Wild pollinator communities benefit from mixed cultivation of oilseed rape and milk vetch

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Abstract

Globally, insect pollinators that are linked to increased yields in many crops have experienced severe population declines. Crop diversification is often proposed as an effective conservation measure to boost pollinator populations. Here, we investigate potential benefits of mixed oilseed rape / milk vetch cultivation for wild pollinator communities by comparing it with oilseed rape monocultures. Studying 8 mixed and 10 monocropping fields positioned along a gradient of increasing semi-natural habitat coverage in a mountainous agricultural landscapes, we found that agricultural landscapes with mixed cultivation harbored higher wild pollinator diversity than oilseed rape monocropping landscapes. This positive effect was observed irrespective of the proportion of semi-natural habitat. Meanwhile, the pollinator community composition in mixed cultivation landscapes was similar to that of oilseed rape monoculture landscapes, and, contrary to expectations, mixed cultivation did not benefit specific pollinator trait groups like cavity-nesting bees. Overall, we believe the higher pollinator diversity linked to mixed cultivation can increase insect-pollinated crop yields, and mixed oilseed rape-milk vetch cultivation might represent a potential mitigation measure for the negative impacts agricultural intensification has on wild pollinator communities.

Keywords: crop diversification, wild bee, canola, pollinator diversity, pollinator conservation

Introduction

Insects provide important pollination services for many crops (Klein *et al.*, 2007; Liu *et al.*, 2020; Layek *et al.*, 2022). However, wild pollinator communities are declining globally due to a variety of stressors such as habitat loss, environmental pollution and alien species invasions (Rhodes, 2018; Dicks *et al.*, 2021; Shi *et al.*, 2023). Many modern, intensive agricultural practices have been linked to pollinator declines that in turn can result in insufficient pollination services for insect-pollinated crops (Tscharntke *et al.*, 2012). Novel farming approaches and practices are therefore required to mitigate the negative impacts of intensive modern agriculture on pollinator communities in agroecosystems (Walton *et al.*, 2021).

Numerous studies have reported positive impacts of crop diversification on wild pollinator communities (Aguilera *et al.*, 2020; Tamburini *et al.*, 2020; Järvinen *et al.*, 2022), but these effects seem highly variable (Martínez-Núñez *et al.*, 2022). Intercropping systems involving regular planting of two or more crop species on the same field are argued to maintain pollinator diversity (Norris *et al.*, 2018; Brandmeier *et al.*, 2021; Dingha *et al.*, 2021; Järvinen *et al.*, 2022), but the strength of their impact is contested (Campbell *et al.*, 2016; Guzman *et al.*, 2019). Crop diversity has also been reported to enhance pollinator diversity at the landscape level (Aguilera *et al.*, 2020). Benefits of crop diversification to pollinator communities have been linked to different crop flowering times and flower types that offer complementary food resources with varying quality and quantity of nectar and pollen along spatio-temporal gradients (Fornoff *et al.*, 2017a; Aguilera *et al.*, 2020; Walston *et al.*, 2022). Due to varying flowering phenology, intercropping of flowering crops often extends the overall flowering time in the agroecosystem, while monocultures of mass-flowering crops may only bloom over very limited periods. This can result in a short-term oversupply of food, potentially linked to low pollination rates, followed by food deficiency for local pollinator communities once crop flowering ceases (Blasi *et al.*, 2021). By sustaining higher pollinator abundance and diversity, crop diversification can lead to yield increases across pollinator-dependent crops (Griffiths-Lee *et al.*, 2020; Layek *et al.*, 2021).

Oilseed rape-rice rotation cropping and Chinese milk vetch-rice rotation cropping are two common traditional systems in Southern China's smallholder agricultural landscapes. Oilseed rape (*Brassica napus*) and Chinese milk vetch (*Astragalus sinicus*) are cultivated between October and May, and both species bloom jointly in spring (March to April), before being replaced by rice grown between May/June and October. Both oilseed rape and milk vetch serve chiefly as green manure in these rotation cropping systems (Zhang *et al.*, 2022), while oilseed rape is also used by farmers to produce oil. This crop requires insect pollination to reach maximum yield (Stanley *et al.*, 2013; Zou *et al.*, 2017; Perrot *et al.*, 2018). Like oilseed rape, milk vetch can serve as a good nectar source for pollinators (Wang *et al.*, 2006), which could benefit pollinators that rely on legumes (Woodcock *et al.*, 2019). It has been argued that the traditional mixed cultivation practices including both oilseed rape and milk vetch as cover crops might support an enhanced wild pollinator diversity by offering more diverse floral resources to monocultures (Fründ *et al.*, 2010). However, given the similar flowering periods of these two species and the significant supply of nectar offered by mass-flowering rape seed, any effects might be limited - we currently lack the detailed understanding required to verify the existence and quantity of benefits.

As a conservation approach, mixed oilseed rape-milk vetch cultivation may also benefit wild pollinators differentially according to specific pollinator traits such as body size or nesting habits. Links between trait differentiation and the success of conservation or restoration initiatives targeting wild pollinators, and particularly wild bees, have remained scarce (Kremen and M'Gonigle, 2015). As foragers, wild bees chiefly target food resources in the vicinity of their nests to support their broods, making them highly susceptible to agricultural intensification (Mallinger *et al.*, 2016; Klein *et al.*, 2017). Small-bodied and above ground-nesting species show a particular vulnerability (Williams *et al.*, 2010; Shi *et al.*, 2022a), as foraging distances of wild bees are positively linked with their body size (Zurbuchen *et al.*, 2010). Therefore, smaller bee species show shorter forage distances and a lower dispersal capability, making them more vulnerable to environmental stressors (Wright *et al.*, 2015). Above ground-nesting bees require hollow structures of dead wood or shrub stems as their nests, and these materials are scarce in intensively managed fields (Williams *et al.*, 2010). In contrast, the nesting substrates for ground nesters such as sweat bees that require open ground on field margins, remain accessible even in intensively cropped landscapes (Williams *et al.*, 2010). Thus, above ground-nesting bees are more susceptible to agricultural intensification than ground nesting ones. Mixed cultivation which creates structural heterogeneity therefore may be particularly beneficial for these vulnerable groups, with additional benefits from the limited use of agrochemicals associated with milk vetch cultivation. Considering the wide distribution of this crop mix in China (Liu *et al.*, 2022) and other Asian countries (Sakai and Matsuka, 1982), understanding the potential benefits of mixed cultivation practices involving milk vetch for wild pollinator diversity, and its potential to mitigate the negative impacts of ongoing agricultural intensification (Shi *et al.*, 2021; Shi *et al.*, 2022a), is a high priority.

Semi-natural habitat like grassland, shrubland or even open forest patches within the agricultural landscape can support wild pollinator diversity (Tscharntke *et al.*, 2005; Zou *et al.*, 2017; Wu *et al.*, 2019) and mitigate negative impacts of agricultural intensification (Shi *et al.*, 2021) by providing safe and sustainable nesting sites and food sources (Eeraerts *et al.*, 2021). For instance, Raderschall *et al.* (2021) found that both crop diversification and semi-natural habitat benefits pollinators of *Faba* beans. Increasing cover of semi-natural habitat may therefore further enhance wild pollinator benefits of oilseed rape-milk vetch mixed cultivation in smallholder farmland. Alternatively, pollinator resource saturation linked to mixed cultivation may minimize additional positive effects from semi-natural habitat coverage. The positive influence of mixed cultivation furthermore may become less pronounced with increasing semi-natural habitat cover, as widespread semi-natural habitats may sustainably provide large amounts of floral resources to sustain wild bee communities, resulting in potential interactive effects of these two factors.

In this study, we aim to assess the impact of oilseed rape-milk vetch mixed cultivation on wild pollinator communities in agricultural landscapes across a semi-natural habitat gradient. We address three research questions: i) Does oilseed rape-milk vetch mixed cultivation benefit wild pollinator species richness and abundance? We hypothesize that in landscapes with mixed cultivation, wild insect pollinator diversity and abundance is enhanced. ii) Does mixed cultivation specifically benefit taxa in specific trait groups vulnerable to intensive agricultural practices? We hypothesize that landscapes with mixed cultivation harbor an increased abundance of small-bodied pollinators, including wild bees, while above ground-nesting bees will particularly benefit from increased semi-natural habitat cover. iii) Are there interactive effects between semi-natural habitat cover and mixed cultivation on wild pollinator diversity? We hypothesize that significant taxon- and trait-specific interactions occur between these factors.

Materials and Methods

Study sites

This study was conducted from late February to late April 2022 in the mountainous smallholder farmland in Kaihua County, Quzhou, China (118.2207°E, 29.2306°N) (Figure 1). In total, 18 oilseed rape fields were investigated (Figure 1), 8 representing landscapes with oilseed rape-milk vetch mixed cultivation patterns (see Appendix 1) and 10 where oilseed rape is planted in monoculture. The shortest distance between neighbouring sites was 1.9km, covered by mountainous terrain (Figure 1) and exceeding foraging distances of most wild pollinator species (Chifflet *et al.*, 2011). All fields fell into smallholder size categories (<2 ha, see Lowder *et al.* (2016), and size differences between mixed cultivation fields (750±154m^2, mean±SD) and monoculture fields (800±233m^2) were not different. Study field elevations ranged from 317 to 574m. The research period represented the main oilseed rape blooming season, when no pesticides were applied by farmers on the study fields. Semi-natural habitats encountered in the study area included forest, grassland and shrubland (Zou *et al.*, 2017; Shi *et al.*, 2021). All semi-natural habitat in the landscape surrounding the study fields, as well as the proportion of oilseed rape fields, was recorded in a 1100 m radius around each study field using ground-truthing methods in 2022 in combination with Arcmap 10.8. This radius is slightly larger than that in calculating our semi-natural habitats (i.e. 1000m), to ensure that all of our sites have a full range of land use map. Since heavily wooded habitats have often been reported to benefit wild pollinators in agroecosystems (Papanikolaou *et al.*, 2017; Eeraerts *et al.*, 2021) but see also e.g. Wu *et al.* (2019), forests were included in semi-natural habitat cover.

Pollinator sampling

Both pan and window traps were deployed within the selected study fields to sample wild pollinators, allowing the collection of large, standardized samples (Shi *et al.*, 2022b). A pan trap, composed of three cups (~550ml volume) painted with UV blue, UV white and UV yellow paint, respectively, was arranged on a pole at a height of 1.5m (Westphal *et al.*, 2008). Window traps were composed of a transparent acrylic plate (55cm*50cm*0.3cm) fixed between two wooden poles (1.7m height), with a plastic sampling tray (60cm*43cm; 11cm depth) positioned beneath the plate. Saturated salt water with several drops of detergent (to break the water surface tension) was used in both the pan and window traps as killing and preservation agent, which follow the study of Shi et al. (2021). At each field, four pan traps and one window trap were deployed. All pan traps were placed 2 m from the field edge, while one window trap was placed at a focal field edge in order to intercept the insect pollinators entering the field for foraging. Insect pollinators were collected every week, and the traps were refilled. The overall sampling period from February to April covered 52 days. Insect samples were kept frozen (-20°C) prior to identification. In total, 85.9% of all individuals were identified to species level, with the remaining specimens identified to genus or family level (Appendix 2). Wild bees were categorized into large (body length>12mm) and small (body length<12mm)-bodied species following Albrecht *et al.* (2007). The details (body size and nesting location of wild bees) can be found in Appendix 2. Data from both standardized sampling methods was pooled for each field for further analysis to allow a good representation of the overall assemblage composition at each site, and to generate sufficiently large sample sizes allowing for a robust statistical analysis, following an established approach in wild pollinator studies (Russo *et al.*, 2011; Rader *et al.*, 2014).

Statistics analysis

We used multiple linear models to explore the impact of introducing milk vetch into oilseed rape cultivation, creating the two treatments of oilseed rape monoculture and mixed cultivation, while also establishing the relative effect of the proportion of semi-natural habitat and the interactive effects of these factors on wild pollinator diversity and abundance. Due to the inconsistent sampling size, we used Hulbert rarefied species richness (Hurlbert, 1971) to represent pollinator biodiversity. Samples were rarefied to 91 individuals, the highest common number of wild pollinator individuals collected at all sample sites. In addition, we calculated the total expected species richness (TES) to evaluate sampling completeness. TES is based on the asymptotic parametric approximation models for the extrapolation of individual-based rarefaction that is recently developed by Zou et al. (2023), which is robust in estimating species richness of incompletely sampled communities (Zou et al., 2023). The total number of expected species (TES) for this region was 77.54 ± 34.10. We calculated the wild pollinator abundance per sampling day to standardize results and make them more easily comparable with other studies (Shi *et al.*, 2021). We fitted multiple linear regressions for rarefied species richness and wild pollinator abundance using the three predictors: type of landscape-scale cultivation practices (oilseed rape-milk vetch mixed cultivation and oilseed rape monocropping), % semi-natural habitat, and % oilseed rape cover. We then selected the best model based on the corrected Akaike Information Criterion (AICc).

We furthermore used linear models to compare abundance and proportion of small-bodied pollinators in pollinator communities of the agricultural landscapes between mixed cultivation and oilseed rape monoculture. In the model, semi-natural habitat and oilseed rape cultivation within a 1000m radius around the study field and cultivation practice types (mixed cultivation and monocropping) were all included as independent variables. We then repeated this approach to compare abundance and proportion of wild bees, small-bodied wild bees and above-ground nesting (cavity-nesting) bees in the pollinator communities.

We finally used Principal Coordinate Analysis (PCoA) based on Bray-Curtis distances to compare the composition of the pollinator assemblages in agricultural landscapes with mixed cultivation and oilseed rape monoculture (Amy *et al.*, 2018). The one-way analysis of similarities (ANOSIM) based on Bray-Curtis distance was conducted with 9999 permutations for PCoA. All statistical analysis was conducted in R 4.2.2 (R Core Team, 2022). We calculated rarefied species using the 'vegan' package (Oksanen et al., 2019) and the total expected species richness using the R functions "TES()" (Zou *et al.*, 2023). Models were selected using the "dredge()" function in the "MuMIn" package (Barton, 2019). Model residuals' spatial autocorrelation was checked using Moran's I coefficient (Gittleman & Kot, 1990). We found no significant spatial autocorrelation in any of our models ($p < 0.05$).

Results

Species composition of wild pollinators

A total of 2970 individuals of wild pollinators representing 53 species were collected in the pan and window traps (Appendix 2). *Eucera floralia* (480), *Apis cerana* (343), *Gametis jucunda* (319), *Pieris rapae* (256) and *Xylocopa tranquabaroroum* (183) were the five most abundant wild pollinator species across sampling sites. Wild bees accounted for 2054 individuals spread across 33 species, representing 69.2% of all wild pollinators collected. Eleven pollinator species were found exclusively in mixed cultivation landscapes, while ten pollinator species were exclusively found in monoculture cultivation landscapes, respectively (details see Appendix 2).

Impact of mixed cultivation on wild pollinator communities

Rarefied species richness of wild pollinators in fields with mixed cultivation was significantly higher than that at monocropping fields (p=0.004) (Figure 2A), while wild pollinator abundance showed no significant difference (Figure 2B). Wild pollinator community composition in landscapes with mixed cultivation similarly did not differ significantly from monoculture landscapes ($p=0.396$), with the community ordination plots showing strong overlaps (Figure 3). Despite the aforementioned species uniquely found in either of the two landscape categories, the ordination plot indicates that assemblages found in areas with mixed cultivation represent a subset of communities found in monoculture-dominated landscapes. Surprisingly, small-bodied pollinator abundance and proportions in the community showed no significant differences between mixed cultivation and monoculture practice ($p>0.05$, Figure 4A). A lack of significant differences between mixed cultivation and monoculture landscapes was also observed for the abundance of wild bees ($p>0.05$, Figure 4B), and for above-ground nesting bees ($p>0.05$, Figure 4C).

The proportion of semi-natural habitat at 1000m radius around the study fields was positively correlated with rarefied pollinator species richness ($p<0.05$) (Table 1; Figure 5). The results were consistent when a smaller radius of 500m was used (Appendix 3). In the full model, the interaction between mixed cultivation and semi-natural habitat had no significant impact on wild pollinator species richness and abundance ($p>0.05$). After model selection, interaction terms between semi-natural habitat and farming type were not included in any of the most parsimonious models. The three individual variables total semi-natural habitat cover, total oilseed rape cover and farming type were also excluded in the most parsimonious models explaining wild pollinator abundance and small pollinator abundance (Table 1). For wild bee abundance, only semi-natural habitat was included in the most parsimonious model, with a marginally significant impact ($p=0.05$; Table 1). Monoculture landscapes negatively impacted on above-ground nesting bee abundance, and the interactions between oilseed rape and semi-natural habitat had a significantly positive impact on above-ground nesting bee abundance (Table 1).

Discussion

While oilseed rape-milk vetch mixed cultivation is commonly encountered in the agricultural landscape of Southern China (Hong *et al.*, 2017), studies exploring the impact of this mixed cultivation practice associated with co-blossom of two distinct flower types on the wild pollinator communities have been lacking. We provide new empirical insights into the positive impact that this mixed cultivation practice has on the species richness of wild pollinator communities in the smallholder farmland of Southern China, but similar positive effects are likely to be seen for this mixed cultivation type across Asian countries such as Japan (Sakai and Matsuka, 1982) or Korea (Cho and Choe, 1999).

The observed increased wild pollinator species richness in mixed cultivation landscapes when compared to monocropping landscapes is consistent with previous studies exploring the impact of crop diversification on wild pollinator diversity (Aguilera *et al.*, 2020; Dingha *et al.*, 2021; Raderschall *et al.*, 2021). Aguilera *et al.* (2020) found that crop diversity in a 1000m radius in the agricultural landscape was positively linked with pollinator diversity in Southern Sweden. Dingha *et al.* (2021) found that pollinator diversity and abundance in the cowpea intercropping with pollinator dependent crops (squash, watermelon and okra) were both higher than in the monocropping fields. Brandmeier *et al.* (2021) reported that cereal-legume intercropping can both increase pollinator abundance and richness in a three-year study in western Germany. One possible reason is that milk vetch, as a nectar source for wild pollinator communities (Wang *et al.*, 2006), attracts a different set of pollinators to oilseed rape, given differences in flower color (yellow vs. purple), morphology, odor and height (oilseed rape 1.6-1.7m, milk vetch ~11cm). Milk vetch is generally considered as providing supplementary food resources for pollinators. Previous studies have shown that different color (Freitas Moreira *et al.*, 2016), odor (Pombal *et al.*, 2000), morphology and flower height (Fornoff *et al.*, 2017b) do attract different pollinator species. In addition, pesticide usage was rarely observed on Chinese milk vetch, while pesticides have been widely applied on Chinese oilseed rape fields (Wen *et al.*, 2021). Furthermore, Chinese milk vetch may provide a food resource low in pesticides, although pesticides applied to oilseed rape may easily drift to nearby non-target species like milk vetch within the small-grained agricultural landscape mosaic present in our study area (Ward *et al.*, 2022). Future studies are herein suggested to verify this by analyzing the pollen and nectar from nearby apiaries.

Mixed cultivation did not increase pollinator abundance compared to monocropping, which is in contrast with previous results (Gowton *et al.*, 2021). The possible reason for this lack of a significant response could be that, despite offering an alternative nectar and pollen source, mixed cultivation did not increase the overall food resources in the fields on a landscape scale, with the abundance of flower visitors generally assumed to be directly linked to the overall abundance of flowers in the fields (Feltham *et al.*, 2015). Considering the fact that pollinator abundance is a vital factor determining pollination services (Woodcock *et al.*, 2019; Wu *et al.*, 2021), mixed cultivation may not increase the yield of oilseed rape or other insect-pollinated crops in the wider landscape through abundance-related effects. Instead, it could be argued that co-blooming of multiple pollinator-dependent crops within a landscape may even lead to pollinator competition, and hence to reduced yields of targeted crops (Grab *et al.*, 2017). It therefore remains unknown if milk vetch grown close to oilseed rape can facilitate the latter's pollination, or compete with oilseed rape for similar wild pollinator cohorts. Future studies are required to evaluate the impact of mixed cultivation on the specific pollination services, and therefore overall yield of oilseed rape (Stanley *et al.*, 2013). In addition, wild pollinators in this study were sampled using passive traps (pan traps and flight interception traps), rather than observing direct flower visitations. As samples collected in pan traps might not fully represent flower visitation (Shi *et al.*, 2022b), it is possible that some of the pollinators recorded may not actually pollinate oilseed rape. To better evaluate the impact of mixed cultivation on wild bee communities and their pollination services, future studies should integrate direct observation on flowering oilseed rape plants in pollinator sampling (Tronstad *et al.*, 2022).

While there were unique taxa associated with mixed-cultivation landscapes, we furthermore did not find mixed cultivation to benefit specific trait groups such as small-bodied pollinators or cavity-nesting bees. The lack of an abundance signal in all studied taxonomic and trait groups might be related to two factors: First of all, the flowering period of both crop species is very similar, meaning that a temporal differentiation in resource provisioning will be very limited. Furthermore, sampling was conducted only at the main flowering time for both crops, further limiting the visibility of any temporal effects relating e.g. to different lengths in flowering periods. Secondly, both crops, but particularly oilseed rape, show an extremely high concentration of nectar resources for the short flowering period (Pierre *et al.*, 1999; Carruthers *et al.*, 2017). It is hence unlikely that at this time, the actual provisioning of nectar and/or pollen is a limiting factor for the overall abundance of pollinators using this resource, since communities will struggle to respond to the very sudden and time-limited spike in resource availability by, for example, building up their populations or recruiting from the wider landscape where neighbouring oilseed rape or mixed cultivation fields will be similarly attractive to regional pollinator assemblages.

The lack of differences encountered between the pollinator community composition of monoculture and mixed cultivation landscapes again contrasts previous results (Norris *et al.*, 2018; Järvinen *et al.*, 2022). This lack of distinction may be due to the fact that all of our study locations are situated in environments with a sizable amount of semi-natural habitat coverage (49%-92% at a 1000m radius). Even for the lowest relative cover values, these semi-natural habitats in the agricultural landscape can be assumed to already significantly improve the overall structure of the pollinator community (Shi *et al.*, 2022a). This can mask any additional potential positive effects of mixed cultivation practices. This effect can also explain the lack of any significant trends observed for the abundance of small bodied pollinators, wild bees, small bodied bees and above-ground nesting bees.

Despite the already high amount of semi-natural habitat coverage (>50%) found across the investigated landscapes, wild pollinator diversity still increased with the proportion of semi-natural habitat and did not show signs of saturation. This trend is consistent with previous studies of smallholder farmland in Southern China (Zou *et al.*, 2017; Shi *et al.*, 2021). We found that semi-natural habitat, rather than mixed cultivation, had a significant positive impact on wild bee abundance, which is consistent with Wu *et al.* (2019). We also found that there was no interaction between semi-natural habitat proportion and oilseed rape farming type on wild pollinator communities, which contradicts our initial hypothesis. This indicates that mixed cultivation can effectively support wild pollinator species richness in both, landscapes with a high or a low coverage of semi-natural habitats. This cropping practice may hence be applicable as a general pollinator-friendly approach to mitigate negative impacts of farmland consolidation projects for example in the mountainous farmlands in Western Zhejiang, where high cover of semi-natural habitat remains on mountain slopes, or in the cropland-dominated landscapes in China's Eastern delta regions (Shi *et al.*, 2021). We also strongly encourage studies in agricultural landscapes with low semi-natural habitat coverage to further test the potential interactions between mixed cultivation and semi-natural habitat on wild pollinator communities in landscapes where complementarity might be much more strongly developed than in our study landscapes.

In conclusion, at least in our mountainous agricultural study region with relatively high levels of semi-natural habitat coverage, mixed cultivation appears to boost wild pollinator species richness irrespective of the actual proportion of actual semi-natural habitat in the respective study landscape. However, the overall pollinator assemblage composition in mixed cultivation landscapes and oilseed rape monoculture landscapes remains surprisingly similar. In addition, mixed cultivation did not increase wild pollinator abundance, and nor did the amount of semi-natural habitat. Mixed cultivation furthermore did not benefit specific vulnerable pollinator trait groups such as cavity-nesting bees. This appears to indicate limited benefits of co-blooming pollinator-dependent plant species, even where their flower structure differs widely, while such a joint planting might even lead to pollinator competition, potentially lowering the yield of targeted crops (Grab *et al.*, 2017). This nonetheless warrants further investigation, for example using experimental studies of differing mixed cultivation settings, to explore under which conditions the current mixed system facilitates or decreases pollination outcomes and associated yields in oilseed rape.

Data availability statement

All of our data used in this study can be downloaded in repository figshare: https://figshare.com/articles/dataset/data_of_Shi_et_al_2023_xlsx/23542548

Author Contribution Indication

Xiaoyu Shi: Conceptualization (lead), Software (lead), Investigation (lead), Writing - Original Draft (lead), Methodology (lead). **Jan Christoph Axmacher**: Conceptualization (equal), Visualization (equal), Methodology (equal), Writing - Reviewing and Editing (equal). **Arong Luo**: Methodology (equal), Writing - Reviewing and Editing (equal). **Changsheng Ma**: Writing - Reviewing and Editing (equal), Visualization (equal). **Mingqiang Wang**: Methodology (equal), Investigation (equal). **Rui Cheng**: Methodology (equal), Investigation (equal). **Zeqing Niu**: Investigation (equal), Resources (equal). **Qingsong Zhou**: Investigation (equal), Resources (equal). **Yi Zou**: Resources (equal), Writing - Reviewing and Editing (equal), Supervision (lead). **Chaodong Zhu**: Conceptualization (lead), Supervision (lead), Writing - Reviewing and Editing (equal).

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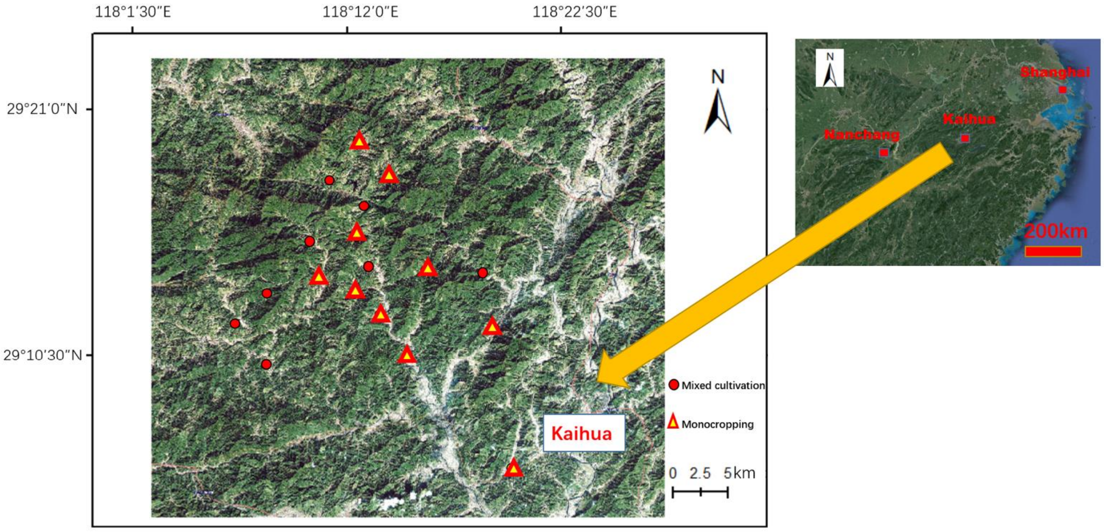

Figure 1. 18 research sites in Kaihua County, Quzhou, China. Red circular points represent sites with oilseed rape monoculture while yellow triangles with red edges represent oilseed rape-milk vetch mixed cultivation.

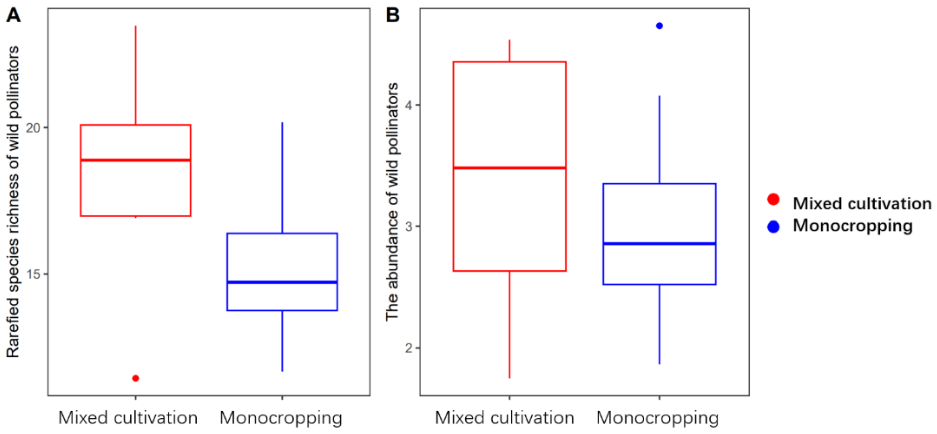

Figure 2. The impact of oilseed rape-milk vetch mixed cultivation on wild pollinator rarefied

species richness (A) and abundance (B).

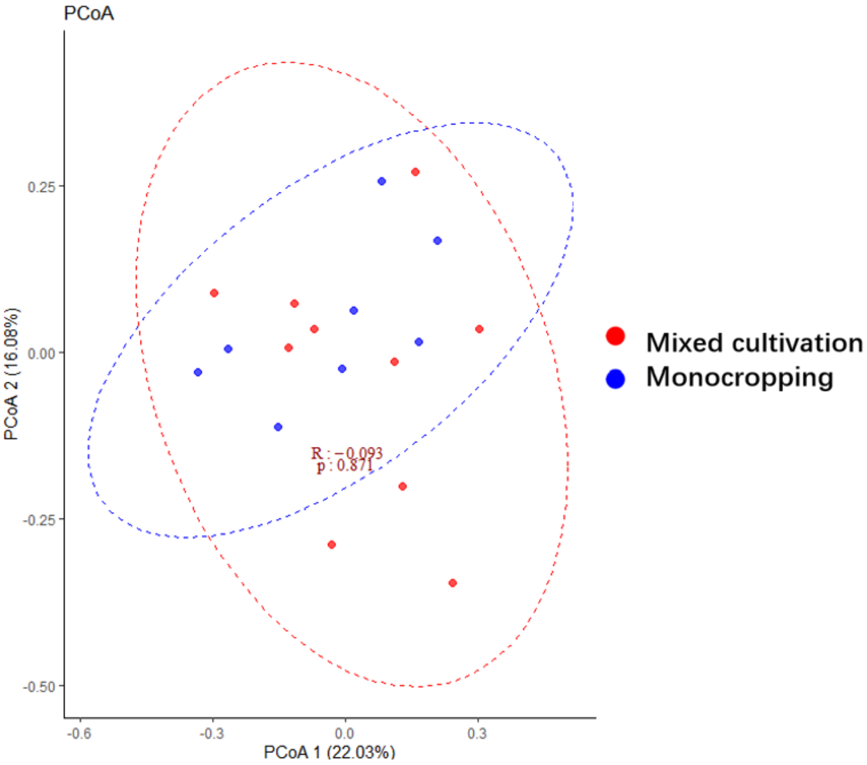

Figure 3. Principal coordinate analysis (PCoA) ordination based on Bray-Curtis distances of two types of farming practices (red: monocropping; blue: mixed cultivation). Ellipses indicate the 95% confidence intervals of locations categorized by farming practices.

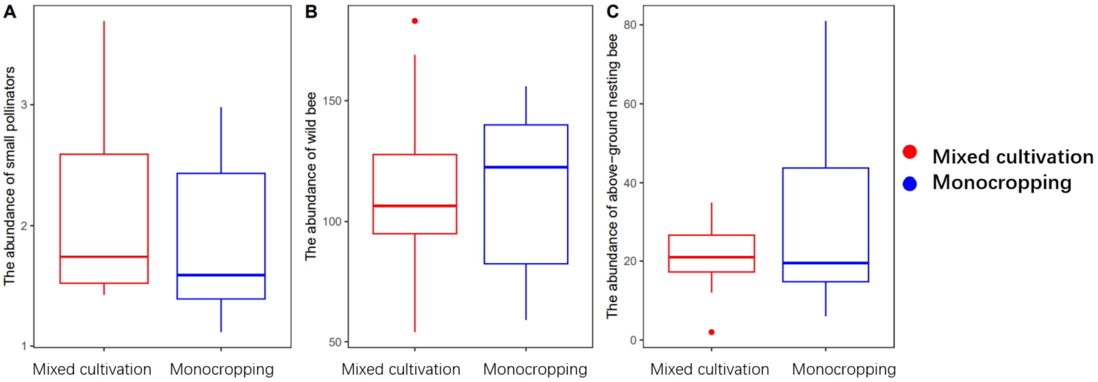

Figure 4. Comparison of landscapes with oilseed rape-milk vetch mixed cultivation vs monocropping of oilseed rape on the abundance (A) of small-bodied wild pollinators; the abundance (B) of wild bees; and the abundance (C) of above-nesting bees.

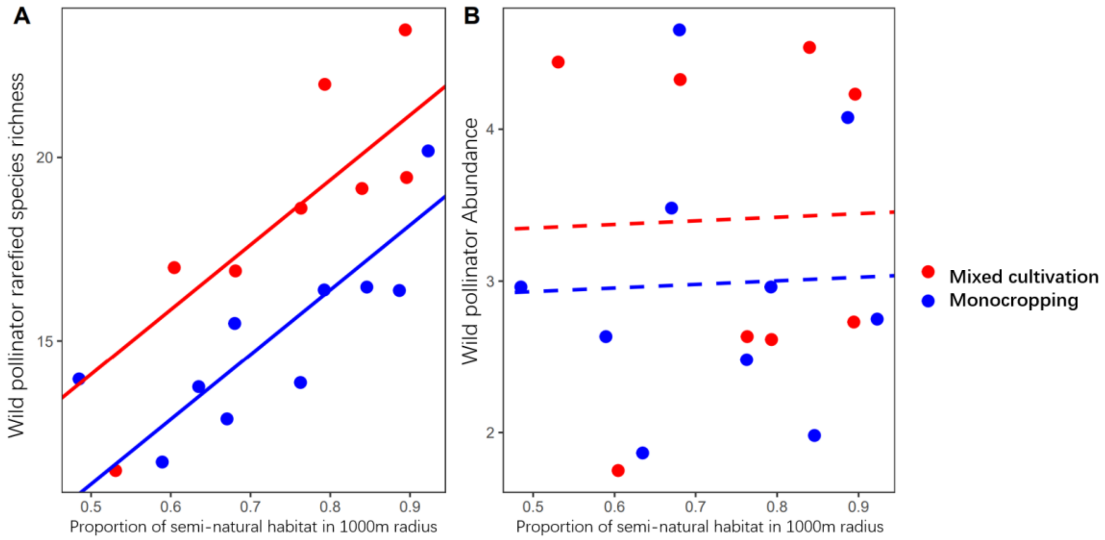

Figure 5. The relationships between the proportion of semi-natural habitat in 1000m radius and wild pollinator rarefied species richness (A) and abundance (B).

Table 1. The results of the most parsimonious models selected to explain rarefied species richness and abundance of wild pollinators in response to mixed cultivation practice (Oilseed rape-milk vetch mixed cultivation and oilseed rape monoculture; based on oilseed rape monoculture areas), proportion of semi-natural habitat at 1000m spatial scales. Values show the model estimate with standard error. The symbol "/" shows that this explanatory variable was not included in the selected model. Asterisks indicate the significance levels in the models ('*' p < 0.05, '**' p < 0.01 and '***' p < 0.001). The interactions between semi-natural habitat, farming type and oilseed rape was not included in any of the selected models.

Explanatory variable	Rarefied species richness	Wild pollinator abundance	Small pollinator abundance	Wild bee abundance	Above-ground nesting bee abundance
Farming type	3.00±0.88**	/	/	/	/
Semi-natural habitat	17.67±3.36***	/	/	2.50 ± 1.18 (p=0.05)	-0.45±1.02
Oilseed rape	/	/	/	/	-204.6±84.82*
Semi-natural habitat* Oilseed rape	/	/	/	/	371.99±125.99*