site, ground-truth methods were employed (Liu et al., 2016; Shi et al., 2021). This radius was selected based on the maximum foraging distance observed for most wild bee species (Chifflet et al., 2011). In addition to a 1000 m radius, semi-natural habitat proportion at a 500 m radius (small scale) was also included in the analysis. All quantification of semi-natural habitat was conducted using Arcmap 10.2.

2.2. Wild bee sampling

Wild bees were sampled at each site using a combination of four sets of pan traps and a flight interception trap, as described previously (Shi et al., 2022). Pan trap arrays consisted of three cups each with UV white, blue, and yellow fixed on a wooden stick at a height of 1.5 m, while the flight interception trap was made of a transparent acrylic board to block flying wild bees (with a plastic tray placed underneath to collect fallen bees). Throughout the sampling period, which lasted for 52 days, the wild bee specimens collected by the traps were pooled together from both trap types each week to achieve a sufficient sample size. All wild bee samples were stored in the refrigerator (−20 °C) for further analyses. The collected wild bees were then sorted into morphospecies and further identified to species. In the sampling process, wild bee species with a body length of <12 mm were categorized as small bees based on the classification by Albrecht et al. (2007). A total of three common early spring oilseed rape pollinators in southern China were selected for the measurement of As and Se in their bodies. These species included a carpenter bee species (*Xylocopa tranquebarorum*), a native honeybee in China (*Apis cerana*), and a long-horn bee species (*Eucera floralia*), as described in Shi et al. (2021). Due to the considerable variation in individual weight among the three wild bee species, different numbers of specimens for each species were selected to reach a similar total weight for each sample (for metal concentration analysis, see below). From each site, one *Xylocopa tranquebarorum*, nine *Apis cerana*, and eight *Eucera floralia* specimens were used. In cases where passive traps did not yield enough wild bee individuals for later As and Se measurements, sweep net sampling was conducted. Before the As and Se measurements were taken, all wild bee samples were carefully washed with distilled water to ensure accurate readings.

2.3. As and Se analysis

The concentration of As and Se in the collected wild bee samples was measured using inductively coupled plasma-mass spectrometry (ICP-MS) with an Agilent 7800 instrument operating in standard (STD) mode. Prior to the analysis, each sample was dried at 70 °C for 48 h in a drying oven (Yuyi, machine type: 202-0A) to obtain dry weights of a 0.16 g, 0.2 g, and 0.18 g approximately. For the acid digestion process, 4 mL of ultrapure nitric acid (65 % *v*/v) and 1 mL of ultrapure hydrogen peroxide (30 % v/v) were added to each sample. The mixture was then subjected to microwave digestion at 170 °C for 30 min using a microwave digestion system (milestone ETHOS A). After digestion and cooling to room temperature, the mixture was filtered using Whatman Grade No. 42 filter paper with a particle retention size of 2.5 μm. To calibrate the ICP-MS instrument for accurate measurements, calibration standards ranging from 0 to 0.25 mg L^{-1} were prepared using commercially available standard solutions maintained in 2 % nitric acid. The calibration curves for both As and Se demonstrated excellent linearity, with R-squared values >0.999. To ensure the accuracy and precision of the measurements, internal standards were incorporated during the measuring process and monitored throughout the study as a quality control measure. The internal standard solution contained Ge, Rh, In, Re, and Bi, each at a uniform concentration of 0.5 mg L^{-1}. Furthermore, a spiked sample was also measured after every ten samples as an additional quality control measurement.

2.4. Statistical analysis

Pearson correlation analyses were employed to investigate the relationships between As and Se concentrations in the bodies of each species. Linear regressions were used to explore the effects of semi-natural habitats at both large (1000 m radius) and smaller scales (500 m radius) on the As and Se concentrations for three bee species. Linear

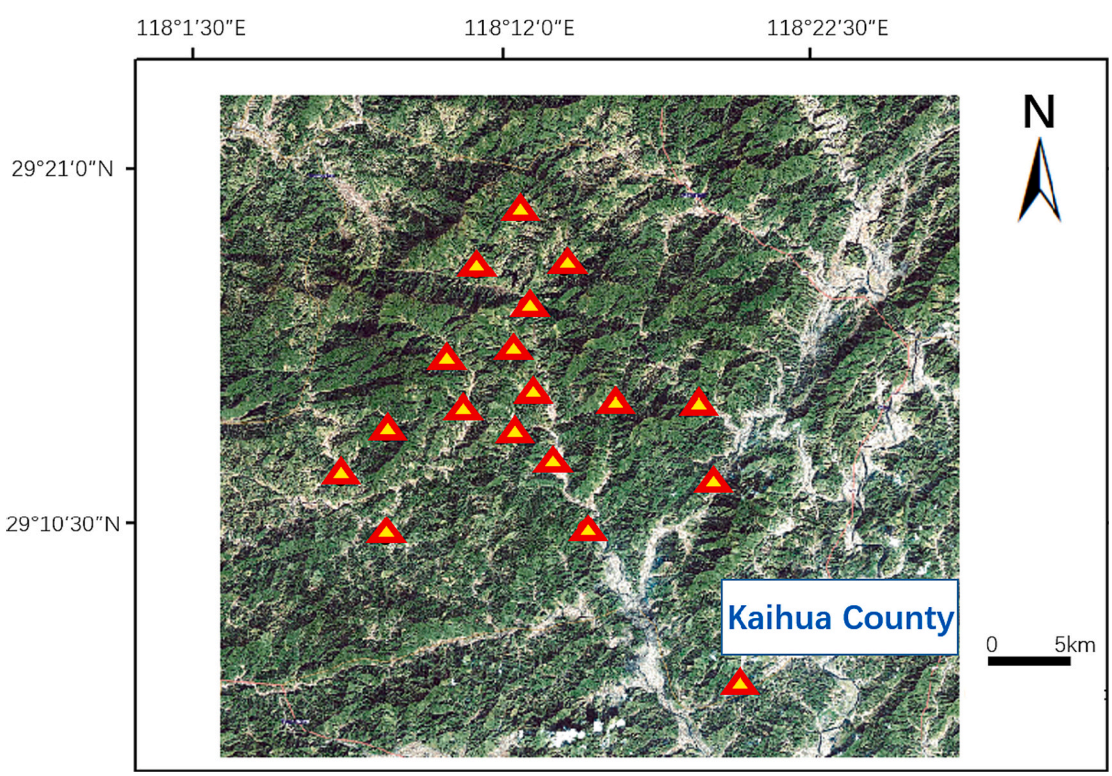

Fig. 1. The 18 research sites in Kaihua County in Quzhou, in Southeast China.

regressions were also used to assess the impact of As and Se pollution on wild bee communities, specifically their rarefied species richness, diversity, and abundance. Rarefied species richness was calculated based on the lowest number of collected wild bee individuals among the 18 sites (54 individuals) (Shi et al., 2021). Wild bee diversity was calculated using the Shannon Index (Földesi et al., 2016), while wild bee abundance was determined by the number of wild bee individuals collected per sampling day in each research site. Linear regression was then employed to explore the impact of As and Se pollution on the proportion of small wild bees in the wild bee community (relative abundance) and the actual abundance of small wild bees.

All analyses in this study were conducted using R (R Core Team, 2020). The "rarefy" function in the "vegan" package was utilized to calculate wild bee rarefied species richness (Oksanen et al., 2009). To compare As and Se concentrations in different wild bee species, the "emmeans" function in the "emmeans" package was employed (Lenth et al., 2019). For the linear mixed modeling, the "lme()" function in the "nlme" package was applied (Pinheiro et al., 2017).

3. Results

A total of 2054 wild bees were sampled, representing 33 different species. The three most abundant wild bee species collected included *Eucera floralia* (480 individuals), *Apis cerana* (343 individuals), and *Xylocopa tranquebarorum* (183 individuals). The detailed species list can be found in Shi et al. (2023a). The concentrations of As in the sampled bees were 0.03–0.34 mg kg^{-1} (*X. tranquebarorum*), 0.18–0.35 mg kg^{-1}, (*A. cerana*) and 0.14–0.29 mg kg^{-1} (*E. floralia*), while the Se concentrations were 0.03–0.17 mg kg^{-1}, 0.11–0.20 mg kg^{-1}, and 0.09–0.24 mg kg^{-1}, respectively. Comparing the concentrations of As in *E. floralia* and *A. cerana* with *X. tranquebarorum*, both *E. floralia* and *A. cerana* showed significantly higher levels (Fig. 2A). However, *E. floralia* and *A. cerana* did not differ significantly in As concentration. Regarding Se concentration, *E. floralia* exhibited significantly higher levels than *A. cerana*, and *X. tranquebarorum* had significantly lower levels than *E. floralia* and *A. cerana* (Fig. 2B). No significant correlations were found in As and Se concentrations across the three wild bee species ($p > 0.05$) and the correlation coefficient in *X. tranquebarorum*, *E. floralia* and *A. cerana* samples were −0.16, 0.24 and 0.22, respectively (Fig. 3).

The proportion of semi-natural habitat in a 500 m radius ranged from 23 % to 82 %, and ranged 49 % to 92 % in a 1000 m radius. The proportion of semi-natural habitat within a 1000 m radius in these agricultural landscapes did not significantly affect As concentrations in the bodies of wild bees ($p > 0.05$) (Fig. 4A, B, and C). However, semi-natural area was significantly negatively correlated with Se concentration in *Eucera floralia* ($p < 0.05$), while it did not show any significant effect on Se concentrations in the other two wild bee species ($p > 0.05$). At a smaller scale with a 500 m radius, the proportion of semi-natural habitat did not have a significant effect on either As or Se concentrations in any of the three wild bee species ($p > 0.05$) (Appendix 1). All model results are summarized in Appendix 1.

The concentration of As in wild bees had a marginally significant negative effect on wild bee rarefied species richness ($p = 0.09$) and a significant negative effect on wild bee diversity ($p < 0.05$) (Fig. 5A and B). However, As concentration did not significantly affect wild bee abundance (Fig. 5C). All results in the models are summarized in Appendix 2. In contrast, the concentration of Se had no significant effect on wild bee rarefied species richness, diversity, or abundance (Fig. 5D, E, and F). Additionally, neither As nor Se concentrations significantly influenced the proportion (relative abundance) of small-bodied wild bees (Fig. 6A and C) or their absolute abundance (Fig. 6B and D) ($p > 0.05$).

4. Discussion

Previous studies have reported negative impacts of As and Se on bees (Hladun et al., 2012; Burden et al., 2016; Monchanin et al., 2021), but their effects are virtually unknown for wild bees under field conditions This study addresses this gap and, for the first time, sheds light on the concentrations of As and Se in the bodies of wild bee species in agroecosystems and the unexpectedly high spatial variation in their concentrations. We also investigated the effect of semi-natural habitats on the exposure of wild bees to As and Se and the impact of these two pollutants on wild bee diversity and abundance, building a foundation for future studies and management action.

The As and Se concentrations in the carpenter bee (*Xylocopa tranquebarorum*), the largest species examined, were lower than those in *Eucera floralia* or *Apis cerana*, which aligns with our prediction. Larger wild bee species generally have longer flight distances, leading to larger foraging zones (Gathmann and Tscharntke, 2002; Zurbuchen et al., 2010), such that they are subject to more variable levels of contamination or can largely avoid it (if able to detect and avoid them). They may also naturally forage more in more distant and natural sites with less contamination, given generally better floral resources in such areas. This would explain the lower levels of As and Se in *Xylocopa tranquebarorum* than those in the smaller *Eucera floralia* and *Apis cerana*, which might

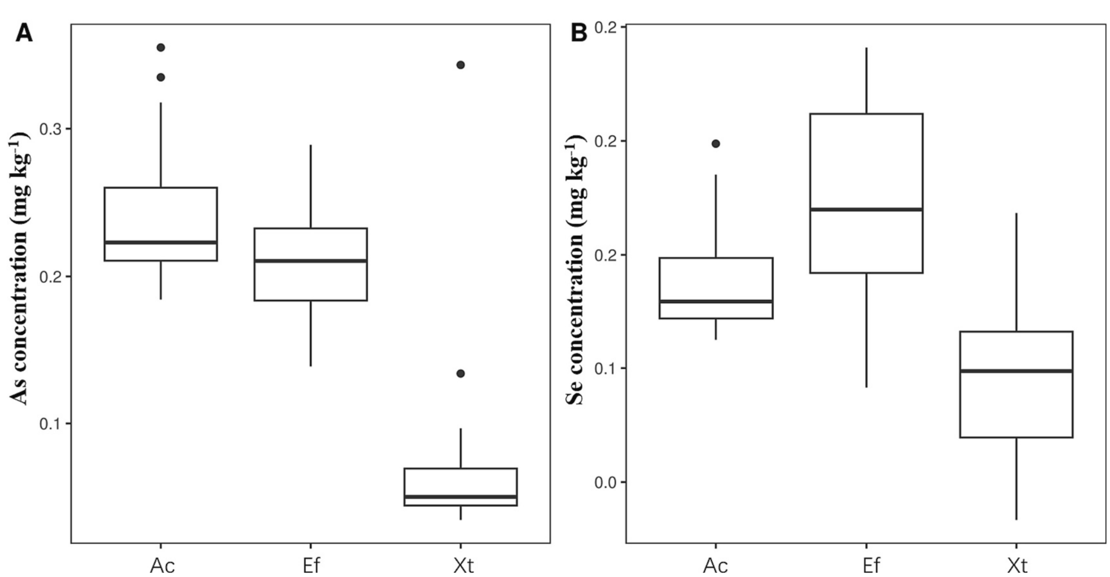

Fig. 2. As (A) and Se (B) concentrations (mg kg^{-1}) in the body of *Apis cerana* (Ac), *Eucera floralia* (Ef) and *Xylocopa tranquebarorum* (Xt).

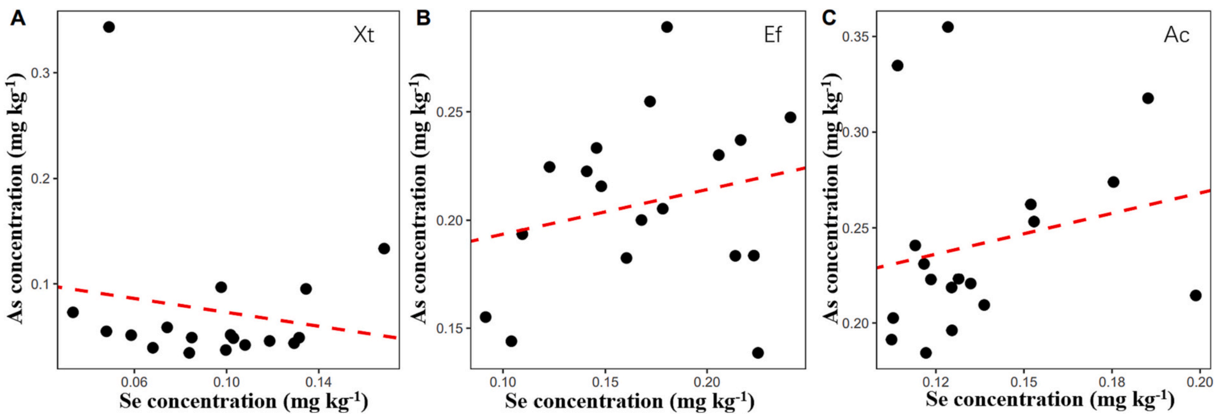

Fig. 3. Correlation plots between As and Se concentrations (mg kg^{-1}) in *Xylocopa tranquebarorum* (Xt, A)*, Eucera floralia* (Ef, B), and *Apis cerana* (Ac, C). The dash lines indicate the correlations were all insignificant.

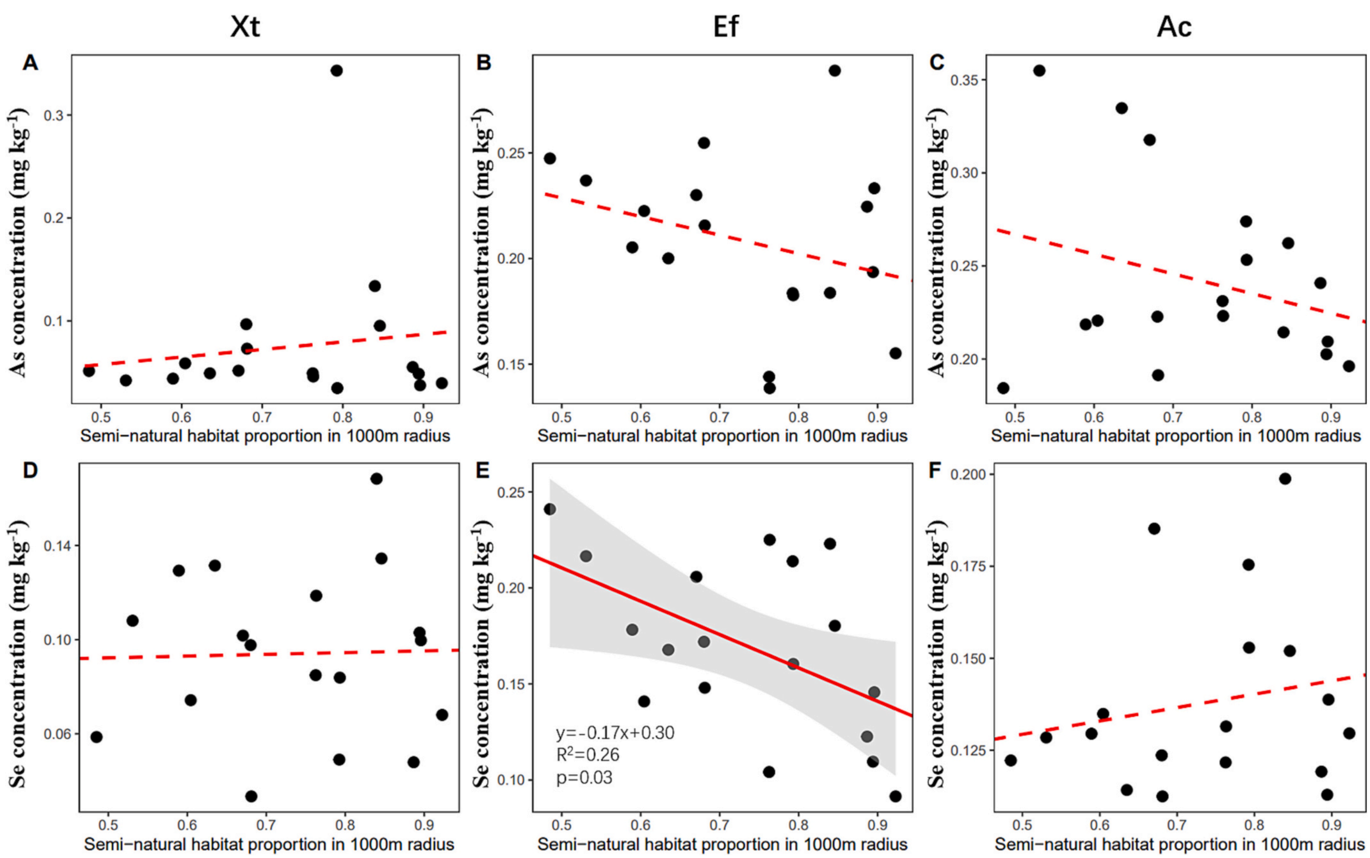

Fig. 4. The impact of semi-natural habitat proportion within 1000 m on As (A, B, and C) and Se (D, E, and F) concentrations (mg kg^{-1}) in three wild bees (*Xylocopa tranquebarorum*, *Eucera floralia*, and *Apis cerana*). Semi-natural habitat proportion is given on a scale from 0 to 1, with 1 indicating entirely semi-natural habitat. The full line indicates the impact was significant while dash line indicates the impact was insignificant. The grey shaded area represents 95 % confidence interval.

have smaller flight ranges. The nesting positions of these bees should not be ignored either: *X. tranquebarorum* and *A. cerana* nest aboveground, while *E. floralia* nests in soil, where it may face higher contamination risk (*A. cerana* may also face higher risk because they collect water to thermoregulate, offsetting the benefits of aboveground nesting). Special attention in similar toxicological studies should therefore be paid to wild bee species with specific traits or smaller body sizes, such as stingless bees in tropical areas (Aldasoro Maya et al., 2023). Additionally, diet likely plays a significant role in determining the exposure of wild bees to As and Se, especially where some bees might specifically target plants that accumulate many metalloids, but further research is needed to fully understand these dynamics, as these data alone are insufficient.

The central-place foraging behavior and fixed foraging zones of bees (Ogilvie and Forrest, 2017) mean that the As and Se found in their bodies should originate from specific areas within a radius corresponding to their foraging distance. These characteristics make wild bees promising candidates as bio-indicators for the levels of As and Se pollution in agroecosystems. It is noteworthy that the As concentrations and Se concentrations were uncorrelated. This could be because As and Se originated from different sources in each site (Liu et al., 2015; Ullah et al., 2023). Further, individual bee species might complicate this by differing in their sequestration of the two pollutants. The variability in

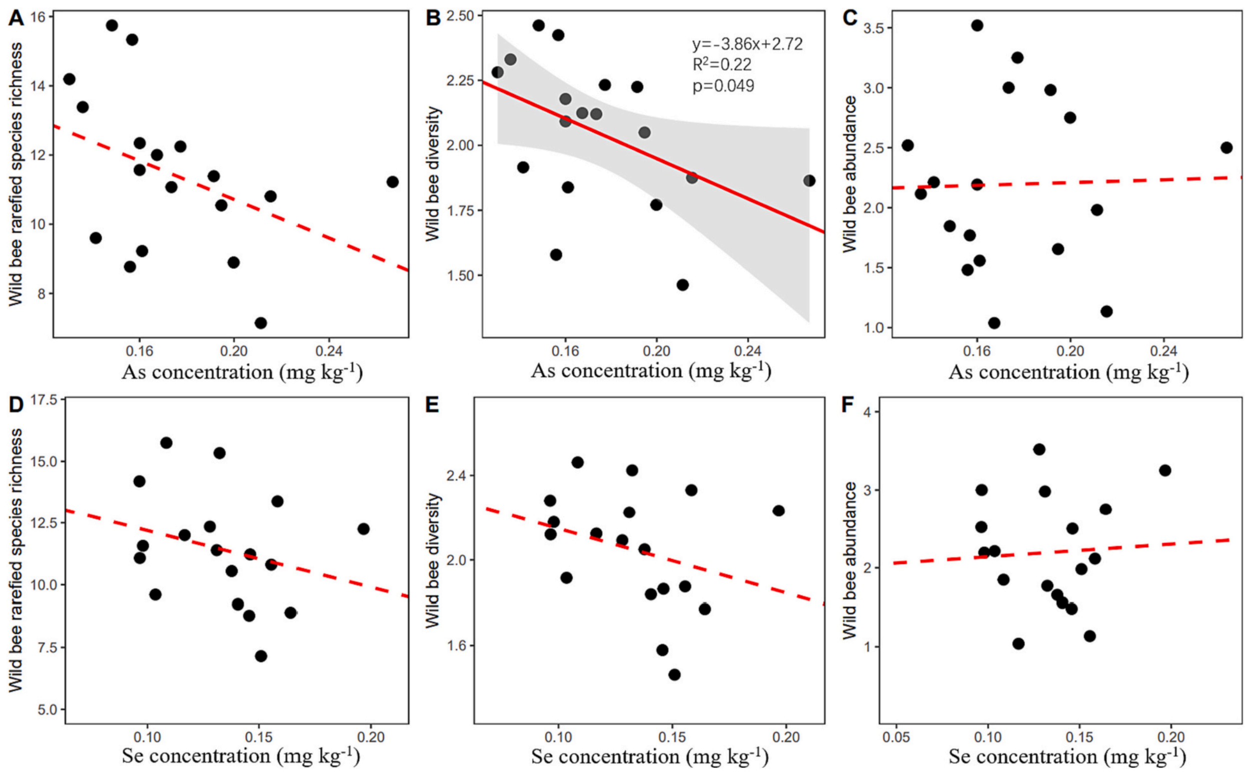

Fig. 5. The impact of As and Se concentrations (mg kg^{-1}) on wild bee rarefied species richness (A and D), wild bee diversity (B and E), and abundance (C and F). The full line indicates the impact was significant while dash line indicates the impact was insignificant. The grey shaded area represents 95 % confidence interval.

the origins and distribution of these elements in the agroecosystem may lead to independent patterns of accumulation in the bodies of wild bees, thereby resulting in the absence of a significant correlation between the two elements in this study.

In line with our hypothesis on semi-natural areas, we saw a reduction in Se contamination for *Eucera floralia* in such areas. These results suggest that pollution reduction may play some role in the beneficial nature of semi-natural habitats (Hevia et al., 2021; Shi et al., 2021). Diverse flowering plants in semi-natural habitats offer wild bees alternative floral resources, potentially reducing their consumption of contaminants such as Se. Surprisingly, only Se for *E. floralia* exhibited a relationship with semi-natural areas (As for none). It may also be that there were fewer low-accumulating plants flowering at this time, such that *E. floralia* with a smaller body size and foraging range might more often be forced to use (or probabilistically use by chance) plants with high metalloid concentrations. Although As and Se accumulation in rice has been intensively studied (Chen et al., 2002; Gustave et al., 2019), the study of wild flowering plants is lacking, but see Zhu et al. (2013). Given the challenges in conducting comprehensive assessments of As and Se concentrations in numerous wild flowering plants in agroecosystems, we suggest considering the nectar and pollen of widely distributed mass-flowering plants that are common, such as *Triadica sebifera* and *Vitex negundo*, to better understand the potential of such plants as bio-accumulation vectors for wild bee communities. By exploring the As and Se concentrations in these key flowering plants, we can better understand the potential sources of these elements and more easily trace their flow to wild bee populations in the agroecosystem. In addition, we also suggest that future studies could explore a wider semi-natural habitat coverage range (i.e. from 10 % to 90 %) to more comprehensively assess the effect of semi-natural habitat coverage on the As and Se concentrations in bees' bodies.

The effects of pollutants on bee communities were mixed, with As pollution negatively impacting on wild bee diversity but not abundance, while Se had no significant effects. We also found that neither As nor Se significantly impacted small-bodied wild bees' abundance and relative abundance. These findings are not entirely consistent with our initial hypothesis, but similar inconsistencies have been observed in previous studies. For instance, Moroń et al. (2012) found that heavy metal pollution, including Cd, Zn, and Cu, reduced cavity-nesting bee diversity and their abundance in Poland and the UK. Conversely, Szentgyoergyi et al. (2011) reported no significant correlation between bumblebee diversity and heavy metal pollution. Such discrepancies in the impact of pollution on insect biodiversity can be attributed to the variation among species in their vulnerability to pollutants, as well as potential differences in local contamination (Kammenga and Riksen, 1996; Shi et al., 2023b). The results in our study seem initially counterintuitive in light of the likely role of flight ranges in explaining exposure levels. As noted prior, species-specific tolerance may also play an important role. In polluted areas, insect species that are more susceptible to pollutants may be disadvantaged, while more resilient species prosper via lowered competition for floral and nesting resources (Migliorini et al., 2004). As a result, As pollution may lead to a decrease in local wild bee diversity but not necessarily in overall wild bee abundance in polluted farmlands, dependent on a mix of more observable traits and less obvious physiological mechanisms.

Given the positive correlation between wild bee diversity and the yield of pollinator-dependent crops (Blitzer et al., 2016; Halinski et al., 2018), declines in wild bee diversity via As pollution may result in reduced crop yields and economic losses for smallholder farmers. Future wild bee monitoring schemes would do well to record the concentrations of As and Se in wild bees, nesting substrates such as soil, as well as their food sources and water within local agroecosystems, to enable the further exploration of these dynamics. For projects involving plantings such as wildflower strips (Hellwig et al., 2022), selecting flowering plant species that do not hyperaccumulate major local pollutants is recommended, to reduce wild bee exposure. Additionally, restrictions should be implemented on the cultivation of flowering crops that tend to accumulate As or other harmful heavy metals to safeguard local wild bee

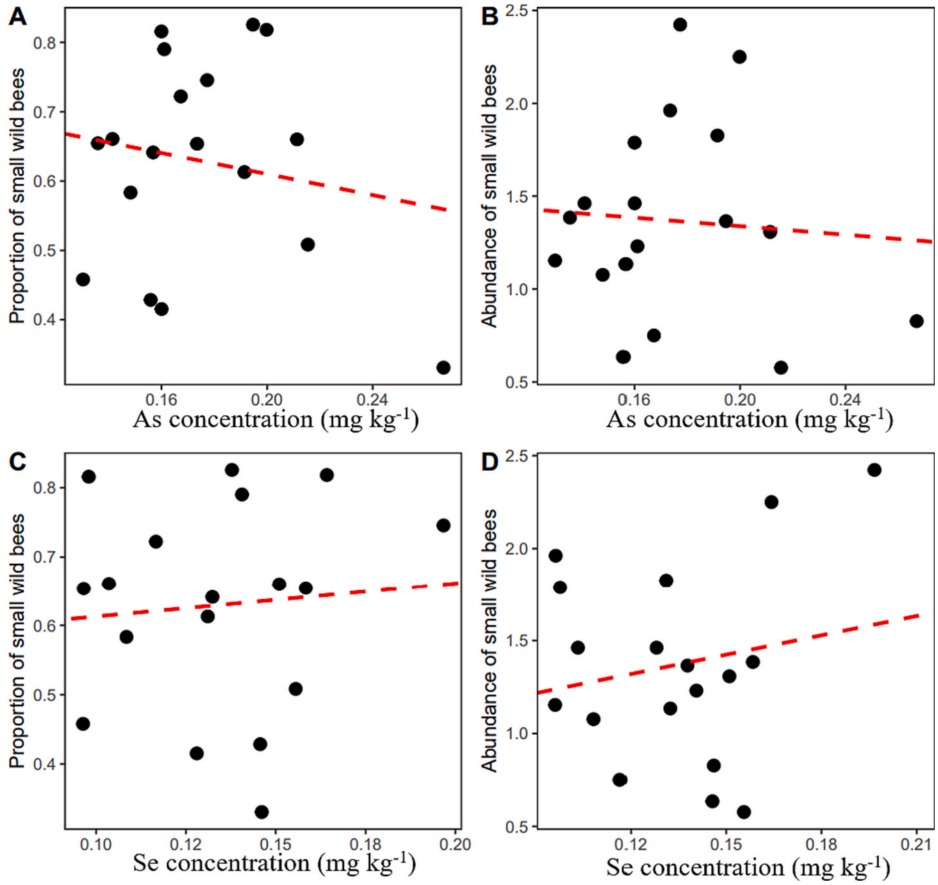

Fig. 6. The impact of As (A, B) and Se (C, D) on the proportion (relative abundance) (A, C) and abundance (B, D) of small-bodied wild bees. The full line indicates the impact was significant while dash line indicates the impact was insignificant.

communities and other insect pollinator taxa. Soil remediation techniques such as phytoextraction and replacement (Wan et al., 2019) should also be considered to improve habitat in especially As-polluted farmlands in southern China.

It is essential to recognize that the effects of As and Se pollution on wild bee diversity may vary across regions and agricultural practices, depending on the extent of pollution and other factors like habitat (Shi et al., 2021) or pesticide use (Whitehorn et al., 2012). To avoid overgeneralizing the results from this study, further research should be conducted in multiple regions with varying levels of stressors to better understand the interactive impacts of As, Se, and other pollutants on wild bee communities while accounting for species traits, particularly for small-bodied wild bee species. This comprehensive approach will help develop more targeted and effective conservation strategies for wild bees across environmental contexts.

We sampled wild bee communities from 18 smallholder farmlands in southeast China and measured the concentrations of As and Se in three bee species (*Xylocopa tranquebarorum*, *Eucera floralia*, and *Apis cerana*). As and Se concentrations in the large carpenter bee, *Xylocopa tranquebarorum*, were significantly lower than in the other two bee species, possibly due to larger body size and flight range. There were no significant correlations between As and Se concentrations in any of the three wild bee species. It was observed that the proportion of semi-natural habitat significantly lowered Se concentration, but not As concentration, in one species. Pollution negatively impacted the diversity of wild bees, but it did not significantly affect their abundance. On the other hand, Se pollution had no significant effect on wild bee diversity and abundance. Neither As nor Se pollution significantly affected the abundance of small-bodied wild bees. Based on these findings, it was necessary to carry out monitoring As and Se concentrations in the bodies of wild bees in future studies to ensure their persistence and the continued provision of their essential pollination services. Understanding the dynamics of these pollutants in wild bee communities can aid in developing effective conservation strategies to safeguard their populations and support sustainable crop pollination in agricultural landscapes.

CRediT authorship contribution statement

Xiaoyu Shi: Conceptualization, Methodology, Software, Investigation, Writing - Original Draft. **Changsheng Ma**: Conceptualization, Methodology, Investigation, Validation. **Williamson Gustave**: Investigation, Writing - Reviewing and Editing. **Michael C. Orr**: Writing - Reviewing and Editing, Validation. **Tuanjit Sritongchuay**: Writing - Reviewing and Editing, Validation. **Zhaofeng Yuan**: Writing - Reviewing and Editing, Validation, **Mei Wang**: Methodology, Validation, **Xiaokai Zhang**: Writing - Reviewing and Editing, Validation, **Qingsong Zhou**: Writing - Reviewing and Editing, Validation, **Yixin Huang**: Writing - Reviewing and Editing, Validation. **Arong Luo**: Conceptualization, Writing - Reviewing and Editing. **Chaodong Zhu**: Conceptualization, Methodology, Writing - Reviewing and Editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.168052.

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