Strengthening pollination services in Korla fragrant pear in China

Qian Li

Propositions

1. Wild bees contribute little to pollination of Korla fragrant pear in the Korla area.
   (this thesis)
2. The use of artificial pheromones to enhance pollination of fruit trees masks a deeper agro-ecological problem.
   (this thesis)
3. Experimental design needs greater attention in academic teaching.
4. Agricultural scientists should get out in the field at least once per year.
5. Biodiversity decline will not lead to an ecological disaster.
6. Statistical significance is meaningless without ecological interpretation.
7. Group learning is a way to convert peer pressure into peer motivation.
8. The first conversation of sandwich PhD candidates and their supervisors should be on their mutual expectations.

Propositions belonging to the thesis, entitled

Strengthening pollination services in Korla fragrant pear in China

Qian Li
Wageningen, 23 February 2024

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Thesis committee

Promotors

Dr W. van der Werf
Associate Professor, Centre for Crop Systems Analysis
Wageningen University & Research

Dr F.J.J.A. Bianchi
Associate Professor, Farming Systems Ecology Group
Wageningen University & Research

Co-promotors

Prof. Dr Y. Lu
Professor of Entomology
Chinese Academy of Agricultural Sciences, Bejing, China

Other members

Prof. Dr D. Kleijn, Wageningen University & Research
Dr K. Winkler, Wageningen University & Research
Dr B. Smith, Coventry University, UK
Dr Z. Yi, Xi’an Jiaotong-Liverpool University, Suzhou, China

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Thesis

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For my parents who give me indispensable support all the time.

Table of contents

Chapter 1

General introduction

1.1 Importance of pollination for crop yield and quality

With an estimated world population of 9.7 billion people in 2050 (Food and Agriculture Organization 2018), the global food demand in 2050 is expected to increase by 60% in comparison with 2010 (van Dijk et al., 2021). As the availability of agricultural land is limited, there is a need to increase crop production to meet the increasing demand for food quantity and food security, while at the same time respecting the planetary boundaries and minimizing environmental impacts (Steffen et al., 2015).

Pollination is a vital ecosystem process for sustaining life on Earth (Garibaldi et al., 2020; Kaur and Kaleka, 2022), and is one of the cornerstones of crop production. Around 75% of the 115 most important crop species (e.g., oilseeds, apple and tomato) that are used for human consumption are dependent on animal pollination, representing approximately 35% of total agricultural production (Klein et al., 2007). The other 25% of these crops, which include major staple crops such as rice, maize and wheat, rely on wind- and self-pollination and are therefore not dependent on pollinators (Klein et al., 2007). While pollination dependent crops may differ in their dependency on pollinators (Klein et al., 2007), yield increases due to pollination can be substantial. For instance, the average yield of insect-pollinated crops was enhanced by insect pollination by 18-71% depending on the crop (Bartomeus et al., 2014). The benefit of pollinators to crops is not limited to yield but also extends to crop quality (Fijen et al., 2018). Pollination can improve the appearance and shelf life of products, thereby improving marketability and contributing to reducing food loss and waste (Gazzea et al, 2023). Pollinators increased, for instance, the percentage of high-quality beans (i.e. larger and light-colored beans) from 9% to 68% (Sliva et al., 2023), and bee-pollinated strawberry fruits showed fewer malformations, greater fruit weight, and longer shelf life, resulting in higher commercial value (Klatt et al., 2014). Furthermore, global agriculture’s reliance on pollinator-dependent crops has increased over the last five decades (IPBES 2016; Figure 1.1). Thus, pollination is critical for maintaining global ecosystem stability, agricultural productivity, and food security (Potts et al., 2010; Willmer et al., 2017).

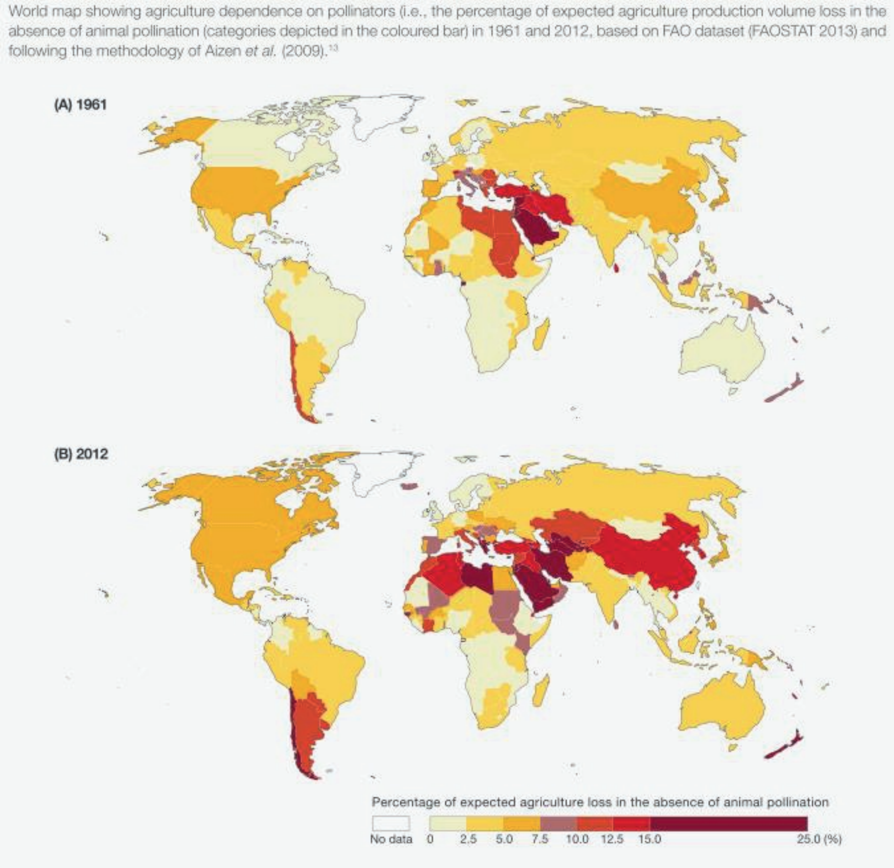

Figure 1.1 World map showing agriculture dependence on pollinators (i.e., the percentage of expected agriculture production volume loss in the absence of animal pollination (categories depicted in the colored bar) in 1961 and 2012, based on FAO dataset (FAOSTAT 2013) and following the methodology of Aizen et al. (2009). Source: IPBES (2016).

1.2 Ecology of pollinators and pollinator decline

1.2.1 Ecology of pollinators

Pollinators include any organism that helps to carry pollen from the male part of the flower (stamen) to the female part of the same or another flower (stigma). Pollinators consist of birds, bats, butterflies, moths, flies, beetles, wasps, small mammals, and most importantly, bees (Requier et al., 2023). There are over 20,000 species of bees around the world, and they are highly diverse in diet breadth, nesting location, sociality, body size, and timing of foraging season (Ascher and Pickering 2020; Zattara and Aizen, 2021). A diverse community of bees generally provides more effective and stable crop pollination than any single species does (Garibaldi et al., 2014; Lemanski et al., 2022). This may be explained by the functional complementarity provided by diverse pollinator communities as different species may visit crops at different times of the day or growing season, or in different weather conditions (Hoehn et al., 2008; Rader et al., 2013). Therefore, different pollinator species can act synergistically (Brittain et al., 2013; Carvalheiro et al., 2011), highlighting the need to conserve diverse pollinator communities.

Honeybees and wild bees are the two main pollinator groups of relevance for global crop production (Blaauw et al., 2016; Garibaldi et al., 2013; Hung et al., 2018). Managed honeybees (*Apis mellifera*) are the most abundant managed pollinators worldwide, representing approximately half of the crop visitors and contributing to the production of insect-pollinated crops (Goodwin et al., 2011; Kleijn et al., 2015; Rucker et al., 2012). Honeybees are valued because they pollinate a wide range of crops and have long foraging ranges compared to most solitary bees (Steffan-Dewenter et al. 2002; Steffan-Dewenter & Kuhn 2003). Even though honeybees may be considered as the “work horse” of crop pollination, it is risky to rely on a single pollinator species in crop production for several reasons. First, Mashilingi et al., (2022) reported that managed honeybees are not sufficient to provide optimal pollination services in agricultural systems due to the increasing honeybee pollination demand worldwide. Second, honeybees are susceptible to parasites (e.g., *Varroa destructor*, Norton et al., 2021) and diseases (e.g. American foulbrood, Eischen et al., 2005). Third, the presence of managed honeybees could have a negative or potential negative effect on wild bees through competition or transmission of pathogens (Angelella et al., 2021; Gealmann and Gonález-Varo, 2018; Mallinger et al., 2017). The introduction of managed species is therefore not always the best option to improve crop yield. Despite the major contribution of honeybees to crop production, it is also necessary to assess the contribution of other pollinator groups, such as wild bees.

Wild bees also comprise highly valued pollinators. A total of 785 different wild bee species have been reported to visit crop flowers and contributed \$3,251 ha^{-1} to the crop production on average (Kleijn et al., 2014). A recent multi-region study found that the overall contribution of wild bees was similar or higher than that of honeybees in most of the crops that were studied (Reilly et al., 2020). For example, bumble bees and solitary bees transport and deposit more pollen on the stigmas than honeybees (Brittain et al., 2013; Zisovich et al., 2012). Furthermore, different insect pollinators may be more or less effective for particular crops (Rader 2013; 2016). For example, long-tongued bumblebees were the most important pollinators for field bean pollination (Garratt et al., 2014), while red mason bees (*Osmia rufa*) were more effective pollinators than hoverflies in oilseed rape (Jauker et al., 2012). However, crop pollination depends strongly on the activity of a relatively small number of wild bee species as 2% of species account for almost 80% of crop visits that were made by wild bees (Kleijn et al., 2015; Winfree et al., 2015). Therefore, information is needed on the pollinator community in different crops, and on the effectiveness of these communities in the pollination of different crops, varieties, and in different locations (Garratt et al., 2014; Rader et al., 2016).

1.2.2 Pollinator decline

While insect pollinators contribute significantly to crop pollination, there is a global concern about their decline and associated pollination service (Biesmeijer et al., 2006; Potts et al., 2010; Wanger et al., 2020; 2021). For example, approximately 25% fewer bee species were found at the global scale between 2006 and 2015 than before 1990 (Zattara and Aizen, 2021). However, studies outside of Europe and USA are relatively scarce (Wagner et al., 2020), underlining the need for studies in different parts of the world.

Global-scale assessment results showed that land-use intensification and habitat loss are the main reasons of reduced abundance and diversity of wild bees, as they drive the loss and homogenization of floral resources (Dicks et al, 2021; Goulson et al., 2015; Tscharntke et al., 2005). Other threats include climate change (Müller et al., 2023), pesticide use, and invasive alien species and diseases (Wanger, 2020). For example, the use of herbicides to control weeds indirectly affects pollinators by reducing the abundance and diversity of flowering plants that provide pollen and nectar. The decline in wild bees caused a direct impact on food production (such as yield reduction and yield instability) and biodiversity (such as wild pollinator diversity and wild plant diversity; IPBES, 2016). To mitigate pollination deficits, farmers have resorted to pollination management practices, such as the rental of beehives, hand pollination or pollen spraying (Garibaldi et al., 2014; Sáez et al., 2019). However, these practices are costly and time-consuming. Several strategies are proposed to mitigate the pollinator decline and associated risks, such as implementation of agri-environment schemes to preserve and restore the habitat of wild bees, which may contribute to stabilizing pollination services, and supporting crop production, food security and human well-being (Potts et al., 2010).

1.3 Pollinators and pollination in agricultural landscapes

Wild pollinators are mobile animals that exploit foraging and nesting sites within their dispersal limits. In agricultural landscapes pollinators may encounter a variety of habitats, including crop fields, pastures and semi-natural habitats. These different land use types could affect wild bee communities through their influence on the abundance and diversity of resources across space and time (Schellhorn et al. 2015; Saturni et al., 2016; Senapathi et al., 2017; Roquer-Beni et al., 2021).

Semi-natural habitats, such as hedgerows, woodlands, and extensively managed grasslands, can support wild bee abundance and diversity by providing floral resources (Timberlake et al. 2019; Eeraerts et al. 2021; Maurer et al. 2022) and nesting sites (Potts et al. 2005; Eeraerts et al., 2023). The abundance and diversity of pollinators is generally positively associated with the availability of flower resources

(Blaauw and Isaacs, 2014; Russo et al., 2013; Martínez-Núñes et al., 2022; Maurer et al., 2022), but this does not mean that the establishment of flowering plants will necessarily increase the pollination of a target crop (Diekötter *et al.*, 2010; Holzschuh *et al.*, 2011). For instance, mass-flowering crops can influence pollinator communities in different ways depending on the balance between the extent that these crops enhance the population build-up of pollinators at the landscape scale, i.e., the "exporter" hypothesis (Morandin and Kremen, 2013; Kremen et al., 2019) or keep pollinators away from the target crop, i.e., the "aggregation" hypothesis (Ventruini et al., 2017). Depending on the dominance of the "exporter" and "aggregation" mechanisms, the presence of alternative floral resources may enhance or compromise pollinator visitation of a target crop. Furthermore, the effect of mass-flowering crops on the target crop is also determined by the stage of blooming. For example, apples as a mass-flowering crop decreased the pollinator abundance in strawberry fields during early and peak apple bloom, but increased pollinator abundance in strawberry fields during the late apple blooming period (Grab et al., 2016). Finally, some crops are pollinator-dependent but not attractive to wild bees, such as pears (*Pyrus* spp.) and kiwifruit. For these crops an increase in the abundance of wild bees will hardly make a significant contribution to crop pollination target because crop flower visitation will remain low (Delaplane & Mayer, 2000). Therefore, the relationship between crop pollination and the composition of the surrounding landscape needs further scientific attention for understudied global regions, such as China.

1.4 The agro-ecological context of Korla

Xinjiang is located in northwest China and is a main fruit production area of China. The climate varies according to altitude, from hot desert climates at low altitudes to montane climates in the mountains. Most of the precipitation occurs in the mountains, while agriculture is concentrated in irrigated low-lying plains at the foot of mountain ranges. Fruit production areas are concentrated in these irrigated agricultural areas, e.g., near the cities of Korla and Aksu, which are situated between the Tianshan mountains in the north and the Taklamatan desert in the south. Cultivated fruit crops in Korla and Aksu include Korla fragrant pear (*Pyrus sinkiangensis*), apple (*Malus domestica)*, jujube (*Ziziphus jujuba*), walnut *(Juglans regia)*, peach *(Amygdalus persica)*, apricot (*Prunus armeniaca)*, and plum (*Prunus salicina)*. The area planted with fruit trees in southern Xinjiang has increased from 334,000 ha in 2006 to 599,000 ha in 2016 due to stimulating policies (Li et al. 2018).

Korla is located in the southern part of Xinjiang (Figure 1.2) and has an arid climate, with an average annual precipitation of 59 mm and potential evaporation of 2788 mm. As one of main fruit production areas in Xinjiang, the agricultural landscape in Korla is dominated by Korla fragrant pear and cotton (*Gossypium hirsutum*), but also comprises a few other arable crops (e.g., maize (*Zea mays*), sugar beet (*Beta vulgaris*), and vegetables) and other fruit crops than Korla fragrant pear. Korla fragrant pears are mostly grown in single species stands, which makes these orchard systems susceptible to disease and pest outbreaks. Also, since Korla fragrant pear trees have a relatively short flowering period and large areas in the landscape are planted with the same species, there could be strong competition for pollinators during pear flowering. At the same time, lack of habitats that provide floral resources after the flowering of fruit trees may hamper the yield-round survival and reproduction of insect pollinators.

1.5 Pollinators and pollination of Korla fragrant pear

Korla fragrant pear (*Pyrus sinkiangensis* Yü) (hereafter "KFP") is a regional fruit with a high economic value in Korla, Xinjiang, China. KFP has been cultivated in Xinjiang for over 1,300 years and was introduced to other parts of the world in 2006. KFP has a sweet and fresh taste, and the global demand for KFP has increased year by year (Sheng et al., 2020). Based on its morphological characteristics, KFP is thought to be of complex hybrid origin involving the common pear, *P. communis*, and Chinese white pears (*P. bretschneideri*). Like most Rosaceae, KFP is a self-incompatible entomophilous crop species that depends on insect pollination from a compatible

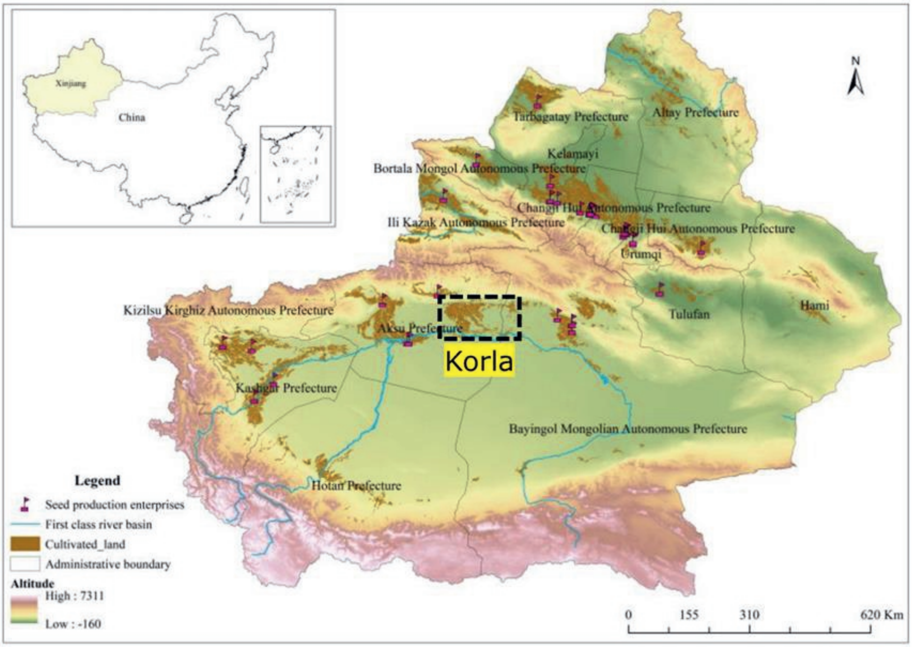

Figure 1.2 The location of Korla in Xinjiang, China. Source: Niu et al. (2021).

cultivar to set fruit (Ma et al., 2009). However, pear flowers are not attractive to many pollinators because of the low sugar content of the nectar (often <10%) (Monzón et al., 2004; Quinet et al., 2016). To ensure sufficient pollination, KFP growers often rely on artificial pollination by spraying a suspension of pollen in water or by hand pollination using a long stick with a cotton wool swab with compatible pollen. Furthermore, KFP hire honeybee hives from beekeepers. However, as fire blight disease (*Erwinia amylovora*) spread in KFP orchards since 2018 (Huang et al., 2023), honeybees were no longer allowed in KFP orchards because of the risk of spread of fireblight by bees (Cellini et al., 2019). Artificial pollination and hand pollination is labor intensive and costly, hence interest in wild bees has soared. During summer, the orchards are managed intensively with frequent insecticide applications after the KFP flowering period (usually once per 2-4 weeks) to suppress the fruit-boring and trunk-boring insect pests (e.g., oriental fruit moth *Grapholitha molesta*, codling moth, *Cydia pomonella*), and spider mites.

KFPs are widely cultivated in Korla, usually in orchards comprising KFP as the main species with a small fraction of Chinese white pear trees (*P. bretschneideri*), cultivar “Dangshan”, as pollinizer. Although largely undocumented, these areas are likely difficult environments for wild pollinators because of low wild floral resource availability during large parts of the year and the copious use of insecticides. Only a few local studies have been conducted on pollinator communities and pollination services in fruit production systems in Xinjiang (Ma et al. 2009).

1.6 Knowledge gap

There is a lack of scientific evidence on how much honeybees and wild pollinators contribute to fruit set and production of KFP, which are the main pollinator species of KFP in the Korla region, and how pollination services can be augmented using orchard or landscape management. This information is essential to inform more ecologically based orchard management at the field and landscape scale to better capitalize on pollination services provided by pollinators. The overall aim of this research is to point out pathways towards strengthening pollination services in intensive fruit production systems in the Xinjiang oasis areas.

1.7 Research questions

This PhD thesis focuses on the pollinators and pollination of Korla fragrant pear in Korla, Xinjiang, China. The study took a landscape perspective towards investigating the pollination problem. I asked the following research questions:

（1） Is there a pollination deficit in Xinjiang pear; what are the causes of this deficit and to what extent is it improved by using honeybees? **(Chapter 2)**

（2） What are the dominant wild bees in Xinjiang pear orchards and how do wild bees respond to landscape factors? **(Chapter 3)**

（3） How do early flowering apricot trees influence the abundance of bees and pollination of Korla fragrant pear? **(Chapter 4)**

（4） How is the honeybee abundance and visitation in Korla fragrant pear orchards affected by the honeybee attraction pheromone? **(Chapter 5)**

1.8 Thesis outline

This thesis contains a general introduction (Chapter 1), four content chapters (Chapters 2-5), and a general discussion (Chapter 6). The outline of the thesis chapters is presented in Figure 1.3.

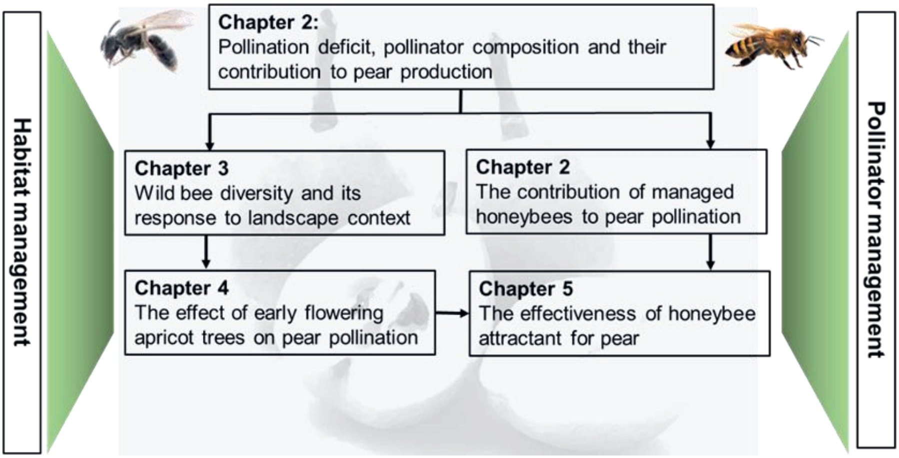

Figure 1.3 The framework of four experimental chapters.

In **Chapter 2**, I assessed the pollination deficit and the composition of pollinator communities in 49 KFP orchards across four years. I quantified the role of honeybees and wild pollinators in KFP pollination by measuring the pollinator visitation rate, fruit set, and fruit quality (i.e., seed set, fruit weight, and sugar content) in KFP orchards with or without honeybee hives.

In **Chapter 3**, I assessed how wild bee abundance and diversity in KFP orchards were influenced by the land use surrounding these orchards. I identified the wild bee diversity at the species level and I characterized the landscapes around orchards using GIS and ground truthing.

In **Chapter 4**, I assessed how early-flowering apricot trees influenced the abundance of bees and pollination success of KFP at the field and landscape level, and how this influence is moderated by apricot flowering time.

In **Chapter 5**, I assessed whether honeybee abundance and visitation could be enhanced using the honeybee attractant based on Nasonov gland pheromone (NGP) in pear orchards with and without beehives.

In **Chapter 6**, I present a general discussion and synthesis of the main findings of this thesis as well as a future outlook.

Chapter 2

High pollination deficit and strong dependence on honeybees in pollination of Korla fragrant pear, *Pyrus sinkiangensis*

Qian Li[1,2,3], Mengxiao Sun[1,2,3], Yangtian Liu[1], Bing Liu[1], Felix J. J. A. Bianchi[3], Wopke van der Werf[2,] and Yanhui Lu[1]

[1] *State Key Laboratory for Biology of Plant Diseases and Insect Pests, Institute of Plant Protection, Chinese Academy of Agricultural Sciences, Beijing, 100193, China;*

[2] *Centre for Crop Systems Analysis, Wageningen University & Research, Wageningen, The Netherlands;*

[3] *Farming Systems Ecology, Wageningen University & Research, Wageningen, The Netherlands*

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Abstract

Pollination deficits can compromise fruit yield and quality and have been reported in several fruit crops. It is unknown whether there is a pollination deficit in the production of Korla fragrant pear, *Pyrus sinkiangensis,* in China, and if so, whether this deficit can be mitigated by the use of managed honeybees (*Apis mellifera*). We assessed insect communities, flower visitation, pollination deficit and honeybee contribution to pear pollination in Korla fragrant pear orchards in Xinjiang, China. Insect communities were monitored using colored pan traps, and pollination deficit was assessed by comparing fruit set with open pollination to that with hand pollination in orchards without beehives from 2018-2021. The contribution of honeybees to pollination was assessed by comparing flower visitation, fruit set, and fruit quality in pear orchards with and without beehives in 2020 and 2021. In orchards without beehives, wild bees (72%) were the dominant pollinator group in pan traps, followed by honeybees (15%), moths, hoverflies, butterflies and wasps (Vespidae). Fruit set in these orchards was much lower with open pollination (8 ± 2%) than with hand pollination (74 ± 4%). When comparing pollination in orchards with and without beehives in 2020 and 2021, we found that honeybees were responsible for most of the flower visits in orchards with (96%) and without beehives (66%). Wild bees were responsible for 1% and 6% of flower visits in orchards with and without beehives, respectively. Fruit set was significantly higher in orchards with beehives (38 ± 9%) than in orchards without beehives (12 ± 3%), while fruit set and sugar content were positively associated with pollinator visitation rate. The findings reveal a large pollination deficit in Korla fragrant pear orchards, and show that this deficit can be mitigated using managed honeybees.

Keywords: hand pollination, *Apis mellifera*, flower visitation, fruit set, pollinator, wild bee

2.1 Introduction

Insect pollinators are essential for the pollination of many vegetable and fruit crops (Klein et al., 2007). With the increasing demand for insect pollinated crop products such as nuts, vegetables and fruits (Aizen et al., 2019) and the reported declines in pollinators (Biesmeijer et al., 2006; Potts et al., 2010; Powney et al., 2019; Wagner et al., 2021; Outhwaite et al., 2022), there may be a risk of pollination deficits compromising crop yield and quality. However, such deficits are species- and region-specific (Garibaldi et al., 2011; Aizen et al., 2019; Tamburini et al., 2019; Reilly et al., 2020). For instance, Holland et al. (2020) reported pollination deficits in sunflowers and oilseed rape, but not in pear or pumpkins in Europe. In the USA, a pollination deficit was found in blueberry in Michigan, Oregon and British Columbia, but not in Florida (Reilly et al., 2020). Pollinators and pollination need therefore to be studied for specific crops or varieties in their agro-ecological context.

The contribution of wild pollinators and honeybees to crop pollination and the associated yield and quality benefits are well documented, for instance in apple (Garratt et al., 2014), sweet cherry (Eeraerts et al., 2019) and almond (Alomar et al., 2018). However, the relative effectiveness of honeybees and wild pollinator groups may be crop species-specific (Potts et al., 2010; Garratt et al., 2016). Species that require buzz-pollination (e.g., tomato), cannot be pollinated by honeybees as they cannot produce the vibrations that are required to remove pollen (De Luca and Vallejo-Marín, 2013; Vallejo-Marín, 2019; Pritchard et al., 2020). In contrast, managed honeybees are the most important pollinators of several Rosaceous crops, such as pear (Stern et al., 2004), and avocado (Sagwe et al., 2021). Furthermore, diverse pollinator communities may benefit crop pollination due to functional complementarity between pollinator species, and due to species interactions (Dainese et al., 2019). For example, wild pollinators enhanced the movement rate of honeybees and enhanced pollination effectiveness in almond (Brittain et al., 2013), sunflower (Carvalheiro et al., 2011) and sweet cherry

(Eeraerts et al., 2020). The implications of pollinator communities composed of managed honeybees and wild pollinators for crop pollination are not fully understood.

Like most Rosaceae, pear (*Pyrus communis*) is a self-incompatible entomophilous crop species that strongly depends on insect pollination from a compatible cultivar to set fruit (De Franceschi et al., 2012). However, pear flowers are not attractive for many pollinators because of the low sugar content of the nectar (often <10%) (Monzón et al., 2004; Quient et al., 2016). For instance, even though bumblebees and solitary bees are efficient pollinators, they often avoid pear trees (Quinet et al., 2016; Quinet and Jacquemart, 2017). Pear pollination therefore often relies on the use of managed honeybees, and in absence of honeybees insufficient pollination is a common cause of poor pear yields (Monzón et al., 2004; Quinet et al., 2016).

Korla fragrant pear (*Pyrus sinkiangensis* Yü) is a premium species of pear that is cultivated in Xinjiang, China, and is distinct from *Pyrus communis*. Based on its morphological characteristics, *P. sinkiangensis* is thought to be of complex hybrid origin involving *P. communis* and Chinese white pears (*P. bretschneideri*) (Yü and Kuan, 1963). Korla fragrant pear has high market value and is widely cultivated in the Korla oasis region in the (semi-)arid part of Xinjiang, China. This oasis region has an area of $7.3*10^5$ ha, and is characterized by intensively managed crops and few semi-natural habitats. Although largely undocumented, this region may be a difficult environment for pollinators because of the low wild floral resource availability during large parts of the year and the intensive use of insecticides. Moreover, because the region is surrounded by desert, it may be experience a high level of isolation with limited exchange with pollinator communities outside the region.

To ensure sufficient pollination, Korla fragrant pear growers often rely on artificial pollination by spraying a suspension of pollen in water, or they use managed honeybees. However, we lack information about the wild pollinator communities in Korla fragrant pear orchards. It is also unknown whether there is a pollination deficit in

Korla fragrant pear, and how effective managed honeybees are in supporting pollination of Korla fragrant pear. Therefore, we assessed the composition of pollinator communities in Korla fragrant pear orchards, and assessed whether there is a pollination deficit of Korla fragrant pear. We quantified the role of wild insects and managed honeybees as pear pollinators by assessing the number of flower visits, fruit set and fruit quality (seed set, fruit weight, and sugar content) in Korla fragrant pear orchards with and without beehives.

2.2 Methods

2.2.1 Study sites and experimental design

The study was conducted in Korla, Xinjiang, north-west China (E 85.48°, N 41.45°), a prime production region of Korla fragrant pear. The pear trees in the selected orchards were 15-20 years old and in full production. The orchards consisted of Korla fragrant pear trees mixed with Dangshan pear (*P. bretschneideri*) trees, which is used as pollinizer but whose fruit have low market value. The orchards were embedded in landscapes which were dominated by pear orchards and cotton, but also comprised maize, peach, apricot and jujube, and about 7% semi-natural habitat (range 0.5 - 14% within a 2 km radius around fields). Pears are frequently treated with insecticides throughout the growing season (e.g., usually once per 2-4 weeks), except from one week before flowering until the end of flowering to avoid direct impacts on pollinators. There are no wild honeybees in Korla.

Two series of measurements were set up (Table 2.1). Measurement series 1 ran over four years (2018-2021) and involved measuring the insect community in orchards without beehives using pan traps and quantifying pollination deficit by comparing the fruit set between open pollinated flowers to that of hand pollinated flowers as a reference. In measurement series 2, conducted in 2020 and 2021, we compared the visitation rate of pollinators, fruit set and fruit quality between orchards with and without beehives. Orchards without beehives were used for both types of measurements in 2020 and 2021.

Table 2.1 Overview of treatments, observations and number of Korla fragrant pear orchards from 2018 to 2021.

Measurement series	Year	Orchard level treatments	Measurements	No. of orchards
1	2018	No beehives	Pan trapping Open and hand pollination	12 11
	2019	No beehives	Pan trapping Open and hand pollination	16 5
	2020	No beehives	Pan trapping Open and hand pollination	13* 4
	2021	No beehives	Pan trapping Open and hand pollination	12* 10
2	2020	With beehives	Flower visitation Fruit set and qualtiy	8
	2020	No beehives	Flower visitation Fruit set and qualtiy	13*
	2021	With beehives	Flower visitation Fruit set and qualtiy	8
	2021	No beehives	Flower visitation Fruit set and qualtiy	12*

* Shared orchards for measurement series 1 and 2.

2.2.2 Monitoring of insect communities

We used pan trapping to assess insect communities in 53 Korla fragrant pear orchards without beehives during flowering for four years (measurement series 1; Table 2.1). Each year, new orchards were selected. Pollinator communities were assessed using colored pan traps (Zou et al., 2017). Pan trap stations consisted of three cups (12.1 cm diameter, 13 cm height) that were painted ultraviolet (UV) yellow (SANO, type No. 1005), UV blue (SANO, type No. 1004) or UV white (SANO, type No. 1010) on both the inside and the outside, and that were fixed on three different branches on the same pear tree at approximately 1.5 m height (Figure S2.1). Four trap stations were arranged on the corners of a 50 by 50 m square in the middle of pear orchards, and stations were located at least 20 m from the edge of the orchard. Sampling was conducted during the flowering period of pear in the first half of April for a period of 7-15 days with traps being emptied at approximately 3-day intervals (13-20 April 2018, 3-18 April 2019, 5-15 April 2020, and 2-14 April 2021, respectively). The total insect catch in each orchard was sorted into six main groups: honeybees (*Apis mellifera*), wild bees (e.g., Halictidae, Sphecidae, and Melittnae), hoverflies (mostly *Syrphus corollae* and *Episyrphus balteatus*), butterflies (mostly *Pieris rapae*), wasps (e.g., *Vespula germanica*) and moth (mostly *Grapholitha molesta*) as these were considered to be potential pollinators (Zou et al., 2017). Other insects in traps, such as other Diptera, Hymenoptera (e.g., Cephidae), Coleoptera (e.g., Coccinellidae and Meloidae), Neuroptera (e.g., Chrysopidae), Hemiptera (e.g., Miridae) were not considered.

2.2.3 Pollination deficit assessment

The pollination deficit was assessed in a subset of 30 out of the 53 Korla fragrant pear orchards mentioned above (11, 5, 4, and 10 orchards in 2018, 2019, 2020 and 2021, respectively) by comparing the fruit set between open pollinated flowers and hand pollinated flowers. At each site, two similar trees were randomly selected at the center of the orchard. One tree was used to measure fruit set with open pollination and the other was used to measure fruit set with hand pollination. Ten branches were randomly selected on each tree, and from each branch one flower cluster was labelled. Each cluster was standardized to three newly open flowers by carefully removing excess flowers by hand. The open pollination treatment did not receive any treatment and therefore depended on naturally occurring pollinators. The flowers of the hand pollination treatment received commercially available pollen of Dangshan pear, which were put on flower stigmas using a cotton pad. The standardization of flower clusters and hand pollination was conducted on 9 April 2018, 8 April 2019, 11 April 2020, and 9 April 2021, and the number of fruitlets on hand and open pollinated trees was recorded on 28 April 2018, 25 April 2019, 26 April 2020, 25 April 2021, respectively.

2.2.4 Flower visitation, fruit set, and fruit quality in orchards with and without beehives

The contribution of honeybees to pear pollination was assessed in 2020 and 2021. Eight orchards with beehives (treatment) were selected in 2020 and 2021, while 13 orchards without beehives (control) were selected in 2020 and 12 control orchards were selected in 2021. In both years, the orchards with beehives were newly selected, while the orchards without beehives were the same as those used in measurement series 1. In these 41 orchards we measured flower visitation, fruit set and fruit quality (seed set, fruit weight, and sugar content). Orchards with and without beehives were located at least 2 km apart.

We assessed flower visitation by visual observation during full bloom. Observations were conducted at four time periods per day (10:00-11:30, 12:00-13:30, 14:00-15:30 and 16:00-17:30) under dry weather conditions with temperatures ranging between 10°C and 22°C and wind speeds below 30 km/h. Four observers were involved. For each observation round, four trees were randomly selected in the center of the orchard. On each selected tree, one branch with an approximate diameter of 1 cm was chosen at around 1.5 m height. A group of 100 open flowers on the branch was marked as the observation area. During a 10 minutes-observation period, we recorded the number of insects visiting, and for each insect we recorded the number of flowers visited in the observation area. A visit was defined as the insect making contact with the stigma of a flower. The flower visitors were sorted into four groups: honeybees (*Apis mellifera*), wild bees, hoverflies, and other flies. We did not find other insects visiting flowers than these four groups. In total, four observation rounds were conducted per orchard, one at each of the four designated times, and we selected four new trees for each observation round. With four observers and four times of observation, the total observation time per orchard was 160 minutes, and all visits of insects in each flower visitor group per orchard were pooled. For each pollinator group, the pollinator visitation rate per orchard was expressed as number of visits per flower per hour. Trees selected for pollinator observations in orchards without beehives were always at least 10 m apart from trees with pan traps to avoid pollinator depletion near the traps.

Fruit set was defined as the proportion fruitlets per flower cluster before thinning (i.e., initial fruit set), which started at the end of April (Stern et al., 2004). During pear flowering, ten trees were selected per orchard in an "X" pattern. For each tree, three 1 to 2-year-old branches were selected in each of four cardinal directions, and one flower cluster per branch was marked with a piece of red string, for a total of 12 flower clusters per tree. The number of flowers per marked cluster was standardized to three. The number of fruitlets per marked cluster was recorded one week after the end of flowering (before thinning). The fruit set rate for each orchard was calculated as the average proportion fruitlets developing from the initial number of marked flowers per tree.

We used three indicators of fruit quality: seed set (which is associated with pear shape, calcium concentration and flesh firmness), fruit weight and sugar content. These were assessed in early September, shortly before commercial harvest. Six pears were randomly selected from five trees separately in an "X" pattern for a total of 30 pears per orchard. Pears were weighed on an electronic balance, and the number of mature, black seeds was counted. The sugar concentration of the pear juice was measured with a mini digital display sugar meter (Product name: Pocket Refractometer; Type: PAL-1; Manufacturer: ATAGO).

2.2.5 Data analysis

Three types of analyses were conducted. Firstly, the insect caught in pan traps were classified into six groups (honeybees, wild bees, moths, butterflies, hoverflies and wasps) to determine the insect community composition in each year. Secondly, the influence of hand pollination and open pollination on fruit set (response variable) was analyzed with a generalized linear model (glm) with quasibinomial error distribution to account for overdispersion. Explanatory variables were treatment (hand versus open pollination), year, and the interaction between treatment and year. Furthermore, glm's were fitted for separate years with treatment (hand versus open pollination) as the only predictor variable. Thirdly, two analyses were conducted to determine the effect of beehives on pollinator visitation rate and pollination service (i.e. fruit set, fruit weight, seed set and sugar content). On the one hand, we analyzed the influence of presence or absence of beehives (treatment) on pollinator visitation rate and metrics for pollination service. Response variables included flower visitation rates of honeybees, wild bees, hoverflies and other flies (square root transformed data for all groups and normal error distribution), fruit set (quasibinomial error distribution), seed set, fruit weight, and sugar content (all using normal error distribution). Explanatory variables were presence or absence of beehives (treatment), year, and the interaction between treatment and year. We used linear models for variables with a normal error distribution and a glm with quasibinomial error distribution for fruit set to account for overdispersion. For year-specific analyses we used the same models with treatment as the only explanatory variable. On the other hand, the relationship between pollinator visitation rate and metrics for pollination services was explored using linear models and generalized linear models. Response variables included fruit set (quasibinomial error distribution), seed set, fruit weight, and sugar content (all normal distribution), and the explanatory variables were visitation rate of total pollinators, honeybees, wild bees, hoverflies andother flies, respectively. The total pollinator visitation rate was calculated as the sum of the visitation rates of honeybees, wild bees, hoverflies and other flies per orchard.

All calculations and analyses were performed in R (version 4.0.5, R Core Team, 2018). The glms were fitted using the function glm() from the "MASS" package and linear models were fitted with lm() from the "stats" package. Model validation was conducted by visual inspection of the plotted residuals versus the predicted values and QQ plots (Zuur et al., 2009). Means and standard errors of the mean are reported throughout the text and figures.

2.3 Results

2.3.1 Monitoring of insect communities

We collected a total of 5047 insects in pan traps in 53 Korla fragrant pear orchards in 7-15 days sampling periods in four years. Wild bees were the most abundant insect group with 3638 individuals (72% of all specimens), followed by honeybees (745 individuals, 15% of all specimens) and moths (490 individuals, 10% of all specimens; Figure 2.1). Hoverflies, butterflies, and wasps made up 4% of the sample with 79, 58, and 37 individuals, respectively (Figure 2.1).

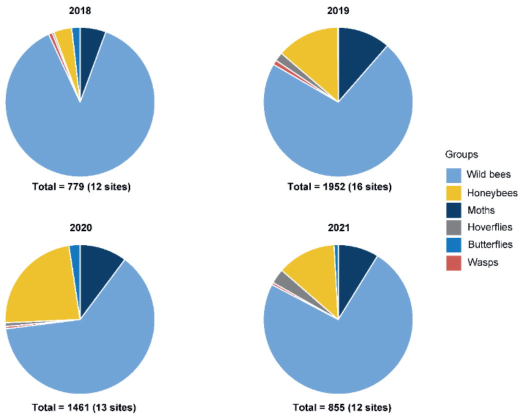

Figure 2.1 Number of individuals of six major groups of pollinating insects caught in pan traps in Korla fragrant pear orchards from 2018 to 2021.

2.3.2 Fruit set

Fruit set was significantly lower in open pollinated pear trees (8 ± 2%) than in hand pollinated pear trees (74± 4%; $P < 0.001$), and this was consistent during the four study years as indicated by a non-significant year effect and year-treatment interaction (Figure 2.2, Tables S2.1).

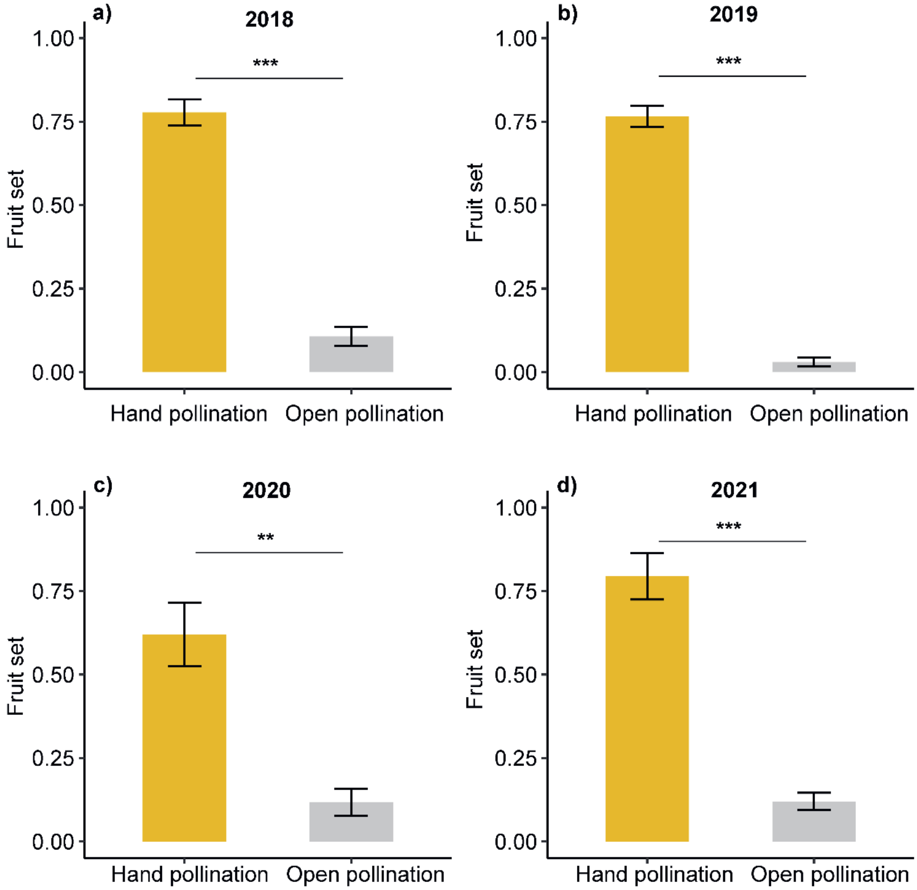

Figure 2.2 Fruit set in hand pollinated (yellow bars) and open pollinated Korla fragrant pear flowers (grey bars) in 2018 (a), 2019 (b), 2020 (c) and 2021 (d), respectively. Asterisks indicate significant differences (*** $P < 0.001$; ** $P < 0.01$) based on the results of a generalized linear model with quasibinomial error distribution (Table S2.1).

2.3.3 Flower visitation, fruit set and fruit quality in orchards with/without beehives

We recorded in total 2207 flower visits in 41 orchards in 2020 and 2021, with 1981 honeybee visits, 36 wild bee visits, 13 hoverfly visits and 177 visits by other flies. No visits by other insects were recorded. Honeybees accounted for 96% and 66% of all visits in orchards with and without beehives. Honeybee visitation was significantly higher in orchards with beehives than in orchards without beehives in both years (0.38 ± 0.06 vs 0.04 ± 0.01 visits/flower/hour in 2020 and 0.41 ± 0.05 vs 0.05 ± 0.02 in 2021, $P < 0.001$), but there was no significant difference in the visitation rate of honeybees between 2020 and 2021. There was no significant effect of the presence of beehives (treatment) on the visitation rate of wild bees, hoverflies or other flies, but the visitation rate of hoverflies and other flies was significantly higher in 2020 than in 2021 (P = 0.029 for hoverflies, $P < 0.001$ for other flies; Figure 2.3, Table S2.2 and Table S2.3).

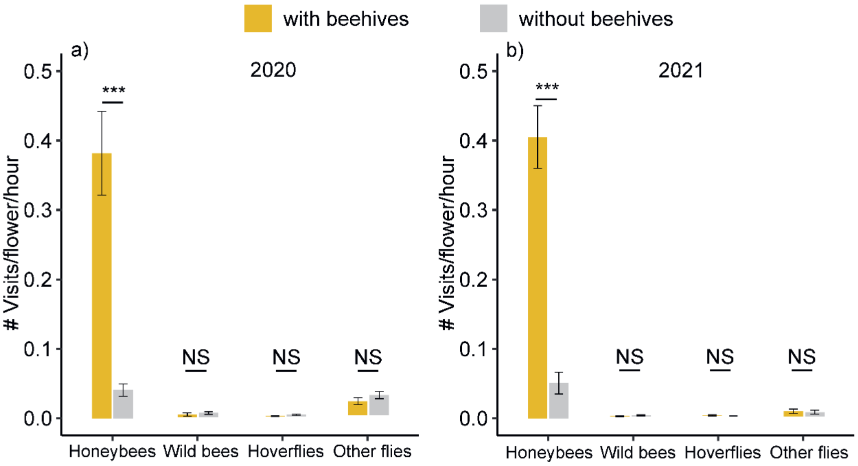

Figure 2.3 Flower visitation rates of honeybees, wild bees, hoverflies and other flies in Korla fragrant pear orchards with beehives (yellow bars) and without beehives (grey bars) in 2020 and 2021. Asterisks (***) indicate significant differences ($P < 0.001$) and NS indicates non-significant differences ($P > 0.05$) based on a linear model (Table S2.4).

Fruit set was significantly higher in pear orchards with beehives than in orchards without beehives ($P < 0.001$), and fruit set was significantly higher in 2021 than in 2020 ($P = 0.006$; Figure 2.4; Table S2.5 and Table S2.6). There was a significant interaction between the effect of beehives and year, indicating that fruit set in pear orchards with beehives were higher in 2021 than in 2020 ($P = 0.001$; Table S2.5 and Table S2.6). Presence of beehives did not significantly influence seed set, fruit weight and sugar content. Sugar content was significantly higher in 2021 than in 2020 ($P < 0.001$), while fruit weight was significantly lower in 2021 than in 2020 (all $P < 0.001$; Figure 2.4, Table S2.5 and Table S2.6).

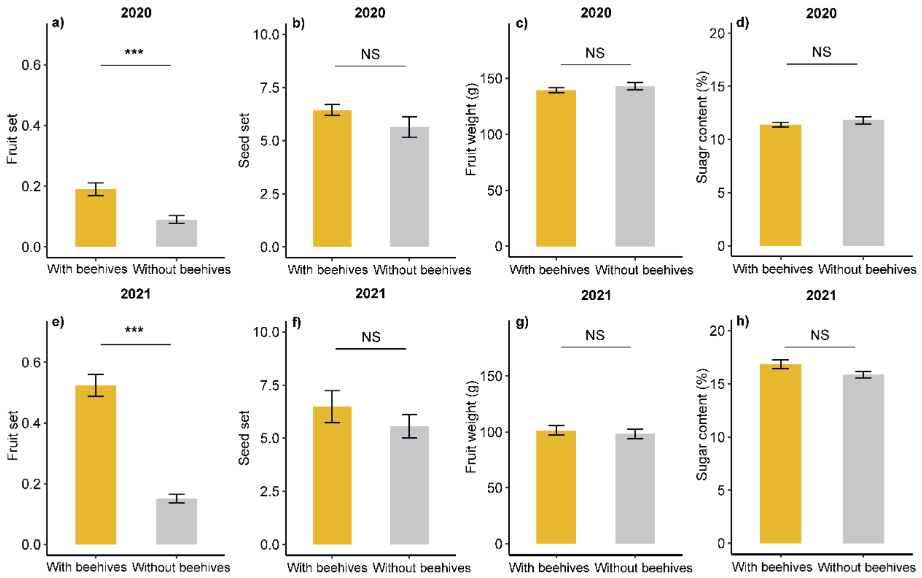

Figure 2.4 Fruit set (a, e), seed set (b, f), fruit weight (c, g) and sugar content (d, h) in Korla fragrant pear orchards with beehives (yellow bars) and without beehives (grey bars) in 2020 (a, b, c, d) and 2021 (e, f, g, h). Asterisks (***) indicate significant differences ($P < 0.001$) and NS indicates non-significant differences ($P > 0.05$) based on the results of a generalized linear model with quasibinomial error distribution for fruit set and linear models for seed set, sugar content and fruit weight (Table S2.7).

Fruit set was positively related with the total visitation rate of honeybees, wild bees, hoverflies and other flies in 2020 ($P = 0.002$) and 2021 ($P < 0.001$; Figure 2.5, Table S2.8). Seed set had a weak relationship with total pollinator visitation rate in 2021 ($P = 0.088$), but not in 2020 (Figure 2.5, Table S2.8). Sugar content was positively related with total pollinator visitation rate in 2021 ($P = 0.036$), but not in 2020 (Figure 2.5, Table S2.8). Fruit weight was not significantly related with total pollinator visitation in either year (Figure 2.5, Table S2.8).

Fruit set was positively related with the visitation rate of honeybees ($P = 0.002$ in 2020, $P < 0.001$ in 2021), but not with the visitation rate of wild bees, hoverflies or other flies in the two years (Table S2.8). Seed set had a weak positive relationship with the visitation rate of honeybees ($P = 0.090$) and wild bees ($P = 0.071$) in 2021, but seed set was not significant related to the visitation rate of honeybees and wild bees in 2020, or with the visitation rate of hoverflies or other flies in 2020 or 2021. Sugar content was positively related with the visitation rate of honeybees in 2021 ($P = 0.038$), but not in 2020, and sugar content was not significantly related to the visitation rate of wild bees, hoverflies or other flies in either year. Fruit weight was not significantly related with the visitation rate of honeybees, wild bees, hoverflies, and other flies in the two years (Table S2.8).

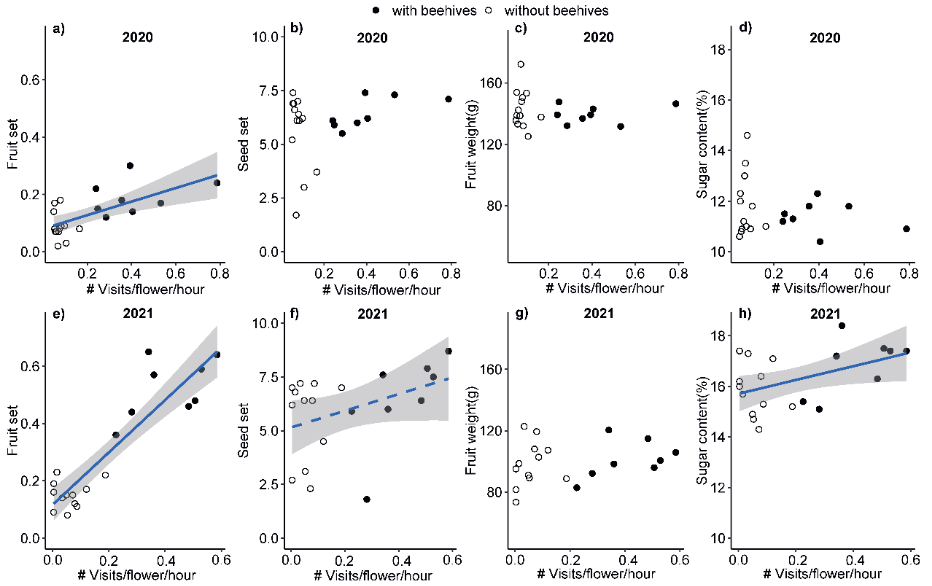

Figure 2.5 Relationship between total pollinator visitation rate of honeybees, wild bees, hoverflies and other flies, and fruit set (a and e), seed set (b and f), fruit weight (c and g) and sugar content (d and h) in Korla fragrant pear orchards in 2020 (a, b, c, d) and 2021 (e, f, g, h). Solid and dashed lines indicate significant ($P < 0.05$) and marginally significant relationships ($P < 0.1$). Relationships are based on results from a generalized linear model with quasibinomial error distribution for fruit set, and from linear models for seed set, sugar content and fruit weight. Open symbols represent data from orchards without beehives, while closed symbols are data from orchards with beehives.

2.4 Discussion

In this study we assessed the adequacy of pollination in Korla fragrant pear and found fruit set to be low. This was shown by the relatively large difference in fruit set between open pollination (8%) and hand pollination (74%) in orchards without beehives, and the higher fruit set in orchards with beehives (38%) compared to orchards without beehives (8%). While wild bees made up more than 70% of the insect collected in pan traps, less than 2% of the recorded pear flower visits were made by wild bees. Instead, honeybees made the majority of flower visits in orchards with beehives (96%) and without beehives (66%). In the orchards without beehives, flies were the second most frequent group of flower visiting insects (26%). Flower visitation by pollinators was positively associated with fruit set and also with pear sugar content in 2021. Thus, our study shows a low pollination success in Korla fragrant pear orchards (as measured by fruit set), unless honeybee beehives were placed to supplement pollination by naturally occurring pollinators.

While we found a clear pollination deficit in Korla fragrant pear in Korla, reports on pollination deficits in European pear (*Pyrus communis*) are mixed. Pollination deficits have been reported for the varieties “Conference” (21% in open pollination vs 30.7% in hand pollination) and “Doyenne du Comice” (7.2% in open pollination vs 16.8% in hand pollination) in Belgium (Quinet and Jacquemart, 2017), while Holland et al. (2020) found no consistent pollination deficit in "Conference" pear in the Netherlands. The absence or relatively low pollination deficit in "Conference" pear may be due to its capacity to produce fruit by spontaneous parthenocarpy, which buffers against a low pollinator visitation rate (Quinet and Jacquemart, 2015). In Korla fragrant pear, the high pollination deficit underlines the lack of effective pollinators and explains why farmers are looking for ways to enhance pollination and regularly resort to artificial pollination.

When comparing pear pollination in orchards with and without beehives, we found honeybee was the dominant pear flower visitor in orchards with (96%) and without beehives (66%), and few wild bees were observed to visit pear flowers. Similar findings have been reported in pear orchards in Argentina (Geslin et al., 2017), apple orchards in Germany (Osterman et al., 2021) and Macadamia in South Africa (Grass et al., 2018) where honeybees were the major visiting flower pollinator and wild pollinators were virtually absent. In addition, our results confirmed that orchards with beehives had 6.0-fold higher pear flower visits and 3.2-fold higher fruit set than orchards without beehives, and that these effects were consistent across two years. Flower visitation was also positively associated with pear sugar content and seed set, but this was only observed in one out of two years. Positive effects of honeybees on fruit set and fruit quality have also been found in kiwi (Sáez et al., 2019) and blueberry

(Martin et al., 2021). Establishing beehives is a relatively easy strategy to sufficiently enhance pear flower visitation, fruit quality and yield. Flower visitation does not necessarily imply pollination because there is great variation in effectiveness among pollinators (Henry et al., 2012). Nevertheless, our analysis of relationships between flower visits by different insect groups and fruit set (Table S8) provides clear evidence that honeybees are mainly responsible for pollination in Korla fragrant pear. Enhancing wild pollinator communities will be more challenging, particularly in intensively managed pear production landscapes, and may require an integral insect conservation strategy (Harvey et al., 2020). Even if such conservation efforts are successful, a higher abundance and diversity of wild pollinators is no guarantee for better pollination of Korla fragrant pear because many wild pollinator species are reluctant to visit pear flowers.

This is the first study showing that there is indeed a large pollination deficit in Korla fragrant pear and that introducing beehives can sufficiently alleviate the pollination deficit and potentially improve fruit quality in Korla fragrant pear. Pear growers are aware of the pollination deficit because they invest in hiring beehives and in artificial pollination. Hand pollination is done with long sticks with a mesh with pollen at the end. The cost is around 80 CNY per mu (1/15th ha) per round of hand pollination (including helpers and pollen). For bee pollination, the local farmers usually place one to two beehives per mu, and each beehive costs around 100 CNY, so the cost of bee pollination is around 100-200 CNY per mu. An advantage of bee pollination is that it is effective over the whole flowering period, if the weather is suitable (Delaplane and Mayer, 2000). On the other hand, hand pollination can only pollinate those flowers that are open at the time of a single round of hand pollination. The fact that farmers use both methods of supplementary pollination (beehives and hand pollination) in practice indicates that the two methods are approximately equally attractive to them. Our observed increase of pear fruit set from 12 to 38% by introducing beehives should be sufficient to attain maximum yield, since growers will typically thin the fruit to 2-3 fruits per flower clusters (usually 7~8 flowers), while a fruit set of 12% is not sufficient to attain maximum pear yield. However, the reliance on honeybees as a single pollinator species can be risky because honeybee is susceptible to parasites (e.g., varroa mite), diseases and insecticides (Henry et al., 2012). Honeybee colony collapses have occurred in the past and may well happen again. Moreover, honeybees may compete with wild pollinators for floral resources (Ropars et al., 2019; Weekers, et al., 2022). Therefore, the call for restoring biodiversity-friendly landscapes (Tscharntke et al., 2021) may certainly also be relevant for Korla fragrant pear production landscapes, which strongly depend on pollinators to support food production and livelihoods.

Acknowledgments

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Supplementary Information

Table S2.1 Year-specific analysis of the Relationship between fruit set (response variable) and treatment (hand pollination versus open pollination). Each line in the table specifies the effect of hand pollination (on the logit scale). A GLM with binomial error distribution was used. Open pollination was considered as reference.

	Estimate	Std. Error	t value	*P* value
2018	3.38	0.38	8.91	**<0.001**
2019	4.74	0.50	9.55	**<0.001**
2020	2.49	0.61	4.11	***0.006***
2021	3.35	0.53	6.37	**<0.001**

Table S2.2 Pollinator visitation rates of honeybees, wild bees, hoverflies and other flies (mean ± standard error) in pear orchards with (treatment) and without beehives (control) in 2020 and 2021. Coefficients are reported * 1000.

	2020		2021	
	Beehives	Control	Beehives	Control
Pollinator visitation rate (***Number of Visits/ flower/ hour***)				
Honeybees	382.00±602.00	40.70±8.90	405.00±45.00	50.60±15.60
Wild bees	3.75±2.35	6.06±2.06	0.47±0.47	1.88±0.73
Hoverflies	0.94±0.61	2.60±1.15	0.94±0.94	0.00±0.00
Other flies	19.70±4.90	28.60±5.30	7.50±3.17	5.25±2.78

Table S2.3 Relationship between visitation rates of honeybees, wild bees, hoverflies and other flies (sqrt transformed; response variables) and treatment (presence or absence of beehives in the orchard) and year. A linear model was used, and pear orchards without beehives (control) in 2020 was taken as the reference.

	Estimate (*1000)	Std. Error (*1000)	z value	*P* value
Pollinator visitation rate (# ***Visits/ flower/ hour***)				
1) Honeybees				
Beehives	418.23	51.58	8.11	**<0.001**
Year	-8.61	46.00	-0.19	0.852
Beehives*Year	31.70	73.52	0.43	0.669
2) Other flies				
Beehives	-28.30	26.10	-1.08	0.285
Year	-100.56	23.25	-4.33	**<0.001**
Beehives*Year	35.30	37.20	0.95	0.349
3) Wild bees				
Beehives	-19.26	20.38	-0.95	0.351
Year	-27.23	18.16	-1.50	0.142
Beehives*Year	-0.71	29.05	-0.03	0.981
4) Hoverflies				
Beehives	-12.84	13.95	-0.92	0.363
Year	-28.14	12.42	-2.27	**0.029**
Beehives*Year	23.66	19.88	1.19	0.242

Table S2.4 Year-specific analysis of the relationship between visitation rates of honeybees, wild bees, hoverflies and other flies (sqrt transformed; response variables) and treatment (presence or absence of beehives in the orchard). A linear model was used, and pear orchard without beehives (control) was taken as the reference.

	Estimate	Std. Error	t value	*P* value
1) Honeybees				
2020	0.42	0.04	9.35	**<0.001**
2021	0.45	0.06	7.64	**<0.001**
2) Other flies				
2020	-0.03	0.03	-1.08	0.294
2021	0.01	0.03	0.27	0.794
3) Wild bees				
2020	-0.02	0.03	-0.77	0.453
2021	-0.02	0.01	-1.44	0.167
4) Hoverflies				
2020	-0.01	0.02	-0.73	0.474
2021	<0.01	<0.001	1.24	0.230

Table S2.5 Mean and standard error of pollination service in pear orchards with and without beehives (Control) in 2020 and 2021.

	2020		2021	
	Beehives	Control	Beehives	Control
Fruit set	0.19±0.02	0.09±0.01	0.52±0.04	0.15±0.01
Seed set	6.44±0.25	5.63±0.49	6.48±0.75	5.57±0.54
Sugar content	11.40±0.21	11.82±0.34	16.84±0.40	15.88±0.30
Fruit weight	139.00±2.00	143.00±3.00	101.00±4.00	98.10±4.30

Table S2.6 GLM analysis of the effect of beehives on pollination services in pear orchards in 41sites in 2020 and 2021 (in 2020: 8 sites with beehives and 13 sites without beehives; in 2021:8 sites with beehives and 12 sites without beehives). The response variables were initial fruit set (Quasibinomial error distribution), seed set (Normal error distribution), fruit weight (Normal error distribution) and sugar content (Normal error distribution). We used GLM was applied for fruit set and LM for seed set, sugar content and fruit weight. The explanatory variables with or without beehives and year. Pear orchards without beehives (control) in 2020 were taken as reference.

	Estimate	Std. Error	t value	*P* value
1) Fruit set				
Beehives	0.87	0.21	4.07	**<0.001**
Year	0.59	0.20	2.90	**0.006**
Beehives*Year	0.95	0.28	3.44	**0.001**
2) Seed set				
Beehives	0.81	0.78	1.04	0.307
Year	-0.06	0.69	-0.09	0.927
Beehives*Year	0.10	1.11	0.09	0.928
3) Sugar content				
Beehives	-0.42	0.48	-0.87	0.388
Year	4.06	0.42	9.58	**<0.001**
Beehives*Year	1.38	0.68	2.03	*0.050*
4) Fruit weight				
Beehives	-3.64	5.47	-0.67	0.510
Year	-44.98	4.87	-9.23	**<0.001**
Beehives*Year	6.83	7.79	0.88	0.386

Table S2.7 Year-specific analysis of GLM and LM analysis of the effect of managed honeybee hives on pollination service in pear orchard in 41 sites in 2020 and 2021 (in 2020: 8 sites with beehives and 13 sites without beehives; in 2021: 8 sites with beehives and 12 sites without beehives). The response variables were initial fruit set (Quasibinomial error distribution), seed set (Normal error distribution), fruit weight (Normal error distribution) and sugar content (Normal error distribution). The explanatory variables with or without beehives (treatment). GLM was applied for fruit set and LM was applied for seed set, sugar content and fruit weight. Pear orchards without beehives (control) were taken as reference.

	Estimate	Std. Error	t value	*P* value
1) Fruit set				
2020	0.87	0.21	4.13	**<0.001**
2021	1.82	0.18	10.32	***<0.001***
2) Seed set				
2020	0.81	0.66	1.23	0.234
2021	0.91	0.91	1.01	0.328
3) Suagr content				
2020	-0.42	0.47	-0.89	0.386
2021	0.96	0.49	1.96	*0.066*
4) Fruit weight				
2020	-3.64	4.68	-0.78	0.446
2021	3.19	6.29	0.51	0.618

Table S2.8 Generalized linear model (GLM) and linear model (LM) analysis of the relationship between pollination services and visitation rate of pollinators in pear orchards with and without beehives in 2020 and 2021. The response variables were fruit set (GLM; Quasibinomial error distribution), seed set (LM; Normal error distribution), sugar content (LM: Normal error distribution) and fruit weight (LM; Normal error distribution). The explanatory variables were visitation rate of total pollinators, honeybees, wild bees, hoverflies and other flies.

		Estimate	Std. Error	t value	Pr(>|t|)
1) Fruit set (GLM)					
2020	Total	1.81	0.51	3.56	**0.002**
	Honeybees	1.83	0.51	3.61	**0.002**
	Wild bees	-12.40	21.42	-0.58	0.570
	Hoverflies	-23.98	44.00	-0.52	0.607
	Other flies	-1.91	8.44	-0.23	0.823
2021	Total	4.37	0.53	8.17	**<0.001**
	Honeybees	4.39	0.53	8.23	**<0.001**
	Wild bees	-148.15	110.85	-1.34	0.198
	Hoverflies	204.34	120.28	1.70	0.107
	Other flies	8.51	24.98	0.36	0.727
2) Seed set (LM)					
2020	Total	2.11	1.65	1.28	0.217
	Honeybees	2.05	1.64	1.25	0.225
	Wild bees	-5.66	48.0	-0.12	0.907
	Hoverflies	13.63	97.32	0.14	0.890
	Other flies	1.99	19.44	0.10	0.919
2021	Total	3.89	2.15	1.81	*0.088*
	Honeybees	3.88	2.17	1.79	*0.090*
	Wild bees	-370.89	193.18	-1.92	*0.071*
	Hoverflies	388.77	262.87	1.48	0.156
	Other flies	30.91	50.48	0.61	0.548
3) Sugar content (LM)					
2020	Total	-1.09	1.18	-0.92	0.369
	Honeybees	-1.04	1.17	-0.89	0.387
	Wild bees	-16.00	33.44	-0.48	0.638
	Hoverflies	28.95	67.92	0.43	0.675
	Other flies	-2.13	13.62	-0.16	0.877
2021	Total	2.72	1.21	2.26	**0.036**
	Honeybees	2.72	1.21	2.24	**0.038**
	Wild bees	-184.02	115.79	-1.59	0.129
	Hoverflies	160.00	157.89	1.01	0.324
	Other flies	21.53	29.31	0.74	0.471
4) Fruit weight (LM)					
2020	Total	-6.63	11.91	-0.56	0.585
	Honeybees	-6.67	11.79	-0.57	0.578
	Wild bees	444.51	319.00	1.39	0.180
	Hoverflies	-144.09	678.64	-0.21	0.834
	Other flies	-44.49	135.30	-0.33	0.746
2021	Total	15.88	15.52	1.02	0.320
	Honeybees	15.04	15.64	0.96	0.349
	Wild bees	-984.02	1427.41	-0.69	0.499
	Hoverflies	896.84	1886.81	0.48	0.640
	Other flies	500.68	327.23	1.53	0.143

Figure S2.1 Korla fragrant pear tree with yellow, blue and white pan traps to sample the insect community around the tree. Picture taken shortly before flowering.

Chapter 3

Species-specific responses of wild bees in *Pyrus sinkiangensis* pear orchards to landscape context

Qian Li[1,2,3], Bing Liu[1], Felix J. J. A. Bianchi[3], Wopke van der Werf[2,] and Yanhui Lu[1]

[1] *State Key Laboratory for Biology of Plant Diseases and Insect Pests, Institute of Plant Protection, Chinese Academy of Agricultural Sciences, Beijing, 100193, China;*

[2] *Centre for Crop Systems Analysis, Wageningen University & Research, Wageningen, The Netherlands;*

[3] *Farming Systems Ecology, Wageningen University & Research, Wageningen, The Netherlands*

Abstract

Pollinator-dependent fruit crops are widely grown in Xinjiang, China. However, the wild bee communities in these fruit-growing landscapes are largely undocumented, and it is not known how these communities are affected by land use and floral resources near orchards. We sampled wild bees using colored pan traps in 52 flowering Korla fragrant pear (*Pyrus sinkiangensis*) orchards from 2018 to 2021 and mapped the land use in the surrounding landscape of focal orchards at four spatial scales (0.5, 1.0, 1.5, and 2.0 km). We also assessed wild bee abundance on ten wild plant species in the field margins of pear orchards using sweep netting after pear flowering in 2020 and 2021. A total of 3594 individuals of 28 wild bee species were collected in pan traps. Three species made up 90% of the samples: *Andrena yamagishi* (57%), *Lasioglossum pseudannulipes* (17%), and *Lasioglossum niveocinctum* (16%). A species-specific analysis for the three dominant wild bee species revealed that the abundance of *A. yamagishi* was significantly positively associated with semi-natural habitat at 0.5-2.0 km scales while the abundance of *L. pseudannulipes* was positively associated with annual crop habitats at the same scales. There was not a significant response of *L. niveocinctum* abundance to land use. Neither total wild bee richness nor diversity was associated with landscape context. *Medicago sativa* and *Apocynum venetum* in orchard margins supported higher wild bee abundance after pear blooming than other flowering plant species. The study shows that bee species within the same genus respond differently to landscape context, highlighting the need for species-specific analyses rather than for the community as a whole. Flowering herbs near orchards are utilized by bees after pear flowering and may therefore be important for the conservation of wild bees in Xinjiang agricultural landscapes.

Keywords: diversity, pollinator, community, land use, semi-natural habitat, landscape ecology, flower

3.1 Introduction

Wild bees provide important pollination services to wild and cultivated plants (Allen-Perkins et al., 2021; Arbetman et al., 2017). Contributions of wild bees to crop production have been observed in various crop systems (Bernauer et al., 2022; Weekers et al., 2022), but worldwide declines in wild bee populations may negatively affect these services (Powney et al., 2019; Wagner et al., 2021). These declines are associated with a myriad of factors, including agricultural intensification, habitat loss, pesticide use, and climate change (Arbetman et al., 2017; Goulson et al., 2015; Potts et al., 2016; Weekers et al., 2022).

China is one of the most biodiverse countries in the world (Ren et al., 2018) and similar threats to wild bee communities in China have been reported (Teichroew et al., 2017; Williams et al., 2009). However, most of these studies focused on bumblebees (Huang and An 2018; Williams et al., 2009), and information on other wild bees is scarce (but see Wu et al., 2021a; Zou et al., 2017). Additional information is needed to better assess the status of wild bees in agricultural landscapes in China. A lack of this kind of basic information hampers the conservation of wild bees.

Generally, complex, resource-rich agricultural landscapes host relatively abundant and diverse wild bee communities because of the availability of nesting sites and diversified floral food resources (Baude et al., 2016; Kovács-Hostyánszki et al., 2017; Potts et al., 2005; Riedinger et al., 2015). However, bee species groups with different life-history traits may respond differently to landscape context (Hall et al., 2019; Hopfenmüller et al., 2014; Ockermüller et al., 2023). These characteristic traits include body size and the associated foraging distance, diet (generalist vs. specialist), and nesting requirements (Potts and Willmer, 1997; Williams et al., 2009). For example, above-ground-nesting wild bees were on average more impaired by isolation from natural habitat and intensive agricultural land use than below-ground-nesters (Williams et al., 2010). However, most of the studies on landscape effects on wild bees consider the wild bee community as a whole (e.g. Eeraerts et al., 2017; Osterman et al., 2021; Wu et al., 2021b). There have been some studies that analyzed functional groups separately (e.g. Hopfenmüller et al., 2014), but there have been only a limited number of studies that explored the responses of wild bee communities at the species level (e.g. Cavigliasso et al., 2022). Species-specific analyses may reveal species responses that may remain concealed in community-level analyses, and may provide therefore more useful information for wild bee diversity conservation.

Besides land use and the associated resource distribution at the landscape scale, wild flowering plants in field margins may offer floral resources and nesting sites for wild bees (Hevia et al., 2021; Von Königslöw et al., 2022). Compared with mass-flowering crops, such as Korla fragrant pear, wildflower communities can provide a more diversified set of floral resources for wild bees for a relatively long period (Parreño et al., 2022; Schmied et al., 2022). Several studies have identified attractive wildflowers species for wild bees in Germany (Kuppler et al., 2023) and the UK (Nichols et al., 2019). However, it is not known which native plant species support wild bee communities in Xinjiang, China.

Xinjiang is the one of main fruit production areas in China for pear, apple, jujube, walnut, apricot, and peach. Due to the high profitability of fruit production, the cultivated area of fruit trees in Xinjiang has increased approximately 10-fold during the past 15 years. The expansion of agricultural land has likely been associated with a loss of semi-natural habitats and an overall simplification of the landscape. For instance, near Korla, Korla fragrant pear (*Pyrus sinkiangensis*) trees are grown in single species stands whereby large parts of the landscape are covered by just this single species of fruit tree. Moreover, the orchards are managed intensively with frequent insecticide applications after the pear flowering period. While these practices likely compromise the year-round survival and reproduction of wild bees (Bakker et al, 2022), landscape-scale studies on the relationship between wild bee diversity and land use are currently lacking.

Here we assessed the wild bee communities in Korla fragrant pear orchards and quantified how wild bee communities are influenced by landscape context and by different wild plant species in orchard margins. Specifically, we addressed the following three research questions: 1) what wild bee communities occur in Korla fragrant pear orchards? 2) How is the abundance and diversity of wild bees influenced by landscape context? 3) How is the abundance of wild bees influenced by wild plants around the orchards?

3.2 Methods

3.2.1 Study sites

This four-year study was conducted in 52 commercial pear orchards in Korla, Xinjiang Uygur Autonomous Region (E 85.48, N 41.45), China from 2018 to 2021 (Figure 3.1). The study region covers approximately 800 km^2. Korla is a typical arid region, with low average annual precipitation (58.6 mm) and high potential evaporation (2788.2 mm). Crop production in Korla relies on irrigation from the Kongque River, which originates from the nearby Tianshan mountain range. Korla has favorable environmental conditions for fruit production because of the relatively large difference between day and night temperatures and sunny conditions, which favors sugar accumulation in fruits. The focal pear orchards were embedded in landscapes that were dominated by pear and cotton, but also comprised other arable crops, such as maize, sugar beet, and vegetables, as well as fruit trees, such as peach, apricot, plum, and jujube.

3.2.2 Orchard selection

In 2018, 2019, 2020, and 2021, 12, 16, 11, and 12 orchards were selected, respectively, and each year new orchards were selected. Candidate orchards were selected after a preliminary screening through Google Earth. The selected orchards had the following characteristics: 1) the pear trees were 15-20 years old; 2) orchards contained the Korla fragrant pear (*Pyrus sinkiangensis*) as the main cultivar tree and Dangshan pear (*P. bretschneideri*) as pollinizer trees; 3) the tree row spacing was approximately 5 x 6 m; and 4) the minimum distance between orchards was at least 4 km in each year. The average orchard size was 1.7 ± 0.2 ha (range 0.1 - 7.1 ha).

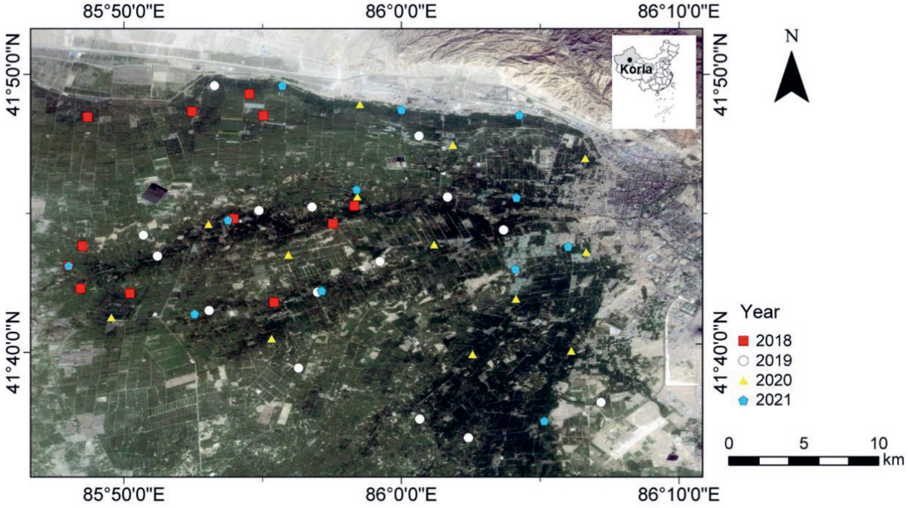

Figure 3.1 Location of 52 Korla fragrant pear orchards near Korla, Xinjiang, China, which were studied from 2018 to 2021. Each year new orchards were selected.

Korla fragrant pear flowered for two weeks in early April and pears were harvested in early September. All orchards were managed according to standard local conventional practices, including the use of artificial fertilizers, application of herbicides and fungicides, and application of boron-based growth regulators to enhance fruit set. Synthetic insecticides were regularly applied during the growing season, except for one week before pear flowering until the end of flowering to avoid direct impacts on pollinators. None of the selected orchards contained honeybee hives during blooming. In the winter, the tree trunks of some orchards were painted with quicklime and polysulfide-containing paint to prevent the bark from cracking and entry of pathogens and insects. In addition, yellow plastic rings were tied around tree trunks to prevent overwintering pests climbing the trees from the ground in spring.

3.2.3 Sampling of bee communities in pear orchards

The wild bee communities in Korla fragrant pear orchards were sampled using colored pan trap sampling during pear flowering (Westphal et al., 2008; Zou et al., 2017). Pan trap stations consisted of three cups that were painted ultraviolet (UV) yellow, UV blue, and UV white on both the inside and outside and fixed on three different branches of the same pear tree. In each orchard, four trap stations were arranged in a square in the middle of the orchard, and trees with pan traps were spaced approximately 30 m apart (Figure 3.2b). Trees with pan traps were always located further than 20 m from the edge of the orchard. Sampling was conducted from the end of March to the middle of April each year (7, 15, 10, and 12 days in 2018, 2019, 2020, and 2021, respectively). The high variation in sampling periods between years was due to weather conditions, and time and labor constraints, especially in 2018. Wild bee samples of each orchard were pooled, sorted, pinned, and identified to species level when possible.

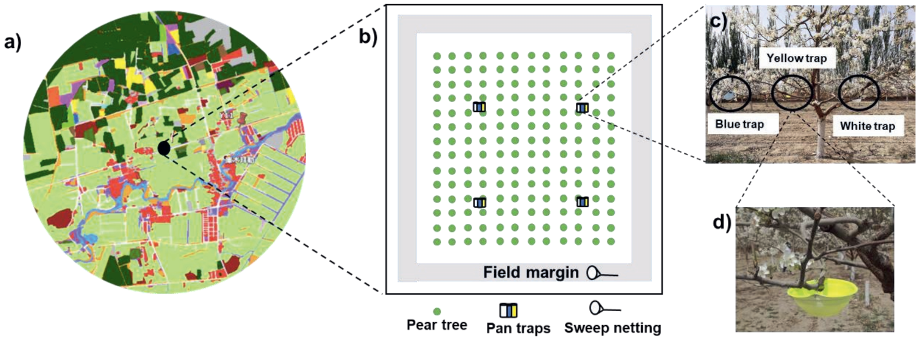

Figure 3.2 Example of a Korla fragrant pear orchard (the solid circle in black) and land use types in the surrounding landscape (a), schematic diagram of the experimental design in Korla fragrant pear orchards (b), Korla fragrant pear tree with a yellow, blue, and white pan trap (c), and a close-up of a yellow pan trap (d).

3.2.4 Sampling of wild bee communities on wild plants

We selected ten wild plant species that were common in the margins of pear orchards (Figure 3.3 and Table S3.1). For each plant species, we selected three orchards where the plant was abundant in the orchard margin, and for each orchard five 1 x 1 m^2 plots were selected to monitor the abundance of wild bees on the focal wild plant species. Each plot was sampled by sweep netting, and the catches were put in plastic bags, taken to the lab, and kept at -20°C until further processing. Sampling was conducted after pear flowering at weekly intervals from May to August 2020 and 2021. There were 11 sampling rounds in 2020 (3 rounds in May, 4 rounds in June, and 4 rounds in July) and 15 rounds in 2021 (2 rounds in May, 4 rounds in June, 5 rounds in July, and 4 rounds in August). No sampling was possible in August 2020 because of a curfew during a Covid-19 outbreak. Because in some cases the field margins were mown and sampling was not meaningful, we sampled 1585 out of 1650 potential plots in 2020 (5 plots/orchard x 3 orchards/plant species x 10 plant species/round x 11 rounds = 1650 plots) and 2088 out of 2250 plots in 2021 (Table S3.2 & S3.3).

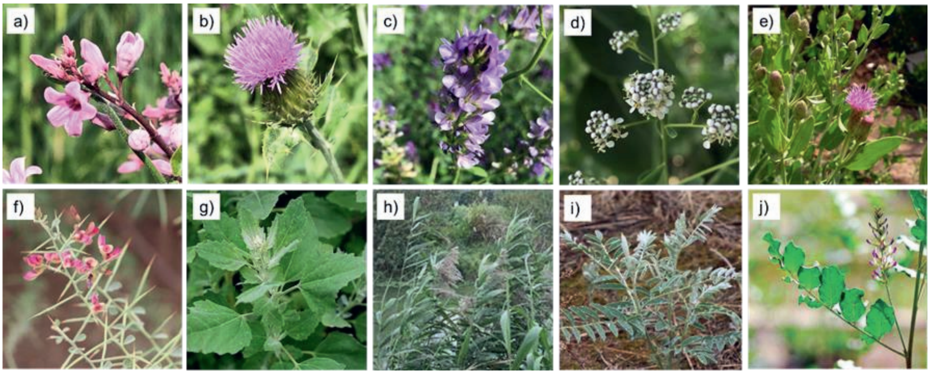

Figure 3.3 Ten common wild plant species which were sampled by sweep netting in the field margins of pear orchards: a) *Apocynum venetum*; b) *Cirsium arvense;* c) *Medicago sativa*; d) *Lepidium latifolium*; e) *Karelinia caspia*; f) *Alhagi sparsifolia*; g) *Chenopodium album*; h) *Phragmites australis*; i) *Sophora alopecuroides*; j) *Glycyrrhiza uralensis*. These photos were taken by Qian Li.

3.2.5 Land use survey

The land use in the landscape surrounding the focal fields was identified within a 2.0 km radius in September of every year from 2018 to 2021. Firstly, the coordinates of each orchard were determined to obtain the open-assess satellite imagery with a 2.0 km radius of each focal orchard using Google Earth. Secondly, the land use types on the maps were verified by ground truthing. Thirdly, the maps were digitized in

ArcGIS 10.8 to calculate the percentage of each land use type around each orchard. A total of 16 land use types were classified into seven categories: annual crops (22.2 ± 2.3%, including cotton, sugar beet, maize, vegetables, and watermelon), perennial crops (46.8 ± 2.0%, including pear, jujube, peach, apricot, and walnut), semi-natural habitats (7.8 ± 0.5%, including tree and grass belts), barren land (9.1 ± 1.2%, including bare fallow fields and weedy but uncultivated fields), infrastructure (6.6 ± 0.9%, including roads and open space), village (6.8 ± 0.9%), and water (0.7 ± 0.1%) (Table S3.4 and S3.5).

3.2.6 Data analysis

We conducted three analyses. Firstly, we explored the relationship between wild bee communities and land use types using generalized linear models (GLM) with a negative binomial error distribution for cumulative landscape sectors (i.e. concentric circles with 0.5, 1.0, 1.5, and 2.0 radius) and individual landscape sectors (i.e. a 0.5 km radius circle and rings for increasing size for the other three spatial scales) (Bianchi et al., 2008). The response variables were wild bee abundance and species richness, and the explanatory variables were the percentage of seven land use types and year. Due to a significant positive correlation between perennial crops and annual crops, we excluded the perennial crops from the model (Table S3.5). To account for differences in the number of sampling days during pan trapping we included the log-transformed sampling days as an offset variable in the full model (Zuur et al., 2009). In ecological terms, this means that the response variable is now expressed as the number of wild bees per day. In addition, a linear model (LM) with normal error distribution was used to assess the effect of land use types on the Shannon entropy of wild bee communities (Jost, 2006). The explanatory variables were the same as above. Variance inflation factor (VIF) values for the explanatory variables in each global model were calculated and were found to be less than four, indicating that covariation between explanatory variables was not a problem. Bias-corrected Akaike’s information criterion (AICc, corrected for small sample sizes) was used to rank and select all alternative candidate models (Burnham and Anderson, 2004). The relative importance of explanatory variables was quantified by the sum of the Akaike weights associated with each variable in models in the top model set (Grueber et al., 2011). All candidate models were selected in the model averaging procedure, from which we derived the importance value and coefficient estimates for each variable. The full average results were used, i.e. a model without a given predictor would contribute a value of 0 to the calculation of the weighted mean coefficient across models of that predictor (Grueber et al., 2011).

Secondly, we also conducted a follow-up analysis to explore the relationship between the three most abundant wild bee species separately (i.e. *A. yamagishi*, *L. pseudannulipes, and L. niveocinctum*) and land use variables. The procedure was the same as for the first analysis.

Thirdly, we explored the relationship between wild bee abundance in field margin plots (pooled abundance data of five plots per orchard, response variable) and wild plant species, the month of sampling, and year (explanatory variables) using a generalized linear mixed model with a negative binomial error distribution. The identifiers “orchard ID” and “plot ID” were included as random factors.

Models were validated using histograms of normalized residuals and plots of residuals against fitted values (Zuur et al., 2013). All calculations and analyses were conducted in R version 4.0.5 (R Core Team, 2018), using the functions “glmer.nb” and “lmer” in the “lme4” package for fitting models (Bates et al., 2015), and the functions “dredge” and “model.avg” in “MuMIn” package for model selection and model averaging (Bartoń, 2017). Means and standard errors of the mean are reported throughout the text.

3.3 Results

3.3.1 Wild bee abundance, species richness, and diversity in pear orchards

A total of 3594 individuals of 28 species from 11 genera were collected in 52 sites over four years (Table S3.6). The three most abundant wild bee species in pear orchards were *Andrena yamagishi* (57%), *Lasioglossum pseudannulipes* (17%), and *Lasioglossum niveocinctum* (16%). Together, these three species accounted for 90% of the catches.

Total wild bee abundance across orchards ranged from 4 to 289 (69.1 ± 7.8), species richness ranged from 2 to 9 (4.9 ± 0.2) and Shannon entropy ranged from 0.45 to 1.66 (1.1 ± 0.1).

3.3.2 Landscape effect on wild bee abundance, richness, and diversity

The pooled species analysis based on circles showed that the total wild bee abundance was significantly positively associated with semi-natural habitat (1.0 km and 1.5 km) (Table 3.1, Figure 3.4c, e) and annual crops (2.0 km) (Table 3.1, Figure 3.5g), and significantly negatively associated with infrastructure (1.0 km) (Table 3.1, Figure S3.1c). The species-specific analyses based on circles showed significant positive associations between the abundance of *A. yamagishi* and semi-natural habitats (Table 3.1, Figure 3.4b, d, f, h) and the abundance of *L. pseudannulipes* and annual crops (Table 3.1, Figure 3.5b, d, f, h) across four spatial scales.

The analyses on landscape data in cumulative landscape sectors (circle analysis) (Table S3.7-S3.14) and individual landscape sectors (ring analysis) (Table S3.15-S3.22) resulted in similar significance levels (Table 3.1).

Neither wild bee richness nor diversity was significantly associated with landscape context (Table S3.23-30).

Table 3.1 Significance levels of landscape variables on total wild bee abundance and the three most abundant species in cumulative landscape sectors (circle analysis) and individual landscape sectors (ring analysis). These results are based on the model averaging results in Table S3.7-S3.22. Significance codes: *** < 0.001; ** < 0.01; * < 0.05; (0.05 ≤ P < 0.1); NS non-significant differences. The symbols (+/-) indicate positive/negative relationships.

	Predictor	Analysis based on circles (km)				Analysis based on ring (km)			
		0.5	1.0	1.5	2.0	0.5	1.0	1.5	2.0
Total wild bee abundance	Infrastructure	NS	* (-)	NS	NS	NS	* (-)	NS	NS
	SNH	NS	. (+)	* (+)	. (+)	NS	. (+)	* (+)	NS
	Barren land	NS	NS	NS	NS	NS	NS	NS	NS
	Annual crops	NS	NS	NS	* (+)	NS	NS	** (+)	*** (+)
	Village	NS	NS	NS	NS	NS	NS	NS	NS
	Water	NS	NS	NS	NS	NS	NS	NS	NS
Andrena yamagishi	Infrastructure	. (-)	NS	NS	NS	. (-)	NS	NS	NS
	SNH	*** (+)	*** (+)	*** (+)	*** (+)	*** (+)	*** (+)	*** (+)	*** (+)
	Barren land	NS	NS	NS	NS	NS	NS	NS	NS
	Annual crops	NS	NS	NS	NS	NS	. (+)	. (+)	NS
	Village	NS	NS	NS	NS	NS	NS	NS	NS
	Water	NS	NS	NS	NS	NS	NS	NS	NS
Lasioglossum pseudannulipes	Infrastructure	NS	NS	NS	NS	NS	NS	NS	NS
	SNH	NS	NS	NS	NS	NS	NS	NS	NS
	Barren land	NS	NS	NS	NS	NS	NS	NS	NS
	Annual crops	** (+)	*** (+)	*** (+)	*** (+)	** (+)	*** (+)	*** (+)	*** (+)
	Village	NS	NS	NS	NS	NS	NS	NS	NS
	Water	NS	NS	NS	NS	NS	NS	NS	NS
Lasioglossum niveocinctum	Infrastructure	NS	NS	. (-)	. (-)	NS	NS	NS	NS
	SNH	NS	NS	NS	NS	NS	NS	NS	NS
	Barren land	NS	NS	. (-)	NS	NS	NS	NS	NS
	Annual crops	NS	NS	NS	NS	NS	NS	NS	NS
	Village	NS	NS	NS	NS	NS	NS	NS	NS
	Water	NS	NS	NS	NS	NS	NS	NS	NS

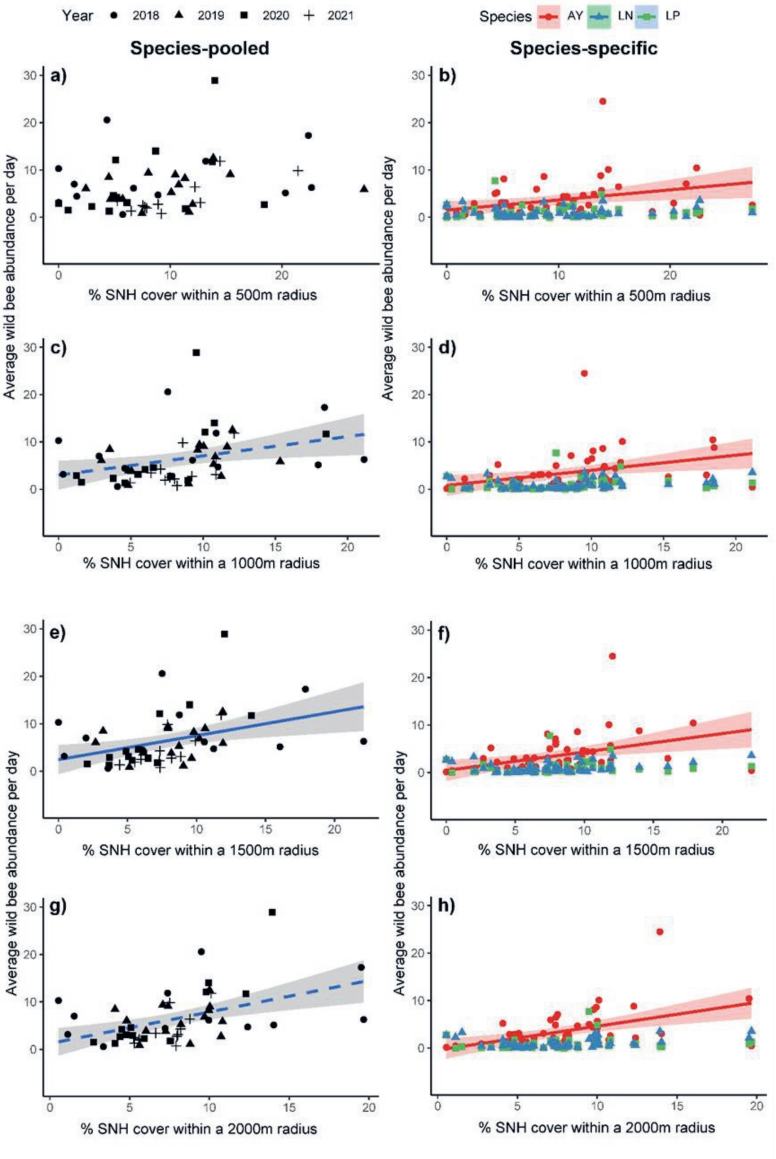

Figure 3.4 Response of total wild bee abundance (left) and three most abundant wild bee species abundance (right) to semi-natural habitats cover at four spatial scales based on the circle analysis (cumulative landscape sectors). Different symbols in the panels on the left represent data from different years. Different colors in the panels on the right represent different species: AY = *Andrena yamagishi* (red), LP = *Lasioglossum pseudannulipes* (blue), and LN = *Lasioglossum niveocinctum* (green). Solid and dashed lines indicate significant ($P < 0.05$) and marginally significant relationships ($P < 0.1$).

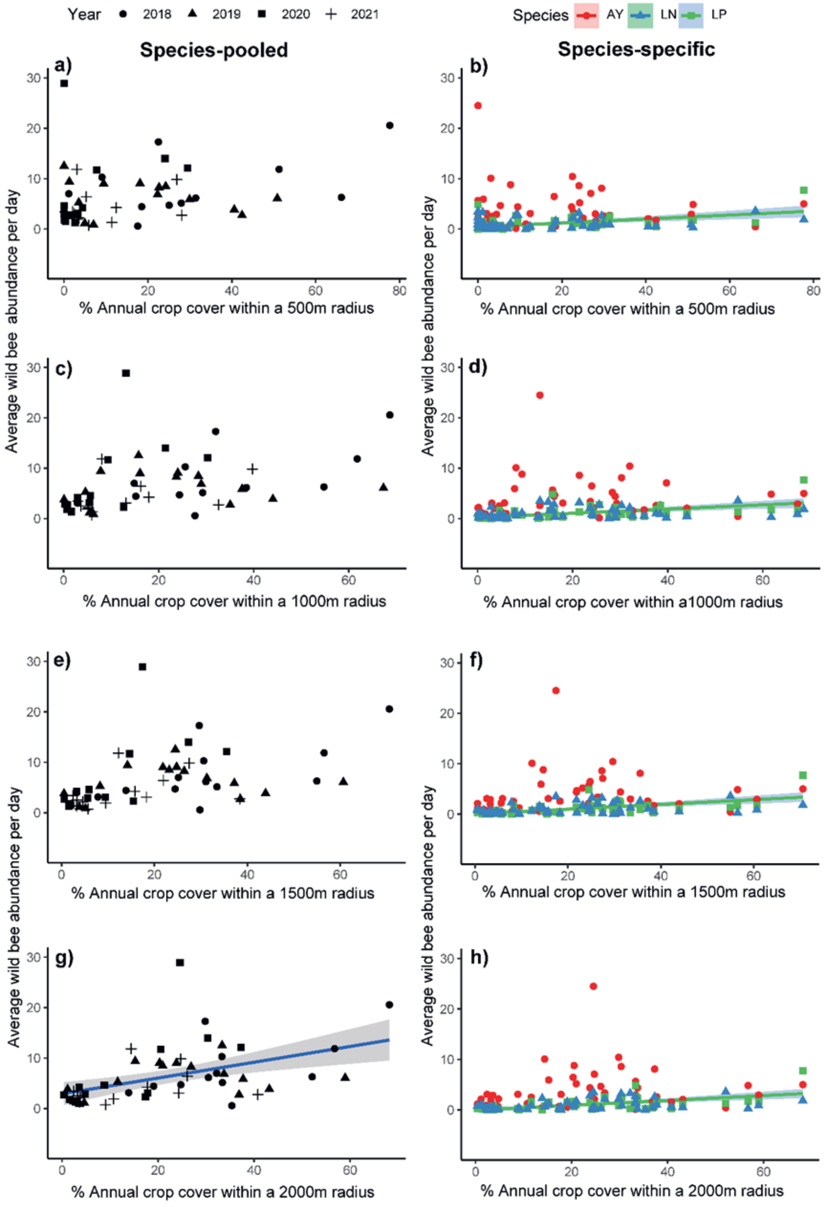

Figure 3.5 Response of total wild bee abundance (left) and three most abundant wild bee species abundance (right) to annual crop cover at four spatial scales based on the circle analysis (cumulative landscape sectors). Different symbols in the panels on the left represent data from different years. Different colors in the panels on the right represent different species: AY = *Andrena yamagishi* (red), LP = *Lasioglossum pseudannulipes* (blue), and LN = *Lasioglossum niveocinctum* (green). Solid and dashed lines indicate significant ($P < 0.05$) and marginally significant relationships ($P < 0.1$).

3.3.3 Wild bee abundance in wild plant species

In 2020, we collected 179 individual wild bees on 10 wild plant species in 1585 plots (75, 29, and 75 individuals in May, July, and July, respectively), and in 2021 142 individuals in 2088 plots (12, 33, 53, and 44 individuals in May, June, July, and August, respectively). The wild bee abundance was significantly higher on *Medicago sativa* (P = 0.001) and *Apocynum venetum* (P = 0.021) than on the other plant species, while the wild bee abundance on *Alhagi sparsifolia* was significantly lower than on the other plant species (P = 0.021). The wild bee abundance was significantly lower in 2021 than in 2020, and it was significantly lower in June than in May (Figure 3.6 and Table S3.31).

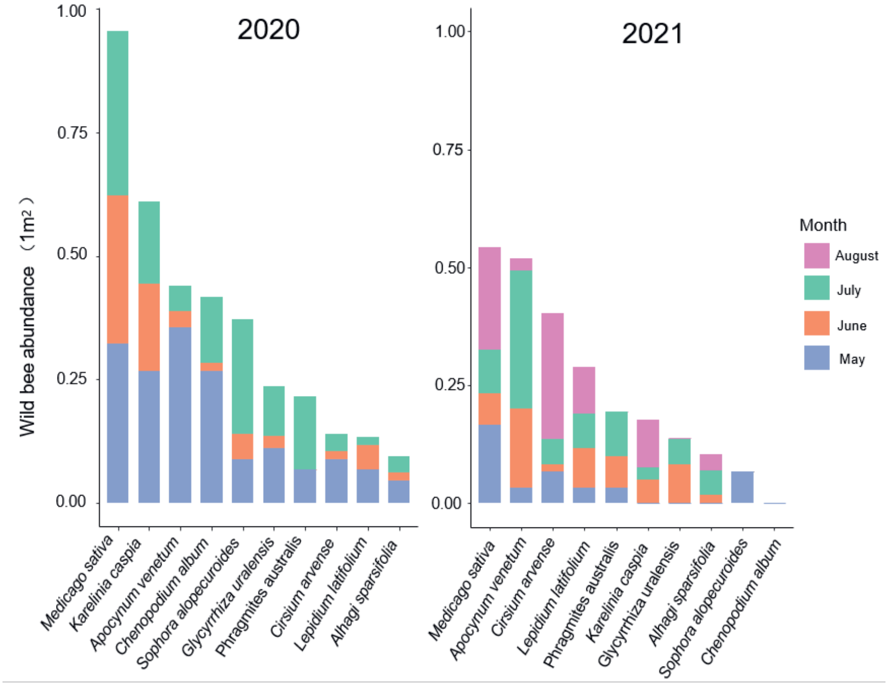

Figure 3.6 Wild bee abundance on 10 flowering plant species during 11 rounds in 2020 and 15 rounds in 2021. The wild bee abundance was averaged across plots per orchard per round and per month. Different colors represent different months. No sampling was possible in August 2020 because of a curfew during a Covid-19 outbreak.

3.4 Discussion

Wild bee communities are instrumental for the pollination of wild and cultivated plants, but these communities are hardly documented in Xinjiang, China, and their ecological prerequisites are not well known. We assessed wild bee communities in 52 Korla fragrant pear orchards and report four main findings: (i) the three most abundant wild bee species in pear orchards were *A. yamagishi*, *L. pseudannulipes*, and *L. niveocinctum*; (ii) the three most abundant wild bee species showed contrasting responses to land use; (iii) wild bee richness and diversity was not related to landscape context; and (iv) the presence of *Medicago sativa* and *Apocynum venetum* in semi-natural habitat of orchard margins can support higher wild bee abundance after pear blooming.

3.4.1 Wild bee communities in pear orchards

We identified 28 wild bee species in 3594 individuals in pan trap catches, and *A. yamagishi*, *L. pseudannulipes*, and *L. niveocinctum* accounted for 90% of the catches. Our results fit in a general pattern that a small proportion of bee species account for the majority of the sample (e.g. Kleijn et al., 2015; Zou et al., 2017). Bee species from the Andrenidae and Halictidae are common in fruit crops, such as peach and apple (Dar et al., 2021; Watson et al., 2011). However, the abundance of wild bees in our catches was relatively low compared to reported abundances in other fruit crop species. For example, the wild bee abundance in our catches was 5.6 times lower than in jujube orchards in Aksu, Xinjiang, China (0.5 vs 2.7 individuals /site/day/trap) (Li et al., 2022), and it was 2.5 times lower than in apple orchards in Shanxi, China (0.5 vs 1.2 individuals /site/day/trap) (Wu et al., 2021b). This relatively low abundance of wild bees could be explained by the low attractiveness of Korla fragrant pear for wild bees, reflected by low visitation rates of wild bees on pear flowers (Li et al., 2022). Therefore, the wild bees collected in the colored pan traps were most likely attracted to the traps rather than to the pear flowers because the wild bee abundance in yellow traps was higher than in the white traps (Figure S3.2), which is the color of pear flowers. Although wild bee communities provide only a limited contribution to the pollination of Korla fragrant pear (Li et al., 2022), they may contribute to the pollination of other fruit crop species (e.g. apricot, peach and plum) and insect-pollinated wild plants, because the wild bees visited on these fruit crop species and wild plants in our study region (pers. obse.).This underlines the critical role of maintaining non-pear flowering plants for the conservation of wild bee communities in the Korla pear production region.

3.4.2 Wild bee species-specific responses to land use

Our analysis with pooled abundances of wild bee species indicated that the wild bee abundance was positively associated with semi-natural habitats and annual crops, and negatively associated with infrastructure. However, these associations were only significant at spatial scales of 1 km and larger (Table 3.1), which is unexpected because the foraging distance of most wild bees is often less than 1 km (Steffan-Dewenter et al., 2002). This apparent scale mismatch may be an artefact from pooling abundances of wild bee species with contrasting habitat use. Indeed, the analysis for *A. yamagishi*, *L. pseudannulipes*, and *L. niveocinctum* separately indicated species-specific responses to land use types, and relationships were more or less consistent across 0.5 to 2 km (Table 3.1).

Generally, the wild bee abundance was expected to be promoted by semi-natural habitat (Maurer et al., 2022). However, only the abundance of *A. yamagishi*, but not the other two species, showed a significant association with semi-natural habitats, which could be explained by species-specific preferences for particular flowering plant species. Many bee species in the genus *Andrena* are host-plant specialists, exhibiting a narrow, specialized preference for pollen sources in some plant taxonomic groups, such as Brassicaceae and Fabaceae (Larkin et al., 2008). These potential host plant taxonomic groups also can be found in the semi-natural habitats in our study region (Table S3.3), which could be used by *A. yamagishi.*

The abundance of *L. pseudannulipes* was positively associated with annual crops, mostly cotton, and some maize, sugar beet and cabbage crops. This is surprising because annual crop fields were still bare during our sampling period and frequently treated with insecticides during the growing season. However, annual crop cover was significantly negatively associated with perennial crop cover (Figure S3 & S4), so the positive response of *L. pseudannulipes* to annual crops may have been spurious and driven by a negative response of *L. pseudannulipes* to perennial crop cover (Table S3.2 & 3.3). Perennial crops in our study region were dominated by pears, which were mass-flowering during our sampling period. Thus, the negative association between *L. pseudannulipes* and perennial crops may reflect a dilution effect of mass-flowering pears on wild bees (Holzschuh et al., 2016). Alternatively, the negative association with perennial crop may also be related to the poor quality of pears as a source of nectar for bees (Monzón et al., 2004; Quinet et al., 2016).

L. niveocinctum only showed weak responses to land use types (negative association with infrastructure at 2 km in the circle analysis, but not in the ring analysis; Table 3.1), indicating that the classification of land use types in our study did not capture the ecological requirements of this species (Fahrig et al., 2011). The contrasting responses between the two closely related *Lasioglossum* species were surprising and indicate that species within the same genus may still have clearly different ecological requirements. Overall, our findings imply that the analysis of pooled abundances of species may mask species-specific responses, and that the separate analysis of abundant species may provide important new insights that may have been overlooked by the standard procedure of the analysis of the pooled abundance data.

3.4.3 Wild bee species richness and diversity responses to land use types

Contrary to findings of previous studies (Alomar et al., 2018; Eeraerts et al., 2020; Garibaldi et al., 2011; St. Clair et al., 2022), neither wild bee species richness nor diversity was significantly associated with landscape context in our study. We expected that the variation in species richness (4.9 ± 0.2, range 2 to 9), Shannon entropy (1.1 ± 0.1, range 0.5 to 1.7) and land use types should be sufficient to detect possible relationships, but these were not found. There are two possible explanations. Firstly, wild bee richness and diversity are not only related to habitat quantity, but also to other factors, such as habitat quality (Franzén and Nilsson, 2010). As wild bees are often adapted to particular habitats, the number of different habitat types available in agricultural landscapes is an important factor supporting species richness (Maurer et al., 2022). Our study area consisted largely of pear and cotton and a few other crops, which suggests the habitat diversity in our study region could be too low to support a diversified wild bee community. The second possible reason could be that our land use types did not effectively capture variation in ecological requirements for wild bees in the landscape, underlying the need for more ecologically-based land use metrics (Farig et al., 2011). Overall, our results suggest solely creating more of the same type of resource habitats (e.g. mass-flowering Korla fragrant pear) may not be enough to support a diversified wild bee community (Bukovinszky et al., 2017).

3.4.4 Wild bee abundance in wild plants in field margin

Flowering wild plant species in the margins of orchards, such as *Medicago sativa* and *Apocynum venetum*, may support wild bee communities after pear blooming. Solitary wild bee species are often only active during a relatively short period during the growing season. For example, *A. yamagishi* emerged in the early spring, and alfalfa leafcutting bees, *Megachile rotundata*, forage only several weeks in the summer in our study region (*pers. obs.*). Therefore, plants that flower during different parts of the growing season may provide floral resources for different wild bee species (Mallinger et al., 2016; Mandelik et al., 2012). Maintaining species rich flowering plant communities in field margins by tailored mowing schemes and refraining from herbicide applications can be a low-cost management option for farmers to support wild bee communities.

3.5 Conclusion

Our four-year study indicated that wild bees in Korla fragrant pear orchards respond in a species-specific way. This highlights the need for (i) conducting landscape analyses at the species or functional group level, if possible, rather than for pooled communities, and (ii) to develop metrics to characterize land use that better capture the ecological requisites of wild bees than standard land use classes. The adoption of pollinator-friendly orchard management, for instance by the establishment and conservation of flower-rich wild plant communities' species in field margins and reducing insecticide use, may help to counteract the decline of wild bee populations in intensively managed pear production landscapes in Xinjiang.

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Supplementary Information

Table S3.1 Plant species traits of ten common wild plant species in the field margins of pear orchards in Korla, Xinjiang, China. Annual and perennial plants are indicated by A and P, respectively.

Family	**Species**	**Flowering period**	**Life cycle**
Leguminosae	*Glycyrrhiza uralensis*	May to June	P
	Alhagi sparsfolia	Middle June-middle July	P
	Sophora alopecuroides	Middle-May to end-June	P
	Medicago sativa	May to August	P
Apocynaceae	*Apocynum venetum*	June to July	P
Brassicaceae	*Lepidium latifolium*	May to July	P
Poaceae	*Phragmites australis*	End-July to August	P
Chenopodiaceae	*Chenopodium album*	July-August	A
Compositae	*Karelinia caspia*	Middle-June to Middle-August	P
	Cirsium arvense	June to August	P

Table S3.2 Sampling periods of 10 plant species in 2020. Ticks indicate conducted samplings during 11 sampling rounds. The number in the row of headers indicated the different sampling rounds.

Wild plant species	Sites	May				June					July	
		1	2	3	4	5	6	7	8	9	10	11
Apocynum venetum	1	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	2	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	3	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Cirsium arvense	4	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	5	☑	☑	☑	☑	☑	☑	☑	☑		☑	☑
	6	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Medicago sativa	7	☑	☑	☑			☑	☑	☑	☑	☑	☑
	8	☑	☑	☑			☑	☑	☑	☑	☑	☑
	9	☑	☑				☑	☑	☑	☑	☑	☑
Lepidium latifolium	10	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	11	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	12	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Karelinia caspia	13	☑	☑	☑		☑	☑	☑	☑	☑	☑	☑
	14	☑	☑	☑		☑	☑	☑	☑	☑	☑	☑
	15	☑	☑	☑		☑	☑	☑	☑	☑	☑	☑
Alhagi sparsifolia	16	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	17	☑	☑	☑		☑	☑	☑	☑	☑	☑	☑
	18	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	
Chenopodium album	19	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	20	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	21	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Phragmites australis	22	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	23	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	24	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Sophora alopecuroides	25	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	26	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	27	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Glycyrrhiza uralensis	28	☑	☑	☑	☑	☑	☑		☑	☑	☑	☑
	29	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	30	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑

Table S3.3 Sampling periods of 10 plant species in 2021. Ticks indicate conducted samplings during 11 sampling rounds. The number in the row of headers indicated the different sampling rounds.

Wild plant species	Sites	May			June					July				August		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Apocynum venetum	1	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	2	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	3	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑				
Cirsium arvense	4	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	5	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	6	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Medicago sativa	7	☑	☑	☑	☑	☑	☑	☑		☑	☑	☑	☑	☑	☑	☑
	8	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	9	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Lepidium latifolium	10	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	11	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	12	☑	☑	☑	☑	☑	☑	☑		☑	☑	☑	☑	☑	☑	☑
Karelinia caspia	13	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	14	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	15	☑	☑	☑	☑	☑	☑	☑		☑	☑	☑	☑	☑	☑	☑
Alhagi sparsifolia	16	☑	☑	☑	☑	☑	☑	☑		☑	☑	☑	☑	☑	☑	☑
	17	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	18	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Chenopodium album	19	☑	☑	☑	☑	☑										
	20	☑	☑	☑	☑	☑										
	21	☑	☑	☑	☑	☑										
Phragmites australis	22	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	23	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	24	☑	☑	☑	☑	☑	☑	☑		☑	☑	☑	☑	☑	☑	☑
Sophora alopecuroides	25	☑	☑	☑	☑	☑	☑	☑		☑	☑	☑	☑	☑	☑	☑
	26	☑	☑	☑												
	27	☑	☑													
Glycyrrhiza uralensis	28	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
	29	☑	☑	☑	☑	☑	☑	☑		☑	☑	☑	☑	☑	☑	☑
	30	☑	☑	☑	☑	☑	☑	☑		☑	☑	☑	☑	☑	☑	☑

Table S3.4 Description of 16 land use types

	Land use types	Category	Description
1	Cotton	Annual crop	Cotton
2	Pear	Perennial crop	Pear orchard
3	Apricot	Perennial crop	Apricot orchard
4	Peach	Perennial crop	Peach orchard
5	Jujube	Perennial crop	Jujube orchard
6	Grape	Perennial crop	Grape orchard
7	Maize	Annual crop	Maize
8	Vegetable	Annual crop	Cabbage, sugar beet, peanut, and greenhouse
9	Alfalfa	Annual crop	Alfalfa
10	Grass belt	Semi-natural habitat	The grass belt in the field margin
11	Tree belt	Semi-natural habitat	The tree belt in the field margin or roadside
12	Barren land	Wasteland	Fallow and uncultured land
13	Road	infrastructure	Concrete pavements and country roads without concrete
14	Open space	infrastructure	The space that with hardened pavement, such as a factory
15	Village	Village	The clustered human settlement or community, normally with fixed dwellings, gardens, and trees
16	Water	Water	River

Table S3.5 The percentage of each land use type at four spatial scales in Korla, Xinjiang, China from 2018 to 2020.

Scales	Land use types	Average (%)	SE (%)	Min (%)	Max (%)
500m	Annual crops	15.30	2.50	0.00	77.68
	Perennial crops	54.31	2.49	5.61	88.24
	Semi-natural habitat	9.77	1.17	0.00	51.44
	Barren land	5.21	0.86	0.00	31.80
	Infrastructure	6.72	0.93	0.68	39.72
	Village	8.08	1.35	0.00	46.08
	Water	0.61	0.16	0.00	4.94
1000m	Annual crops	19.29	2.46	0.09	68.64
	Perennial crops	49.69	2.18	7.76	81.08
	Semi-natural habitat	8.38	0.63	0.00	21.14
	Barren land	9.03	1.03	0.00	47.31
	Infrastructure	7.17	1.05	1.14	39.62
	Village	7.63	1.20	0.00	41.26
	Water	0.68	0.13	0.00	2.71
1500m	Annual crops	20.69	2.33	0.55	70.55
	Perennial crops	48.28	2.03	10.62	76.90
	Semi-natural habitat	7.83	0.58	0.00	22.11
	Barren land	9.03	1.39	0.00	47.31
	Infrastructure	6.69	0.99	1.16	40.80
	Village	6.80	0.87	0.45	32.92
	Water	0.67	0.11	0.00	3.31
2000m	Annual crops	22.19	2.28	0.41	68.16
	Perennial crops	46.78	1.96	16.06	73.82
	Semi-natural habitat	7.77	0.53	0.54	19.67
	Barren land	9.12	1.24	0.22	42.39
	Infrastructure	6.62	0.93	1.23	33.70
	Village	6.81	0.94	0.83	35.91
	Water	0.70	0.12	0.00	4.63

Table S3.6 Species composition of wild bee community in 52 Korla fragrant pear orchards from 2018 to 2022.

	Species	Family	Abundance
1	*Andrena yamagishi*	Andrenidae	2044
2	*Lasioglossum pseudannulipes*	Halictidae	595
3	*Lasioglossum niveocinctum*	Halictidae	559
4	*Andrena gelriae*	Andrenidae	40
5	*Halictus pulvereus*	Halictidae	22
6	*Halictus leucaheneus*	Halictidae	14
7	*Osmia excavata*	Megachilidae	14
8	*Pemphredon* sp.	Sphecidae	12
9	*Lasioglossum* sp.	Halictidae	8
10	*Lasioglossum* sp1	Halictidae	6
11	*Halictus tectus*	Halictidae	5
12	*Podalonia Obo*	Sphecidae	5
13	*Lasioglossum agelastum*	Halictidae	4
14	*Lasioglossum* sp2	Halictidae	4
15	*Lasioglossum* sp3	Halictidae	4
16	*Lasioglossum affine*	Halictidae	4
17	*Lasioglossum problematicum*	Halictidae	3
18	*Dasypoda hirtipes*	Melittidae	3
19	*Halictus pollinosus*	Halictidae	2
20	*Lasioglossum* sp.	Halictidae	2
21	*Megachile desertorum subsp. tsinanensis*	Megactlilidae	2
22	*Osmia* sp.	Megachilidae	2
23	*Anthophora mongolica*	Apidae	2
24	*Lasioglossum* sp4	Halictidae	1
25	*Lasioglossum margelanicum*	Halictidae	1
26	*Osmia turkestanica*	Megachilidae	1
27	*Amegilla quadrifasciata*	Apidae	1
28	*Groytes* sp.	Sphecidae	1
29		unidentified	233

Note: The term “unidentified” indicated that the specimens were damaged in the field or lab and cannot be identified

Table S3.7 Most parsimonious models (ΔAICc < 2) resulting from model selection of all combinations of terms from global models that assessed the effect of land use types on **total wild bee abundance** for cumulative landscape sectors at four spatial scales (**circle analysis).** k, number of parameters of each model; LogLik, log-likelihood of the model; AICc, Akaike's Information Criterion corrected for small sample size; ΔAICc, the difference in AICc value between a model and the best ranked model; Weight, Akaike weight, which can be interpreted as the conditional probabilities for each candidate model.

Scale (km)	Model	k	logLik	AICc	ΔAICc	Weight
0.5	Intercept+Infrastructure+SNH+Waste land+log(days)	5	-261.69	534.7	0.00	0.078
	Intercept+Infrastructure+SNH+log(days)	4	-263.12	535.1	0.39	0.064
	Intercept+Annual +Infrastructure+SNH+Waste land+log(days)	6	-260.69	535.3	0.56	0.059
	Intercept+Annual+Infrastructure+SNH+log(days)	5	-262.23	535.8	1.08	0.045
	Intercept+Infrastructure+SNH+Village+Waste land+log(days)	6	-261.35	536.6	1.87	0.031
1.0	Intercept+Annual+Infrastructure+SNH+log(days)	5	-257.38	526.1	0.00	0.123
	Intercept+Annual+Infrastructure+SNH+Village+log(days)	6	-256.38	526.6	0.52	0.095
	Intercept+Infrastructure+SNH+Waste land+log(days)	5	-257.99	527.3	1.24	0.066
	Intercept+Infrastructure+SNH+log(days)	4	-259.35	527.6	1.49	0.058
	Intercept+Infrastructure+SNH+Village +log(days)	5	-258.21	527.7	1.66	0.054
	Intercept+Infrastructure+SNH+Village+Waste land+log(days)	6	-257.05	528	1.9	0.048
1.5	Intercept+Annual+Infrastructure+SNH+log(days)	5	-255.50	522.3	0.00	0.155
	Intercept+Annual+Infrastructure+SNH+Waste land+log(days)	6	-254.60	523.1	0.77	0.105
	Intercept+Annual+Infrastructure+SNH+Water+log(days)	6	-255.01	523.9	1.58	0.07
	Intercept+Annual+Infrastructure+SNH+Village+log(days)	6	-255.18	524.2	1.94	0.059
2.0	Intercept+Annual+Infrastructure+SNH+Water +log(days)	6	-252.52	518.9	0.00	0.158
	Intercept+Annual+Infrastructure+SNH+log(days)	5	-254.01	519.3	0.41	0.129
	Intercept+Annual+SNH+Water+log(days)	5	-254.21	519.7	0.81	0.105
	Intercept+Annual+SNH+log(days)	4	-255.95	520.8	1.84	0.063

Table S3.8 Results of multi-model inference to determine the effect of land use types on **total wild bee abundance** for cumulative landscape sectors at four spatial scales (**circle analysis).** For each scale, the averaged model was taken from the total candidate models. Z value is the estimate of each coefficient divided by its standard error.

Scales (km)	Variables	Estimate	Std. Error	z value	Pr(>|z|)
0.5	(Intercept)	2.311	0.947	2.436	**0.015**
	Infrastructure	-0.031	0.022	1.409	0.159
	SNH	0.029	0.022	1.324	0.186
	Barren land	-0.014	0.018	0.773	0.440
	Annual	0.003	0.006	0.555	0.579
	Village	-0.002	0.008	0.314	0.753
	Water	-0.001	0.044	0.026	0.979
	fyear2019	0.027	0.190	0.139	0.890
	fyear2020	0.018	0.141	0.129	0.898
	fyear2021	-0.039	0.189	0.203	0.839
1.0	(Intercept)	1.916	0.842	2.268	**0.023**
	Annual	0.006	0.007	0.858	0.391
	Infrastructure	-0.041	0.017	2.419	**0.016**
	SNH	0.047	0.027	1.745	*0.081*
	Barren land	-0.009	0.013	0.660	0.509
	Village	-0.005	0.010	0.479	0.632
	Water	0.007	0.056	0.114	0.909
	fyear2019	0.039	0.192	0.200	0.841
	fyear2020	0.046	0.182	0.251	0.802
	fyear2021	0.006	0.152	0.038	0.969
1.5	(Intercept)	1.494	0.762	1.953	*0.051*
	Annual	0.013	0.009	1.399	0.162
	Infrastructure	-0.032	0.020	1.575	0.115
	SNH	0.056	0.028	1.982	**0.048**
	Barren land	-0.006	0.010	0.620	0.535
	Water	0.028	0.075	0.370	0.711
	Village	-0.008	0.016	0.519	0.604
	fyear2019	0.042	0.194	0.217	0.828
	fyear2020	0.049	0.185	0.263	0.792
	fyear2021	0.013	0.144	0.090	0.928
2.0	(Intercept)	1.027	0.567	1.801	*0.072*
	Annual	0.018	0.009	2.032	**0.042**
	Infrastructure	-0.022	0.021	1.031	0.302
	SNH	0.056	0.030	1.817	*0.069*
	Water	0.111	0.121	0.905	0.366
	Barren land	-0.001	0.005	0.129	0.897
	Village	0.000	0.008	0.024	0.981
	fyear2019	0.040	0.189	0.211	0.833
	fyear2020	0.034	0.155	0.218	0.827
	fyear2021	0.021	0.134	0.153	0.878

Table S3.9 Most parsimonious models (ΔAICc < 2) resulting from model selection of all combinations of terms from global models that assessed the effect of land use types on **the abundance of *Andrena yamagishi*** for cumulative landscape sectors at four spatial scales (**circle analysis).** k, number of parameters of each model; LogLik, log-likelihood of the model; AICc, Akaike's Information Criterion corrected for small sample size; ΔAICc, the difference in AICc value between a model and the best ranked model; Weight, Akaike weight, which can be interpreted as the conditional probabilities for each candidate model.

Scale (km)	Model	k	logLik	AICc	ΔAICc	Weight
0.5	Intercept+Infrastructure+SNH+log(days)+fyear	7	-229.21	475	0.00	0.07
	Intercept+Infrastructure+SNH+fyear	7	-229.21	475	0.00	0.07
	Intercept+Infrastructure+SNH+log(days)	4	-233.11	475.1	0.1	0.067
	Intercept+Annual+Infrastructure+SNH+fyear	8	-228.12	475.6	0.63	0.051
	Intercept+Annual+Infrastructure+SNH+log(days)+fyear	8	-228.12	475.6	0.63	0.051
	Intercept+Infrastructure+SNH+Water+log(days)	5	-232.15	475.6	0.64	0.051
	Intercept+Infrastructure+SNH+Water+log(days)+fyear	8	-228.50	476.4	1.39	0.035
	Intercept+Infrastructure+SNH+Water+log(days)+fyear	8	-228.50	476.4	1.39	0.035
	Intercept+Infrastructure+SNH+Waste land+fyear	8	-228.74	476.8	1.87	0.028
	Intercept+Infrastructure+SNH+Waste land+fyear+ log(days)	8	-228.74	476.8	1.87	0.028
1.0	Intercept+Annual+Infrastructure+SNH+fyear	8	-224.74	468.8	0.00	0.100
	Intercept+Annual+Infrastructure+SNH+fyear+ log(days)	8	-224.74	468.8	0.00	0.100
	Intercept+Annual+SNH+fyear+ log(days)	7	-226.65	469.9	1.03	0.060
	Intercept+Annual+SNH+fyear	7	-226.65	469.9	1.03	0.060
	Intercept+Annual+Infrastructure+SNH+Waste land+fyear	9	-224.20	470.7	1.85	0.040
	Intercept+Annual+Infrastructure+SNH+Waste land+fyear+log(days)	9	-224.20	470.7	1.85	0.040
	Intercept+Infrastructure+SNH+fyear	7	-227.08	470.7	1.89	0.039
	Intercept+Infrastructure+SNH+fyear+log(days)	7	-227.08	470.7	1.89	0.039
1.5	Intercept+Annual+SNH+fyear+log(days)	7	-224.07	464.7	0.00	0.109
	Intercept+Annual+SNH+fyear	7	-224.07	464.7	0.00	0.109
	Intercept+Annual+Infrastructure+SNH+fyear	8	-222.76	464.9	0.18	0.099
	Intercept+Annual+Infrastructure+SNH+fyear+log(days)	8	-222.76	464.9	0.18	0.099
2.0	Intercept+Annual+SNH+fyear+log(days)	7	-223.27	463.1	0.00	0.093
	Intercept+Annual+SNH+fyear	7	-223.27	463.1	0.00	0.093
	Intercept+Annual+SNH+Water+fyear+log(days)	8	-222.30	463.9	0.86	0.06
	Intercept+Annual+SNH+Water+fyear	8	-222.30	463.9	0.86	0.06
	Intercept+Annual+Infrastructure+SNH+Water+fyear+log(days)	8	-222.67	464.7	1.61	0.041
	Intercept+Annual+Infrastructure+SNH+Water+fyear	8	-222.67	464.7	1.61	0.041

Table S3.10 Results of multi-model inference to determine the effect of land use types on **abundance of *Andrena yamagishi*** for cumulative landscape sectors at four spatial scales (**circle analysis).** For each scale, the average model was taken from the total candidate models. Z value is the estimate of each coefficient divided by its standard error.

Scales (km)	Variables	Estimate	Std. Error	z value	Pr(>|z|)
0.5	(Intercept)	0.887	0.927	0.953	0.340
	Infrastructure	-0.048	0.026	1.856	*0.063*
	fyear2019	0.801	0.691	1.154	0.248
	fyear2020	0.873	0.691	1.258	0.209
	fyear2021	0.634	0.590	1.065	0.287
	SNH	0.081	0.021	3.868	**<0.001**
	Annual	0.003	0.007	0.457	0.648
	Water	-0.038	0.082	0.450	0.652
	Barren land	-0.006	0.014	0.406	0.684
	Village	0.000	0.007	0.063	0.950
1.0	(Intercept)	0.111	1.112	0.099	0.921
	Annual	0.013	0.011	1.115	0.265
	Infrastructure	-0.030	0.024	1.246	0.213
	fyear2019	1.224	0.614	1.978	**0.048**
	fyear2020	1.444	0.625	2.291	**0.022**
	fyear2021	1.155	0.585	1.955	*0.051*
	SNH	0.123	0.026	4.528	**<0.001**
	Barren land	-0.004	0.011	0.336	0.737
	Water	-0.027	0.086	0.306	0.759
	Village	0.000	0.007	0.034	0.973
1.5	(Intercept)	-0.378	1.130	0.333	0.739
	Annual	0.019	0.012	1.632	0.102
	fyear2019	1.379	0.575	2.381	**0.017**
	fyear2020	1.527	0.542	2.786	**0.005**
	fyear2021	1.355	0.551	2.429	**0.015**
	SNH	0.148	0.028	5.106	**<0.001**
	Infrastructure	-0.017	0.021	0.803	0.422
	Water	0.008	0.066	0.122	0.902
	Village	-0.003	0.013	0.239	0.811
	Barren land	-0.001	0.007	0.188	0.851
2.0	(Intercept)	-0.497	1.099	0.450	0.653
	Annual	0.015	0.012	1.241	0.215
	fyear2019	1.357	0.641	2.104	**0.035**
	fyear2020	1.282	0.578	2.196	**0.028**
	fyear2021	1.292	0.610	2.099	**0.036**
	SNH	0.160	0.032	4.893	**<0.001**
	Water	0.050	0.101	0.491	0.623
	Infrastructure	-0.011	0.019	0.590	0.555
	Village	0.003	0.011	0.223	0.823
	Barren land	0.001	0.007	0.148	0.883

Table S3.11 Most parsimonious models (ΔAICc < 2) resulting from model selection of all combinations of terms from global models that assessed the effect of land use types on **the abundance of *Lasioglossum pseudannulipes*** for cumulative landscape sectors at four spatial scales (**circle analysis).** k, number of parameters of each model; LogLik, log-likelihood of the model; AICc, Akaike's Information Criterion corrected for small sample size; ΔAICc, the difference in AICc value between a model and the best ranked model; Weight, Akaike weight, which can be interpreted as the conditional probabilities for each candidate model.

Scale (km)	Model	k	logLik	AICc	ΔAICc	Weight
0.5	Intercept+Annual+Water+fyear	7	-159.68	335.9	0.00	0.149
	Intercept+Annual+Water+fyear+log(days)	7	-159.68	335.9	0.00	0.149
1.0	Intercept+Annual+Water+fyear+log(days)	7	-157.47	331.5	0.00	0.112
	Intercept+Annual+Water+fyear	7	-157.47	331.5	0.00	0.112
	Intercept+Annual+SNH+Water+fyear+log(days)	8	-156.81	333	1.47	0.054
	Intercept+Annual+SNH+Water+fyear	8	-156.81	333	1.47	0.054
1.5	Intercept+Annual+fyear	6	-158.03	329.9	0.00	0.088
	Intercept+Annual+fyear+log(days)	6	-158.03	329.9	0.00	0.088
	Intercept+Annual+Water+fyear+log(days)	7	-157.01	330.6	0.63	0.064
	Intercept+Annual+Water+fyear	7	-157.01	330.6	0.63	0.064
	Intercept+Annual+SNH+fyear	7	-157.24	331	1.09	0.051
	Intercept+Annual+SNH+fyear+log(days)	7	-157.24	331	1.09	0.051
2.0	Intercept+Annual+fyear	6	-157.01	327.9	0.00	0.117
	Intercept+Annual+fyear+log(days)	6	-157.01	327.9	0.00	0.117
	Intercept+Annual+Water+fyear+log(days)	7	-156.32	329.2	1.30	0.061
	Intercept+Annual+Water+fyear	7	-156.32	329.2	1.30	0.061

Table S3.12 Results of multi-model inference to determine the effect of land use types on abundance of ***Lasioglossum pseudannulipes*** for cumulative landscape sectors at four spatial scales (**circle analysis).** For each scale, the average model was taken from the total candidate models. Z value is the estimate of each coefficient divided by its standard error.

Scales (km)	Variables	Estimate	Std. Error	z value	Pr(>|z|)
0.5	(Intercept)	0.474	1.059	0.446	0.656
	Annual	0.024	0.009	2.716	**0.007**
	fyear2019	0.743	0.500	1.472	0.141
	fyear2020	-0.650	0.438	1.454	0.146
	fyear2021	-0.525	0.475	1.087	0.277
	Water	0.155	0.121	1.257	0.209
	SNH	0.003	0.010	0.266	0.790
	Village	0.000	0.007	0.047	0.962
	Infrastructure	-0.002	0.010	0.182	0.855
	Barren land	0.001	0.009	0.128	0.899
1.0	(Intercept)	-0.072	1.088	0.066	0.948
	Annual	0.032	0.009	3.594	**<0.001**
	fyear2019	0.745	0.509	1.453	0.146
	fyear2020	-0.379	0.435	0.854	0.393
	fyear2021	-0.299	0.459	0.640	0.522
	Water	0.195	0.161	1.197	0.231
	SNH	0.012	0.022	0.543	0.587
	Infrastructure	-0.003	0.011	0.300	0.764
	Barren land	-0.002	0.010	0.196	0.844
	Village	0.000	0.008	0.036	0.972
1.5	(Intercept)	-0.052	1.083	0.048	0.962
	Annual	0.034	0.009	3.897	**<0.001**
	fyear2019	0.778	0.497	1.552	0.121
	fyear2020	-0.438	0.418	1.027	0.304
	fyear2021	-0.277	0.457	0.596	0.551
	Water	0.073	0.125	0.579	0.563
	SNH	0.012	0.023	0.521	0.602
	Village	-0.004	0.014	0.253	0.800
	Infrastructure	-0.001	0.009	0.146	0.884
	Barren land	0.001	0.007	0.079	0.937
2.0	(Intercept)	-0.155	1.062	0.145	0.884
	Annual	0.037	0.008	4.407	**<0.001**
	fyear2019	0.844	0.487	1.715	*0.086*
	fyear2020	-0.460	0.409	1.102	0.271
	fyear2021	-0.230	0.458	0.494	0.621
	Water	0.039	0.088	0.436	0.663
	Barren land	0.003	0.009	0.293	0.770
	SNH	0.005	0.017	0.313	0.755
	Infrastructure	0.000	0.010	0.020	0.984
	Village	0.000	0.010	0.038	0.970

Table S3.13 Most parsimonious models (ΔAICc < 2) resulting from model selection of all combinations of terms from global models that assessed the effect of land use types on **the abundance of *Lasioglossum niveocinctum*** for cumulative landscape sectors at four spatial scales (**circle analysis).** k, number of parameters of each model; LogLik, log-likelihood of the model; AICc, Akaike's Information Criterion corrected for small sample size; ΔAICc, the difference in AICc value between a model and the best ranked model; Weight, Akaike weight, which can be interpreted as the conditional probabilities for each candidate model.

Scale (km)	Model	k	logLik	AICc	ΔAICc	Weight
0.5	Intercept+Village+Waste land+fyear	7	-167.57	351.7	0.00	0.042
	Intercept+Village+Waste land+fyear+log(days)	7	-167.57	351.7	0.00	0.042
	Intercept+Waste land+fyear	6	-168.93	351.7	0.04	0.041
	Intercept+Waste land+fyear+log(days)	6	-168.93	351.7	0.04	0.041
	Intercept+fyear	5	-170.52	352.3	0.64	0.031
	Intercept+fyear+log(days)	5	-170.52	352.3	0.64	0.031
	Intercept+Waste land+Village	4	-171.99	352.8	1.14	0.024
	Intercept+Village+fyear	6	-169.53	352.9	1.23	0.023
	Intercept+Village+fyear+log(days)	6	-169.53	352.9	1.23	0.023
	Intercept+Waste land	3	-173.49	353.5	1.79	0.017
1.0	Intercept+Infrastructure+Village+Waste land	5	-167.79	346.9	0.00	0.072
	Intercept+Infrastructure+Village+Waste land+fyear	8	-164.27	347.9	1.00	0.044
	Intercept+Infrastructure+Village+Waste land+fyear+log(days)	8	-164.27	347.9	1.00	0.044
	Intercept+Infrastructure+Village+Waste land+log(days)	5	-168.60	348.5	1.61	0.032
	Intercept+Infrastructure+SNH+Village+Waste land	6	-167.38	348.6	1.74	0.030
1.5	Intercept+Infrastructure+Waste land	4	-167.77	344.4	0.00	0.071
	Intercept+Infrastructure+Village+Waste land	5	-166.64	344.6	0.19	0.065
	Intercept+Infrastructure+Waste land	4	-168.04	344.9	0.54	0.055
	Intercept+Infrastructure+SNH+Waste land	5	-166.98	345.3	0.88	0.046
	Intercept+Infrastructure+SNH+Waste land+log(days)	5	-167.08	345.5	1.08	0.042
	Intercept+Infrastructure+SNH+Waste land+Village	6	-166.06	346	1.60	0.032
	Intercept+Infrastructure+SNH+Waste land+log(days)	5	-167.42	346.1	1.76	0.030
2.0	Intercept+Infrastructure+Waste land+log(days)	4	-167.94	344.7	0.00	0.072
	Intercept+Infrastructure+Waste land	4	-167.99	344.8	0.10	0.069
	Intercept+Infrastructure+SNH+Waste land	5	-167.23	345.8	1.03	0.043
	Intercept+Infrastructure+SNH+Waste land+log(days)	5	-167.29	345.9	1.16	0.04

Table S3.14 Results of multi-model inference to determine the effect of land use types on abundance of ***Lasioglossum niveocinctum*** for cumulative landscape sectors at four spatial scales (**circle analysis).** For each scale, the average model was taken from the total candidate models. Z value is the estimate of each coefficient divided by its standard error.

Scales (km)	Variables	Estimate	Std. Error	z value	Pr(>|z|)
0.5	(Intercept)	1.714	1.063	1.610	0.107
	fyear2019	-0.068	0.447	0.149	0.881
	fyear2020	-0.143	0.362	0.386	0.699
	fyear2021	-0.988	0.692	1.418	0.156
	Village	-0.011	0.015	0.709	0.478
	Barren land	-0.036	0.033	1.078	0.281
	Annual	0.001	0.004	0.160	0.873
	SNH	0.002	0.011	0.211	0.833
	Water	-0.016	0.060	0.267	0.789
	Infrastructure	-0.002	0.011	0.202	0.840
1.0	(Intercept)	2.040	1.148	1.773	*0.076*
	Infrastructure	-0.031	0.025	1.253	0.210
	Village	-0.025	0.022	1.122	0.262
	Barren land	-0.046	0.030	1.524	0.128
	fyear2019	-0.041	0.374	0.108	0.914
	fyear2020	-0.003	0.318	0.010	0.992
	fyear2021	-0.603	0.664	0.903	0.367
	SNH	0.010	0.020	0.462	0.644
	Annual	0.000	0.005	0.093	0.926
	Water	-0.014	0.068	0.208	0.835
1.5	(Intercept)	2.014	1.163	1.728	*0.084*
	Infrastructure	-0.049	0.028	1.738	*0.082*
	Barren land	-0.045	0.023	1.909	*0.056*
	Village	-0.017	0.023	0.705	0.481
	SNH	0.011	0.022	0.477	0.633
	fyear2019	-0.018	0.294	0.062	0.951
	fyear2020	-0.014	0.247	0.055	0.956
	fyear2021	-0.369	0.593	0.621	0.535
	Annual	0.001	0.005	0.106	0.916
	Water	-0.015	0.079	0.184	0.854
2.0	(Intercept)	1.700	1.156	1.468	0.142
	Infrastructure	-0.058	0.031	1.814	*0.070*
	Barren land	-0.030	0.025	1.209	0.227
	SNH	0.013	0.026	0.507	0.612
	Annual	0.001	0.006	0.214	0.831
	Water	0.003	0.065	0.038	0.969
	Village	-0.007	0.018	0.393	0.694
	fyear2019	-0.004	0.333	0.011	0.991
	fyear2020	-0.048	0.279	0.168	0.866
	fyear2021	-0.493	0.640	0.766	0.443

Table S3.15 Most parsimonious models (ΔAICc < 2) resulting from model selection of all combinations of terms from global models that assessed the effect of land use types on **total wild bee abundance** for individual landscape sectors at four spatial scales (**ring analysis).** k, number of parameters of each model; LogLik, log-likelihood of the model; AICc, Akaike's Information Criterion corrected for small sample size; ΔAICc, the difference in AICc value between a model and the best ranked model; Weight, Akaike weight, which can be interpreted as the conditional probabilities for each candidate model.

Scale (km)	Model	k	logLik	AICc	ΔAICc	Weight
0.5	Intercept+Infrastructure+SNH+Waste land+log(days)	5	-261.69	534.7	0.00	0.078
	Intercept+Infrastructure+SNH+log(days)	4	-263.12	535.1	0.39	0.064
	Intercept+Annual +Infrastructure+SNH+Waste land+log(days)	6	-260.69	535.3	0.56	0.059
	Intercept+Annual+Infrastructure+SNH+log(days)	5	-262.23	535.8	1.08	0.045
	Intercept+Infrastructure+SNH+Village+Waste land+log(days)	6	-261.34	536.6	1.87	0.031
1.0	Intercept+Annual+Infrastructure+SNH+log(days)	5	-256.73	524.8	0.00	0.174
	Intercept+Annual+Infrastructure+SNH+Waste land+log(days)	4	-256.14	526.1	1.37	0.088
1.5	Intercept+Annual+Infrastructure+SNH+log(days)	5	-255.17	521.6	0.00	0.165
	Intercept+Annual+SNH+log(days)	4	-256.61	522.1	0.43	0.133
	Intercept+Annual+Infrastructure+SNH+Village+log(days)	6	-254.82	523.5	1.87	0.065
	Intercept+Annual+SNH+Village+log(days)	5	-256.14	523.6	1.95	0.062
2.0	Intercept+Annual+SNH+log(days)	4	-255.35	519.5	0.00	0.143
	Intercept+Annual+SNH+Water+log(days)	5	-254.18	519.7	0.11	0.135
	Intercept+Annual+Water+log(days)	4	-256.05	520.9	1.39	0.071
	Intercept+Annual+Infrastructure+SNH+log(days)	5	-254.98	521.3	1.72	0.060

Table S3.16 Results of multi-model inference to determine the effect of land use types on **total wild bee abundance** for individual landscape sectors at four spatial scales (**ring analysis)**. For each scale, the average model was taken from the total candidate models. Z value is the estimate of each coefficient divided by its standard error.

Scales (km)	Variables	Estimate	Std. Error	z value	Pr(>|z|)
0.5	(Intercept)	2.380	0.867	2.742	**0.006**
	Infrastructure	-0.027	0.021	1.264	0.206
	SNH	0.013	0.015	0.868	0.385
	Barren land	-0.026	0.023	1.108	0.268
	Annual	0.003	0.005	0.549	0.583
	Village	-0.002	0.008	0.328	0.743
	Water	0.001	0.044	0.016	0.987
	fyear2019	0.034	0.201	0.167	0.867
	fyear2020	0.025	0.152	0.163	0.870
	fyear2021	-0.040	0.199	0.198	0.843
1.0	(Intercept)	1.727	0.835	2.063	**0.039**
	Annual	0.010	0.008	1.206	0.228
	Infrastructure	-0.033	0.016	2.006	**0.045**
	SNH	0.047	0.027	1.733	*0.083*
	Barren land	-0.005	0.010	0.508	0.611
	Village	-0.004	0.009	0.433	0.665
	Water	0.010	0.055	0.185	0.853
	fyear2019	0.060	0.230	0.261	0.794
	fyear2020	0.079	0.239	0.331	0.741
	fyear2021	0.024	0.175	0.133	0.894
1.5	(Intercept)	1.159	0.690	1.673	*0.094*
	Annual	0.021	0.008	2.610	**0.009**
	Infrastructure	-0.013	0.016	0.827	0.408
	SNH	0.057	0.027	2.066	**0.039**
	Barren land	-0.007	0.014	0.511	0.609
	Water	-0.002	0.005	0.346	0.730
	Village	0.007	0.043	0.165	0.869
	fyear2019	0.058	0.223	0.260	0.795
	fyear2020	0.069	0.219	0.315	0.753
	fyear2021	0.024	0.159	0.147	0.883
2.0	(Intercept)	0.851	0.475	1.778	0.075
	Annual	0.023	0.007	3.309	**<0.001**
	Infrastructure	0.043	0.032	1.336	0.181
	SNH	0.074	0.086	0.850	0.395
	Water	-0.004	0.010	0.399	0.690
	Barren land	0.001	0.005	0.203	0.839
	Village	0.002	0.008	0.283	0.778
	fyear2019	0.048	0.209	0.227	0.820
	fyear2020	0.033	0.147	0.221	0.825
	fyear2021	0.024	0.138	0.170	0.865

Table S3.17 Most parsimonious models (ΔAICc < 2) resulting from model selection of all combinations of terms from global models that assessed the effect of land use types on **the abundance of *Andrena yamagishi*** for individual landscape sectors at four spatial scales (**ring analysis).** k, number of parameters of each model; LogLik, log-likelihood of the model; AICc, Akaike's Information Criterion corrected for small sample size; ΔAICc, the difference in AICc value between a model and the best ranked model; Weight, Akaike weight, which can be interpreted as the conditional probabilities for each candidate model.

Scale (km)	Model	k	logLik	AICc	ΔAICc	Weight
0.5	Intercept+Infrastructure+SNH+log(days)+fyear	7	-229.21	475	0	0.07
	Intercept+Infrastructure+SNH+fyear	7	-229.21	475	0	0.07
	Intercept+Infrastructure+SNH+log(days)	4	-233.11	475.1	0.1	0.067
	Intercept+Annual+Infrastructure+SNH+fyear	8	-228.12	475.6	0.63	0.051
	Intercept+Annual+Infrastructure+SNH+log(days)+fyear	8	-228.12	475.6	0.63	0.051
	Intercept+Infrastructure+SNH+Water+log(days)	5	-232.15	475.6	0.64	0.051
	Intercept+Infrastructure+SNH+Water+log(days)+fyear	8	-228.50	476.4	1.39	0.035
	Intercept+Infrastructure+SNH+Water+log(days)+fyear	8	-228.50	476.4	1.39	0.035
	Intercept+Infrastructure+SNH+Waste land+fyear	8	-228.74	476.8	1.87	0.028
	Intercept+Infrastructure+SNH+Waste land+fyear+ log(days)	8	-228.74	476.8	1.87	0.028
1.0	Intercept+Annual+SNH+fyear+ log(days)	7	-226.59	469.7	0	0.12
	Intercept+Annual+SNH+fyear	7	-226.59	469.7	0	0.12
	Intercept+Annual+Infrastructure+SNH+fyear+ log(days)	8	-225.34	470	0.3	0.104
	Intercept+Annual+Infrastructure+SNH+fyear	8	-225.34	470	0.3	0.104
1.5	Intercept+Annual+SNH+fyear+ log(days)	7	-225.29	467.1	0	0.118
	Intercept+Annual+SNH+fyear	7	-225.29	467.1	0	0.118
	Intercept+Annual+Infrastructure+SNH+fyear	8	-224.36	468.1	0.95	0.074
	Intercept+Annual+Infrastructure+SNH+fyear+ log(days)	8	-224.36	468.1	0.95	0.074
	Intercept+Annual+SNH+Village+fyear	8	-224.54	468.4	1.31	0.061
	Intercept+Annual+SNH+Village+fyear+ log(days)	8	-224.54	468.4	1.31	0.061
2.0	Intercept+Annual+SNH+fyears	7	-225.81	468.2	0	0.058
	Intercept+Annual+SNH+fyears+ log(days)	7	-225.81	468.2	0	0.058
	Intercept+Annual+SNH+Water+fyears	8	-224.45	468.3	0.1	0.055
	Intercept+Annual+SNH+Water+fyears+ log(days)	8	-224.45	468.3	0.1	0.055
	Intercept+SNH+log(days)	3	-231.36	469.2	1.07	0.034
	Intercept+SNH+fyear	6	-227.86	469.6	1.44	0.028
	Intercept+SNH+log(days)+fyear	6	-227.86	469.6	1.44	0.028
	Intercept+Annual+Village+SNH+fyear	8	-225.24	469.8	1.68	0.025
	Intercept+Annual+Village+SNH+fyear+log(days)	8	-225.24	469.8	1.68	0.025
	Intercept+Annual+Village+SNH+Water+fyear	9	-223.85	470	1.82	0.023
	Intercept+Annual+Village+SNH+Water+fyear+log(days)	9	-223.85	470	1.82	0.023
	Intercept+Annual+Village+SNH+Waste land+fyear	8	-225.37	470.1	1.94	0.022
	Intercept+Annual+Village+SNH+Waste land+fyear+log(days)	8	-225.37	470.1	1.94	0.022

Table S3.18 Results of multi-model inference to determine the effect of land use types **on the abundance of *Andrena yamagishi*** for individual landscape sectors at four spatial scales (**ring analysis**). For each scale, the average model was taken from the total candidate models. Z value is the estimate of each coefficient divided by its standard error.

Scales (km)	Variables	Estimate	Std. Error	z value	Pr(>|z|)
0.5	(Intercept)	0.887	0.927	0.953	0.340
	Infrastructure	-0.048	0.026	1.856	*0.063*
	fyear2019	0.801	0.691	1.154	0.248
	fyear2020	0.873	0.691	1.258	0.209
	fyear2021	0.634	0.590	1.065	0.287
	SNH	0.081	0.021	3.868	**<0.001**
	Annual	0.003	0.007	0.457	0.648
	Water	-0.038	0.082	0.450	0.652
	Barren land	-0.006	0.014	0.406	0.684
	Village	0.000	0.007	0.063	0.950
1.0	(Intercept)	-0.278	1.130	0.245	0.807
	Annual	0.021	0.011	1.898	*0.058*
	fyear2019	1.390	0.571	2.415	**0.016**
	fyear2020	1.700	0.559	3.001	**0.003**
	fyear2021	1.387	0.542	2.528	**0.011**
	SNH	0.122	0.027	4.365	**<0.001**
	Infrastructure	-0.015	0.018	0.800	0.424
	Village	0.000	0.007	0.042	0.966
	Barren land	-0.001	0.008	0.164	0.870
	Water	-0.013	0.067	0.188	0.851
1.5	(Intercept)	-0.317	1.114	0.283	0.777
	Annual	0.020	0.011	1.800	*0.072*
	fyear2019	1.377	0.583	2.342	**0.019**
	fyear2020	1.489	0.540	2.724	**0.006**
	fyear2021	1.354	0.563	2.377	**0.017**
	SNH	0.140	0.029	4.771	**<0.001**
	Infrastructure	-0.009	0.016	0.551	0.581
	Village	-0.008	0.017	0.484	0.629
	Barren land	0.000	0.005	0.033	0.973
	Water	0.001	0.048	0.015	0.988
2.0	(Intercept)	0.851	0.475	1.778	*0.075*
	SNH	0.023	0.007	3.309	**<0.001**
	Annual	0.043	0.032	1.336	0.181
	Water	0.074	0.086	0.850	0.395
	Infrastructure	-0.004	0.010	0.399	0.690
	Barren land	0.001	0.005	0.203	0.839
	Village	0.002	0.008	0.283	0.778
	fyear2019	0.048	0.209	0.227	0.820
	fyear2020	0.033	0.147	0.221	0.825
	fyear2021	0.024	0.138	0.170	0.865

Table S3.19 Most parsimonious models (ΔAICc < 2) resulting from model selection of all combinations of terms from global models that assessed the effect of land use types on **the abundance of *Lasioglossum pseudannulipes*** for individual landscape sectors at four spatial scales (**ring analysis).** k, number of parameters of each model; LogLik, log-likelihood of the model; AICc, Akaike's Information Criterion corrected for small sample size; ΔAICc, the difference in AICc value between a model and the best ranked model; Weight, Akaike weight, which can be interpreted as the conditional probabilities for each candidate model.

Scale (km)	Model	k	logLik	AICc	ΔAICc	Weight
0.5	Intercept+Annual+Water+fyear	7	-159.68	335.9	0.00	0.149
	Intercept+Annual+Water+fyear+log(days)	7	-159.68	335.9	0.00	0.149
1.0	Intercept+Annual+SNH+fyear+log(days)	7	-157.81	332.2	0.00	0.069
	Intercept+Annual+SNH+fyear	7	-157.81	332.2	0.00	0.069
	Intercept+Annual+Water+fyear	7	-158.01	332.6	0.42	0.056
	Intercept+Annual+Water+fyear+log(days)	7	-158.01	332.6	0.42	0.056
	Intercept+Annual+Water+SNH+fyear	8	-156.78	332.9	0.76	0.047
	Intercept+Annual+Water+SNH+fyear+log(days)	8	-156.78	332.9	0.76	0.047
	Intercept+Annual+fyear	6	-159.60	333.1	0.92	0.044
	Intercept+Annual+fyear+log(days)	6	-159.60	333.1	0.92	0.044
	Intercept+Annual+Infrastructure+SNH+fyear	8	-157.28	333.9	1.75	0.029
	Intercept+Annual+Infrastructure +SNH+fyear+log(days)	8	-157.28	333.9	1.75	0.029
1.5	Intercept+Annual+fyear+log(days)	6	-157.47	328.8	0.00	0.114
	Intercept+Annual+fyear	6	-157.47	328.8	0.00	0.114
	Intercept+Annual+SNH+fyear	7	-156.81	330.2	1.38	0.057
	Intercept+Annual+SNH+fyear+log(days)	7	-156.81	330.2	1.38	0.057
	Intercept+Annual+Village+fyear	7	-157.05	330.7	1.85	0.045
	Intercept+Annual+Village+fyear+log(days)	7	-157.05	330.7	1.85	0.045
2.0	Intercept+Annual+fyear+log(days)	6	-157.29	328.4	0.00	0.129
	Intercept+Annual+fyear	6	-157.29	328.4	0.00	0.129
	Intercept+Annual+Waste land+fyear+log(days)	7	-156.91	330.4	1.93	0.049
	Intercept+Annual+ Waste land+fyear	7	-156.91	330.4	1.93	0.049
	Intercept+Annual+Water+fyear+log(days)	7	-156.92	330.4	1.94	0.049
	Intercept+Annual+Water+fyear	7	-156.92	330.4	1.94	0.049

Table S3.20 Results of multi-model inference to determine the effect of land use types on abundance of ***Lasioglossum pseudannulipes*** for individual landscape sectors at four spatial scales (**ring analysis)**. For each scale, the average model was taken from the total candidate models. Z value is the estimate of each coefficient divided by its standard error.

Scales (km)	Variables	Estimate	Std. Error	z value	Pr(>|z|)
0.5	(Intercept)	0.474	1.059	0.446	0.656
	Annual	0.024	0.009	2.716	**0.007**
	fyear2019	0.743	0.500	1.472	0.141
	fyear2020	-0.650	0.438	1.454	0.146
	fyear2021	-0.525	0.475	1.087	0.277
	Water	0.155	0.121	1.257	0.209
	SNH	0.003	0.010	0.266	0.790
	Village	0.000	0.007	0.047	0.962
	Infrastructure	-0.002	0.010	0.182	0.855
	Barren land	0.001	0.009	0.128	0.899
1.0	(Intercept)	-0.065	1.088	0.060	0.952
	Annual	0.030	0.008	3.526	**<0.001**
	fyear2019	0.722	0.506	1.414	0.157
	fyear2020	-0.432	0.437	0.968	0.333
	fyear2021	-0.342	0.458	0.735	0.462
	SNH	0.025	0.030	0.825	0.409
	Water	0.091	0.126	0.719	0.472
	Infrastructure	-0.004	0.011	0.374	0.709
	Village	-0.001	0.008	0.084	0.933
	Barren land	-0.002	0.009	0.211	0.833
1.5	(Intercept)	0.006	1.070	0.006	0.996
	Annual	0.034	0.008	4.135	**<0.001**
	fyear2019	0.720	0.488	1.462	0.144
	fyear2020	-0.525	0.410	1.254	0.210
	fyear2021	-0.310	0.450	0.678	0.498
	SNH	0.011	0.022	0.492	0.623
	Village	-0.005	0.014	0.346	0.730
	Barren land	0.001	0.006	0.231	0.817
	Water	0.010	0.054	0.175	0.861
	Infrastructure	0.000	0.008	0.055	0.956
2.0	(Intercept)	-0.126	1.057	0.119	0.905
	Annual	0.036	0.008	4.389	**<0.001**
	fyear2019	0.812	0.484	1.660	*0.097*
	fyear2020	-0.589	0.400	1.443	0.149
	fyear2021	-0.277	0.452	0.602	0.547
	Barren land	0.003	0.008	0.363	0.717
	Water	0.016	0.049	0.310	0.757
	Village	0.002	0.009	0.192	0.848
	SNH	0.002	0.014	0.166	0.868
	Infrastructure	0.001	0.009	0.093	0.926

Table S3.21 Most parsimonious models (ΔAICc < 2) resulting from model selection of all combinations of terms from global models that assessed the effect of land use types on **the abundance of *Lasioglossum niveocinctum*** for individual landscape sectors at four spatial scales (**ring analysis).** k, number of parameters of each model; LogLik, log-likelihood of the model; AICc, Akaike's Information Criterion corrected for small sample size; ΔAICc, the difference in AICc value between a model and the best ranked model; Weight, Akaike weight, which can be interpreted as the conditional probabilities for each candidate model.

Scale (km)	Model	k	logLik	AICc	ΔAICc	Weight
0.5	Intercept+Village+Waste land+fyear	7	-167.57	351.7	0.00	0.042
	Intercept+Village+Waste land+fyear+log(days)	7	-167.57	351.7	0.00	0.042
	Intercept+Waste land+fyear	6	-168.93	351.7	0.04	0.041
	Intercept+Waste land+fyear+log(days)	6	-168.93	351.7	0.04	0.041
	Intercept+fyear	5	-170.52	352.3	0.64	0.031
	Intercept+fyear+log(days)	5	-170.52	352.3	0.64	0.031
	Intercept+Waste land+Village	4	-171.99	352.8	1.14	0.024
	Intercept+Village+fyear	6	-169.53	352.9	1.23	0.023
	Intercept+Village+fyear+log(days)	6	-169.53	352.9	1.23	0.023
	Intercept+Waste land	3	-173.49	353.5	1.79	0.017
1.0	Intercept+Infrastructure+Village+Waste land	5	-167.99	347.3	0.00	0.056
	Intercept+Infrastructure+Village+Waste land+fyear	8	-164.17	347.7	0.40	0.046
	Intercept+Infrastructure+Village+Waste land+fyear+log(days)	8	-164.17	347.7	0.40	0.046
	Intercept+Infrastructure+Waste land	4	-169.75	348.3	1.06	0.033
	Intercept+Infrastructure+Village+Waste land+SNH	6	-167.36	348.6	1.30	0.029
	Intercept+Infrastructure+Waste land+SNH	5	-168.74	348.8	1.50	0.026
	Intercept+Infrastructure+Village+Waste land+SNH+fyear+log(days)	9	-163.30	348.9	1.61	0.025
	Intercept+Infrastructure+Village+Waste land+SNH+fyear	9	-163.30	348.9	1.61	0.025
1.5	Intercept+Infrastructure+Waste land	4	-168.57	346	0.00	0.051
	Intercept+Infrastructure+Waste land+log(days)	4	-168.74	346.3	0.35	0.043
	Intercept+Infrastructure+Village+Waste land	5	-167.84	347	0.99	0.031
	Intercept+Annual+Infrastructure+Waste land+log(days)	5	-167.90	347.1	1.12	0.029
	Intercept+Infrastructure+SNH+Waste land	5	-167.99	347.3	1.31	0.027
	Intercept+Infrastructure+Waste land+fyear	7	-165.45	347.4	1.46	0.025
	Intercept+Infrastructure+Waste land+fyear+log(days)	7	-165.45	347.4	1.46	0.025
	Intercept+Infrastructure+Village+Waste land+log(days)	5	-168.11	347.5	1.55	0.024
	Intercept+Annual+Infrastructure+Waste land	5	-168.16	347.6	1.65	0.022
	Intercept+Infrastructure+SNH+Waste land+log(days)	5	-168.33	348	1.99	0.019
2.0	Intercept+Infrastructure+fyear	6	-166.59	347.1	0	0.044
	Intercept+Infrastructure+fyear+log(days)	6	-166.59	347.1	0	0.044
	Intercept+Infrastructure+SNH+fyear	7	-165.54	347.6	0.56	0.033
	Intercept+Infrastructure+SNH+fyear+log(days)	7	-165.54	347.6	0.56	0.033
	Intercept+Infrastructure+Waste land+ log(days)	4	-169.43	347.7	0.66	0.031
	Intercept+Infrastructure+Waste land	4	-169.45	347.7	0.69	0.031
	Intercept+Infrastructure+Waste land+fyear	7	-165.81	348.2	1.12	0.025
	Intercept+Infrastructure+Waste land+fyear+ log(days)	7	-165.81	348.2	1.12	0.025
	Intercept+Annual+Infrastructure+Waste land+fyear	7	-165.87	348.3	1.22	0.024
	Intercept+Annual+Infrastructure+Waste land+fyear+ log(days)	7	-165.87	348.3	1.22	0.024
	Intercept+Annual+fyear	6	-167.43	348.7	1.67	0.019
	Intercept+Annual+fyear+ log(days)	6	-167.43	348.7	1.67	0.019

Table S3.22 Results of multi-model inference to determine the effect of land use types on **abundance of *Lasioglossum niveocinctum*** for individual landscape sectors at four spatial scales (**ring analysis**). For each scale, the average model was taken from the total candidate models. Z value is the estimate of each coefficient divided by its standard error.

Scales (km)	Variables	Estimate	Std. Error	z value	Pr(>|z|)
0.5	(Intercept)	1.714	1.063	1.61	0.107
	fyear2019	-0.068	0.447	0.149	0.881
	fyear2020	-0.143	0.362	0.386	0.699
	fyear2021	-0.988	0.692	1.418	0.156
	Village	-0.011	0.015	0.709	0.478
	Barren land	-0.036	0.033	1.078	0.281
	Annual	0.001	0.004	0.160	0.873
	SNH	0.002	0.011	0.211	0.833
	Water	-0.016	0.060	0.267	0.789
	Infrastructure	-0.002	0.011	0.202	0.840
1.0	(Intercept)	1.943	1.134	1.709	*0.087*
	Infrastructure	-0.034	0.023	1.481	0.139
	Village	-0.018	0.019	0.943	0.346
	Barren land	-0.038	0.027	1.383	0.167
	fyear2019	-0.051	0.394	0.129	0.898
	fyear2020	-0.008	0.334	0.024	0.981
	fyear2021	-0.693	0.672	1.025	0.305
	SNH	0.015	0.025	0.604	0.546
	Annual	0.000	0.005	0.051	0.960
	Water	-0.006	0.054	0.104	0.917
1.5	(Intercept)	1.687	1.165	1.444	0.149
	Infrastructure	-0.042	0.031	1.353	0.176
	Barren land	-0.026	0.019	1.348	0.178
	Village	-0.009	0.018	0.506	0.613
	Annual	0.004	0.008	0.506	0.613
	SNH	0.009	0.021	0.435	0.664
	fyear2019	-0.010	0.362	0.028	0.977
	fyear2020	-0.063	0.307	0.200	0.842
	fyear2021	-0.592	0.675	0.874	0.382
	Water	-0.037	0.090	0.403	0.687
2.0	(Intercept)	1.362	1.147	1.184	0.236
	Infrastructure	-0.043	0.031	1.366	0.172
	fyear2019	0.026	0.424	0.062	0.951
	fyear2020	-0.088	0.348	0.249	0.804
	fyear2021	-0.804	0.647	1.233	0.217
	SNH	0.013	0.025	0.500	0.617
	Barren land	-0.010	0.016	0.626	0.532
	Annual	0.005	0.009	0.512	0.609
	Village	-0.002	0.012	0.184	0.854
	Water	0.006	0.045	0.132	0.895

Table S3.23 Most parsimonious models (ΔAICc < 2) resulting from model selection of all combinations of terms from global models that assessed the effect of land use types on **wild bee species richness** for cumulative landscape sectors at four spatial scales (**circle analysis).** k, number of parameters of each model; LogLik, log-likelihood of the model; AICc, Akaike's Information Criterion corrected for small sample size; ΔAICc, the difference in AICc value between a model and the best ranked model; Weight, Akaike weight, which can be interpreted as the conditional probabilities for each candidate model.

Scale (km)	Model	k	logLik	AICc	ΔAICc	Weight
0.5	Intercept	2	-100.48	205.2	0	0.107
	Intercept+Annual	3	-99.65	205.8	0.59	0.079
	Intercept+Water	3	-99.76	206	0.81	0.071
	Intercept+SNH	3	-100.25	207	1.79	0.044
	Intercept+Village	4	-100.26	207	1.82	0.043
1.0	Intercept	2	-100.48	205.2	0	0.109
	Intercept+annaul	3	-99.39	205.3	0.07	0.106
	Intercept+Water	3	-100.15	206.8	1.59	0.049
	Intercept+SNH	3	-100.34	207.2	1.97	0.041
	Intercept+waste.land	3	-100.35	207.2	1.99	0.04
1.5	Intercept+Annual	3	-99.28	205.1	0	0.114
	Intercept	2	-100.48	205.2	0.15	0.106
	Intercept+Water	3	-100.26	207	1.96	0.043
2.0	Intercept	2	-100.48	205.2	0	0.115
	Intercept+Annual	3	-99.47	205.4	0.24	0.103
	Intercept+Water	3	-100.29	207.1	1.89	0.045

Table S3.24 Results of multi-model inference to determine the effect of land use types on **wild bee species richness** for cumulative landscape sectors at four spatial scales (**circle analysis).** For each scale, the averaged model was taken from the total candidate models. Z value is the estimate of each coefficient divided by its standard error.

Scales (km)	Land use variables	Estimate	Std. Error	z value	Pr(>|z|)
0.5	(Intercept)	1.503	0.342	4.378	**<0.001**
	Annual	0.002	0.003	0.508	0.611
	Water	-0.022	0.047	0.468	0.640
	SNH	0.001	0.006	0.232	0.817
	Village	-0.001	0.004	0.203	0.840
	Infrastructure	0.001	0.005	0.162	0.871
	Barren land	0.000	0.005	0.028	0.978
	fyear2019	-0.029	0.153	0.187	0.852
	fyear2020	-0.020	0.102	0.196	0.845
	fyear2021	-0.021	0.118	0.181	0.856
1.0	(Intercept)	1.482	0.345	4.277	**<0.001**
	Annual	0.002	0.004	0.646	0.518
	Water	-0.013	0.043	0.293	0.770
	SNH	0.001	0.007	0.159	0.874
	Barren land	-0.001	0.005	0.164	0.869
	Village	0.000	0.004	0.001	0.999
	Infrastructure	0.000	0.005	0.104	0.917
	fyear2019	-0.026	0.146	0.179	0.858
	fyear2020	-0.018	0.098	0.184	0.854
	fyear2021	-0.019	0.112	0.171	0.864
1.5	(Intercept)	1.470	0.351	4.171	**<0.001**
	Annual	0.003	0.004	0.684	0.494
	Water	-0.010	0.044	0.232	0.816
	Barren land	-0.001	0.004	0.153	0.879
	SNH	0.001	0.008	0.138	0.890
	Village	0.000	0.006	0.033	0.974
	Infrastructure	0.000	0.005	0.004	0.997
	fyear2019	-0.026	0.145	0.178	0.859
	fyear2020	-0.018	0.097	0.182	0.856
	fyear2021	-0.018	0.110	0.166	0.868
2.0	(Intercept)	1.461	0.358	4.061	**<0.001**
	Annual	0.003	0.004	0.647	0.518
	Water	-0.012	0.043	0.274	0.784
	Infrastructure	-0.000	0.006	0.038	0.969
	SNH	0.001	0.009	0.112	0.911
	Village	0.001	0.006	0.126	0.900
	Barren land	0.000	0.004	0.024	0.981
	fyear2019	-0.027	0.149	0.182	0.855
	fyear2020	-0.020	0.102	0.191	0.849
	fyear2021	-0.020	0.115	0.175	0.861

Table S3.25 Most parsimonious models (ΔAICc < 2) resulting from model selection of all combinations of terms from global models that assessed the effect of land use types on **wild bee species diversity** for cumulative landscape sectors at four spatial scales (**circle analysis).** k, number of parameters of each model; LogLik, log-likelihood of the model; AICc, Akaike's Information Criterion corrected for small sample size; ΔAICc, the difference in AICc value between a model and the best ranked model; Weight, Akaike weight, which can be interpreted as the conditional probabilities for each candidate model.

Scale (km)	Model	k	logLik	AICc	ΔAICc	Weight
0.5	Intercept+Annual+Infrastructure	4	-6.23	21.3	0	0.05
	Intercept+Infrastructure+fyear	6	-3.83	21.5	0.2	0.045
	Intercept+Annual+Infrastructure+log(days)	6	-3.83	21.5	0.2	0.045
	Intercept+Infrastructure+Water+fyear	7	-2.55	21.7	0.33	0.043
	Intercept+Infrastructure+Water+fyear+log(days)	7	-2.55	21.7	0.33	0.043
	Intercept+Annual+Infrastructure+fyear	7	-2.75	22.1	0.73	0.035
	Intercept+Annual+Infrastructure+fyear+log(days)	7	-2.75	22.1	0.73	0.035
	Intercept+Annual+Infrastructure+Waste land	5	-5.38	22.1	0.75	0.035
	Intercept+Annual+Infrastructure+Water	5	-5.77	22.8	1.51	0.024
	Intercept+Annual+Infrastructure+SNH	5	-5.78	22.9	1.54	0.023
1.0	Intercept+Infrastructure+Water+fyear	7	-1.56	19.7	0	0.078
	Intercept+Infrastructure+Water+fyear+log(days)	7	-1.56	19.7	0	0.078
	Intercept+Water+fyear	6	-3.62	21.1	1.44	0.038
	Intercept+Water+fyear+log(days)	6	-3.62	21.1	1.44	0.038
1.5	Intercept+Water+fyear	6	-4.32	22.5	0	0.056
	Intercept+Water+fyear+log(days)	6	-4.32	22.5	0	0.056
	Intercept+Infrastructure+Water+fyear	7	-3.18	22.9	0.38	0.046
	Intercept+Infrastructure+Water+fyear+log(days)	7	-3.18	22.9	0.38	0.046
	Intercept+Infrastructure+Village+Water+fyear	7	-3.66	23.9	1.36	0.028
	Intercept+Infrastructure+Village+Water+fyear+log(days)	7	-3.66	23.9	1.36	0.028
	Intercept+Infrastructure+SNH+Water+fyear	7	-3.86	24.3	1.76	0.023
	Intercept+Infrastructure+SNH+Water+fyear+log(days)	7	-3.86	24.3	1.76	0.023
2.0	Intercept+Water+fyear	6	-3.23	20.3	0	0.09
	Intercept+Water+fyear+log(days)	6	-3.23	20.3	0	0.09
	Intercept+Infrastructure+Water+fyear	7	-2.62	21.8	1.46	0.044
	Intercept+Infrastructure+Water+fyear+log(days)	7	-2.62	21.8	1.46	0.044
	Intercept+Infrastructure+Village+Water+fyear	7	-2.66	21.9	1.53	0.042
	Intercept+Infrastructure+Village+Water+fyear+log(days)	7	-2.66	21.9	1.53	0.042

Table S3.26 Results of multi-model inference to determine the effect of land use types on **wild bee diversity** for cumulative landscape sectors at four spatial scales (**circle analysis**). For each scale, the averaged model was taken from the total candidate models. Z value is the estimate of each coefficient divided by its standard error.

Scales (km)	Variables	Estimate	Std. Error	z value	Pr(>|z|)
0.5	(Intercept)	0.399	0.888	0.450	0.653
	Annual	0.002	0.003	0.719	0.472
	Infrastructure	0.013	0.008	1.600	0.110
	fyear2019	-0.301	0.388	0.775	0.438
	fyear2020	-0.262	0.257	1.015	0.310
	fyear2021	-0.384	0.366	1.046	0.296
	Water	-0.020	0.033	0.593	0.553
	Barren land	-0.001	0.004	0.259	0.796
	SNH	-0.001	0.004	0.300	0.764
	Village	<0.001	0.002	0.119	0.905
1.0	(Intercept)	0.385	0.926	0.415	0.678
	Infrastructure	0.007	0.997	1.062	0.288
	fyear2019	-0.323	0.390	0.828	0.408
	fyear2020	-0.328	0.258	1.266	0.205
	fyear2021	-0.444	0.353	1.256	0.209
	Water	-0.073	0.056	1.294	0.196
	SNH	-0.002	0.006	0.389	0.698
	Annual	0.001	0.003	0.441	0.659
	Barren land	<-0.001	0.003	0.128	0.898
	Village	<-0.001	0.003	0.034	0.973
1.5	(Intercept)	0.418	0.930	0.449	0.653
	fyear2019	-0.331	0.392	0.843	0.399
	fyear2020	-0.335	0.261	1.278	0.201
	fyear2021	-0.448	0.354	1.262	0.207
	Water_1.5	-0.080	0.062	1.275	0.202
	Infrastructure	0.003	0.006	0.588	0.557
	Village_1.5	0.002	0.005	0.352	0.725
	SNH_1.5	-0.002	0.006	0.308	0.758
	Annual_1.5	0.001	0.002	0.234	0.815
	Barren land	-0.001	0.003	0.196	0.845
2.0	(Intercept)	0.371	0.961	0.386	0.699
	fyear2019	-0.414	0.400	1.032	0.302
	fyear2020	-0.415	0.245	1.687	*0.092*
	fyear2021	-0.559	0.336	1.656	0.098
	Water_2.0	-0.105	0.054	1.902	*0.057*
	Infrastructure	0.002	0.004	0.369	0.712
	Village_2.0	0.001	0.004	0.321	0.748
	SNH_2.0	-0.002	0.006	0.258	0.796
	Barren land	0.001	0.003	0.160	0.873
	Annual_2.0	0.000	0.002	0.022	0.982

Table S3.27 Most parsimonious models (ΔAICc < 2) resulting from model selection of all combinations of terms from global models that assessed the effect of land use types on **wild bee species richness** for individual landscape sectors at four spatial scales (**ring analysis).** k, number of parameters of each model; LogLik, log-likelihood of the model; AICc, Akaike's Information Criterion corrected for small sample size; ΔAICc, the difference in AICc value between a model and the best ranked model; Weight, Akaike weight, which can be interpreted as the conditional probabilities for each candidate model.

Scale (km)	Model	k	logLik	AICc	ΔAICc	Weight
0.5	Intercept	2	-100.48	205.2	0.00	0.107
	Intercept+Annual	3	-99.65	205.8	0.59	0.079
	Intercept+Water	3	-99.76	206	0.81	0.071
	Intercept+SNH	3	-100.25	207	1.79	0.044
	Intercept+Village	4	-100.26	207	1.82	0.043
1.0	Intercept+Annual	3	-99.35	205.2	0.00	0.112
	Intercept	2	-100.48	205.2	0.00	0.111
	Intercept+Waste land	3	-100.31	207.1	1.90	0.043
	Intercept+Water	3	-100.34	207.2	1.97	0.042
1.5	Intercept+Annual	3	-99.29	205.1	0.00	0.118
	Inatercept	2	-100.48	205.2	0.13	0.110
2.0	Intercept	2	-100.48	205.2	0.00	0.131
	Intercept+Annual	3	-99.78	206.1	0.85	0.085

Table S3.28 Results of multi-model inference to determine the effect of land use types on **wild bee species richness** for individual landscape sectors at four spatial scales (**ring analysis)**. For each scale, the averaged model was taken from the total candidate models. Z value is the estimate of each coefficient divided by its standard error.

Scales (km)	Land use variables	Estimate	Std. Error	z value	Pr(>|z|)
0.5	(Intercept)	1.503	0.342	4.378	**<0.001**
	Annual	0.002	0.003	0.508	0.611
	Water	-0.022	0.047	0.468	0.640
	SNH	0.001	0.006	0.232	0.817
	Village	-0.001	0.004	0.203	0.840
	Infrastructure	0.001	0.005	0.162	0.871
	Barren land	0.000	0.005	0.028	0.978
	fyear2019	-0.029	0.153	0.187	0.852
	fyear2020	-0.020	0.102	0.196	0.845
	fyear2021	-0.021	0.118	0.181	0.856
1.0	(Intercept)	1.474	0.345	4.257	**<0.001**
	Annual	0.003	0.004	0.684	0.494
	Barren land	-0.001	0.004	0.206	0.836
	Water	-0.006	0.034	0.178	0.859
	SNH	0.001	0.007	0.112	0.911
	Village	0.000	0.004	0.082	0.935
	Infrastructure	0.000	0.004	0.089	0.929
	fyear2019	-0.026	0.146	0.178	0.858
	fyear2020	-0.018	0.098	0.183	0.855
	fyear2021	-0.019	0.111	0.170	0.865
1.5	(Intercept)	1.469	0.350	4.184	**<0.001**
	Annual	0.003	0.004	0.68	0.497
	Barren land	0.000	0.003	0.141	0.888
	Infrastructure	-0.001	0.005	0.104	0.917
	SNH	0.001	0.008	0.128	0.898
	Village	0.000	0.005	0.011	0.991
	Water	-0.004	0.032	0.131	0.896
	fyear2019	-0.026	0.147	0.180	0.857
	fyear2020	-0.018	0.098	0.185	0.853
	fyear2021	-0.018	0.110	0.166	0.868
2.0	(Intercept)	1.463	0.362	4.024	**<0.001**
	Annual	0.002	0.004	0.552	0.581
	Infrastructure	-0.001	0.005	0.124	0.902
	Water	-0.007	0.029	0.229	0.819
	SNH	0.001	0.008	0.074	0.941
	Barren land	0.001	0.003	0.209	0.834
	Village	0.001	0.005	0.189	0.850
	fyear2019	-0.030	0.156	0.192	0.848
	fyear2020	-0.022	0.109	0.205	0.837
	fyear2021	-0.023	0.123	0.188	0.851

Table S3.29 Most parsimonious models (ΔAICc < 2) resulting from model selection of all combinations of terms from global models that assessed the effect of land use types on **wild bee species diversity** for individual landscape sectors at four spatial scales (**ring analysis).** k, number of parameters of each model; LogLik, log-likelihood of the model; AICc, Akaike's Information Criterion corrected for small sample size; ΔAICc, the difference in AICc value between a model and the best ranked model; Weight, Akaike weight, which can be interpreted as the conditional probabilities for each candidate model.

Scale (km)	Model	k	logLik	AICc	ΔAICc	Weight
0.5	Intercept+Annual+Infrastructure	4	-6.24	21.3	0.00	0.050
	Intercept+Infrastructure+fyear	6	-3.83	21.5	0.2	0.045
	Intercept+Annual+Infrastructure+log(days)	6	-3.83	21.5	0.2	0.045
	Intercept+Infrastructure+Water+fyear	7	-2.55	21.7	0.33	0.043
	Intercept+Infrastructure+Water+fyear+log(days)	7	-2.55	21.7	0.33	0.043
	Intercept+Annual+Infrastructure+fyear	7	-2.75	22.1	0.73	0.035
	Intercept+Annual+Infrastructure+fyear+log(days)	7	-2.75	22.1	0.73	0.035
	Intercept+Annual+Infrastructure+Waste land	5	-5.38	22.1	0.75	0.035
	Intercept+Annual+Infrastructure+Water	5	-5.77	22.8	1.51	0.024
	Intercept+Annual+Infrastructure+SNH	5	-5.78	22.9	1.54	0.023
1.0	Intercept+Infrastructure+Water+fyear	7	-2.19	20.9	0.00	0.071
	Intercept+Infrastructure+Water+fyear+log(days)	7	-2.19	20.9	0.00	0.071
	Intercept+Water+fyear	6	-3.94	21.7	0.83	0.047
	Intercept+Water+fyear+log(days)	6	-3.94	21.7	0.83	0.047
1.5	Intercept+Village+fyear	6	-5.68	25.2	0.00	0.040
	Intercept+Village+fyear+log(days)	6	-5.68	25.2	0.00	0.040
	Intercept+fyear	5	-7.10	25.5	0.29	0.034
	Intercept+fyear+log(days)	5	-7.10	25.5	0.29	0.034
	Intercept+Water+Village+fyear	7	-4.56	25.7	0.45	0.032
	Intercept+Water+Village+fyear+log(days)	7	-4.56	25.7	0.45	0.032
	Intercept+Water+fyear	6	-6.01	25.9	0.67	0.028
	Intercept+Water+fyear+log(days)	6	-6.01	25.9	0.67	0.028
	Intercept+Waste land	3	-9.93	26.4	1.13	0.023
	Intercept	2	-11.20	26.7	1.43	0.019
	Intercept+Waste land+Water	4	-9.17	27.2	1.97	0.015
2.0	Intercept+Water+fyear	6	-4.27	22.4	0.00	0.077
	Intercept+Water+fyear+log(days)	6	-4.27	22.4	0.00	0.077
	Intercept+Water+Waste land+fyear	7	-3.56	23.7	1.27	0.041
	Intercept+Water+Waste land+fyear+log(days)	7	-3.56	23.7	1.27	0.041
	Intercept+Water+Annual +fyear	7	-3.83	24.2	1.81	0.031
	Intercept+Water+Annual+fyear+log(days)	7	-3.83	24.2	1.81	0.031
	Intercept+Water+Village +fyear	7	-3.91	24.4	1.97	0.029
	Intercept+Water+Village+fyear+log(days)	7	-3.91	24.4	1.97	0.029

Table S3.30 Results of multi-model inference to determine the effect of land use types on **wild bee diversity** for individual landscape sectors at four spatial scales (**ring analysis).** For each scale, the averaged model was taken from the total candidate models. Z value is the estimate of each coefficient divided by its standard error.

Scales (km)	Land use variables	Estimate	Std. Error	z value	Pr(>|z|)
0.5	Intercept	0.399	0.888	0.450	0.653
	Annual	0.002	0.003	0.719	0.472
	Infrastructure	0.013	0.008	1.600	0.110
	fyear2019	-0.301	0.388	0.775	0.438
	fyear2020	-0.262	0.257	1.015	0.310
	fyear2021	-0.384	0.366	1.046	0.296
	Water	-0.020	0.033	0.593	0.553
	Barren land	-0.001	0.004	0.259	0.796
	SNH	-0.001	0.004	0.300	0.764
	Village	<0.001	0.002	0.119	0.905
1.0	Intercept	0.3872	0.9262	0.418	0.676
	Infrastructure	0.005	0.006	0.917	0.359
	fyear2019	-0.314	0.388	0.809	0.418
	fyear2020	-0.330	0.259	1.267	0.205
	fyear2021	-0.440	0.351	1.250	0.211
	Water	-0.063	0.051	1.219	0.223
	SNH_	-0.002	0.006	0.342	0.733
	Annual	0.001	0.003	0.410	0.682
	Barren land	-0.001	0.003	0.170	0.865
	Village	<0.001	0.002	0.030	0.976
1.5	Intercept	0.414	0.921	0.450	0.653
	fyear2019	-0.311	0.388	0.799	0.424
	fyear2020	-0.329	0.272	1.201	0.230
	fyear2021	-0.403	0.351	1.145	0.252
	Village	0.004	0.007	0.625	0.532
	Water	-0.022	0.036	0.599	0.549
	Barren land	-0.001	0.002	0.269	0.788
	Infrastructure	0.001	0.003	0.196	0.844
	SNH	-0.001	0.005	0.198	0.843
	Annual	<0.001	0.002	0.170	0.865
2.0	Intercept	0.362	0.960	0.376	0.707
	fyear2019	-0.421	0.402	1.044	0.296
	fyear2020	-0.422	0.248	1.689	*0.091*
	fyear2021	-0.558	0.339	1.642	0.101
	Water	-0.054	0.040	1.329	0.184
	Barren land	0.001	0.003	0.400	0.689
	Annual	<0.001	0.002	0.246	0.806
	Village	0.001	0.003	0.277	0.782
	SNH	-0.002	0.006	0.258	0.797
	Infrastructure	0.000	0.003	0.042	0.967

Table S3.31 Results of LMM analysis with normal error distribution for wild bee abundance in different wild plant species, sampling months and years. The response variable was wild bee abundance, and the explanatory variables were wild plant species, sampling months, and years. Sampling orchards and plots were included as random factors. The wild bee abundance in *Cirsium arvense*, in May and in 2020 were considered as references, respectively.

	Estimate	Std. Error	Z value	P value
Intercept	-2.167	0.265	-8.177	**<0.001**
Glycyrrhiza uralensis	-0.341	0.338	-1.008	0.314
Karelinia caspia	0.312	0.301	1.037	0.300
Chenopodium album	-0.021	0.358	-0.058	0.954
Lepidium latifolium	-0.189	0.327	-0.579	0.563
Sophora alopecuroides	-0.009	0.346	-0.026	0.979
Apocynum venetum	0.677	0.293	2.314	**0.021**
Alhagi sparsifolia	-0.895	0.387	-2.316	**0.021**
Phragmites australis	-0.283	0.331	-0.855	0.392
Medicago sativa	0.912	0.284	3.211	**0.001**
June	-0.601	0.210	-2.869	**0.004**
July	0.026	0.187	0.141	0.888
August	0.124	0.270	0.460	0.646
2021	-0.476	0.164	-2.898	**0.004**

Table S3.32 Most parsimonious models (ΔAICc < 2) resulting from model selection of all combinations of terms from global models that assessed the effect of land use types (with perennial crop cover but without annual crop cover) on the abundance of ***Lasioglossum pseudannulipes*** for individual landscape sectors at four spatial scales (**circle analysis).** k, number of parameters of each model; LogLik, log-likelihood of the model; AICc, Akaike's Information Criterion corrected for small sample size; ΔAICc, the difference in AICc value between the a model and best ranked model; Weight, Akaike weight, which can be interpreted as the conditional probabilities for each candidate model.

Scale (km)	Model	k	logLik	AICc	ΔAICc	Weight
0.5	Intercept+fyear+perennial+water+ldays	7	-161.558	339.7	0	0.077
	Intercept+fyear+perennial+water	7	-161.558	339.7	0	0.077
	Intercept+build+fyear+perennial+water+ldays	8	-160.626	340.6	0.94	0.048
	Intercept+build+fyear+perennial+water	8	-160.626	340.6	0.94	0.048
	Intercept+build+fyear+perennial+village+water+ldays	8	-160.962	341.3	1.61	0.034
	Intercept+build+fyear+perennial+village+water	8	-160.962	341.3	1.61	0.034
	Intercept+build+fyear+perennial+ ldays	7	-162.476	341.5	1.84	0.031
	Intercept+build+fyear+perennial	7	-162.476	341.5	1.84	0.031
1.0	Intercept+build+fyear+perennial+village+ldays	8	-159.403	338.2	0	0.046
	Intercept+build+fyear+perennial+village	8	-158.011	338.3	0.15	0.043
	Intercept+build+fyear+perennial+village+waste land	9	-158.011	338.3	0.15	0.043
	Intercept+build+fyear+perennial+village+waste land+ldays	9	-156.555	338.5	0.32	0.039
	Intercept+build+fyear+perennial+village+waste land+water+ldays	10	-156.555	338.5	0.32	0.039
	Intercept+build+fyear+perennial+village+waste land+water+ldays	10	-158.298	338.9	0.73	0.032
	Intercept+build+fyear+perennial+village+water	9	-158.298	338.9	0.73	0.032
	Intercept+build+fyear+perennial+village+water+ldays	9	-161.256	339.1	0.9	0.029
	Intercept+build+fyear+perennial+waste land	7	-161.256	339.1	0.9	0.029
	Intercept+build+fyear+perennial+ waste land +ldays	7	-160.045	339.4	1.28	0.024
	Intercept+build+fyear+perennial+water+waste land	8	-160.045	339.4	1.28	0.024
	Intercept+build+fyear+perennial+waste land+water+ldays	8	-158.62	339.5	1.37	0.023
	Intercept+build+fyear+perennial+water	9	-158.62	339.5	1.37	0.023
	Intercept+build+fyear+perennial+ water+ldays	9	-161.51	339.6	1.41	0.023
1.5	Intercept+fyear+perennial+village+ldays	7	-159.246	335	0	0.068
	Intercept+fyear+perennial+village	7	-159.246	335	0	0.068
	Intercept+fyear+build+perennial+village+ldays	8	-158.121	335.6	0.55	0.052
	Intercept+fyear+build+perennial+village	8	-158.121	335.6	0.55	0.052
	Intercept+fyear+perennial+village+waste land+ldays	9	-156.753	335.8	0.75	0.047
	Intercept+fyear+perennial+waste land+village	9	-156.753	335.8	0.75	0.047
	Intercept+fyear+perennial+waste land+ldays	8	-158.631	336.6	1.57	0.031
	Intercept+fyear+perennial+waste land	8	-158.631	336.6	1.57	0.031
	Intercept+fyear+build+perennial+waste land+ldays	8	-158.64	336.6	1.59	0.031
	Intercept+fyear+build+perennial+waste land	8	-158.64	336.6	1.59	0.031
2.0	Intercept+fyear+perennial+village+ldays	7	-157.987	332.5	0	0.095
	Intercept+fyear+perennial+village	7	-157.987	332.5	0	0.095
	Intercept+fyear+build+perennial+village+ldays	8	-157.200	333.7	1.23	0.051
	Intercept+fyear+build+perennial+village	8	-157.200	333.7	1.23	0.051
	Intercept+fyear+build+perennial+waste land+village+ldays	8	-157.402	334.2	1.63	0.042
	Intercept+fyear+build+perennial+ waste land+village	8	-157.402	334.2	1.63	0.042

Table S3.33 Results of multi-model inference to determine the effect of land use types (with perennial cover but without annual crop) on the abundance of ***Lasioglossum pseudannulipes*** for individual landscape sectors at four spatial scales (**circle analysis).** For each scale, the averaged model was taken from the total candidate models. Z value is the estimate of each coefficient divided by its standard error.

Scales (km)	Land use variables	Estimate	Std. Error	z value	Pr(>|z|)
0.5	Intercept	2.297	1.096	2.088	**0.037**
	fyear2019	0.547	0.503	1.076	0.282
	fyear2020	-0.897	0.433	2.031	**0.042**
	fyear2021	-0.930	0.474	1.931	*0.053*
	Perennial	-0.019	0.009	1.989	**0.047**
	Water	0.117	0.121	0.954	0.340
	Build	-0.012	0.019	0.638	0.524
	Village	-0.006	0.012	0.521	0.602
	Waste.land	-0.003	0.013	0.209	0.834
	SNH	0.001	0.010	0.051	0.960
1.0	Intercept	2.489	1.128	2.196	**0.028**
	Build	-0.029	0.022	1.290	0.197
	fyear2019	0.587	0.510	1.142	0.254
	fyear2020	-0.726	0.486	1.472	0.141
	fyear2021	-0.633	0.538	1.162	0.245
	Perennial	-0.024	0.011	2.156	**0.031**
	Village	-0.018	0.019	0.901	0.368
	Waste land	-0.015	0.022	0.656	0.512
	Water	0.086	0.130	0.652	0.515
	SNH	0.007	0.020	0.366	0.714
1.5	Intercept	2.728	1.120	2.424	**0.015**
	fyear2019	0.638	0.499	1.267	0.205
	fyear2020	-0.634	0.449	1.387	0.165
	fyear2021	-0.713	0.530	1.327	0.184
	Perennial	-0.028	0.011	2.523	**0.012**
	Village	-0.035	0.030	1.162	0.245
	Build	-0.017	0.021	0.805	0.421
	Waste land	-0.012	0.018	0.668	0.504
	SNH	0.004	0.017	0.257	0.797
	water	0.024	0.082	0.291	0.771
2.0	Intercept	2.907	1.107	2.613	**0.009**
	fyear2019	0.728	0.488	1.475	0.140
	fyear2020	-0.676	0.432	1.535	0.125
	fyear2021	-0.718	0.501	1.412	0.158
	Perennial	-0.033	0.010	3.340	**0.001**
	Village	-0.032	0.028	1.124	0.261
	Build	-0.017	0.023	0.725	0.469
	Waste land	-0.009	0.016	0.561	0.575
	Water	0.010	0.059	0.163	0.871
	SNH	0.001	0.015	0.045	0.964

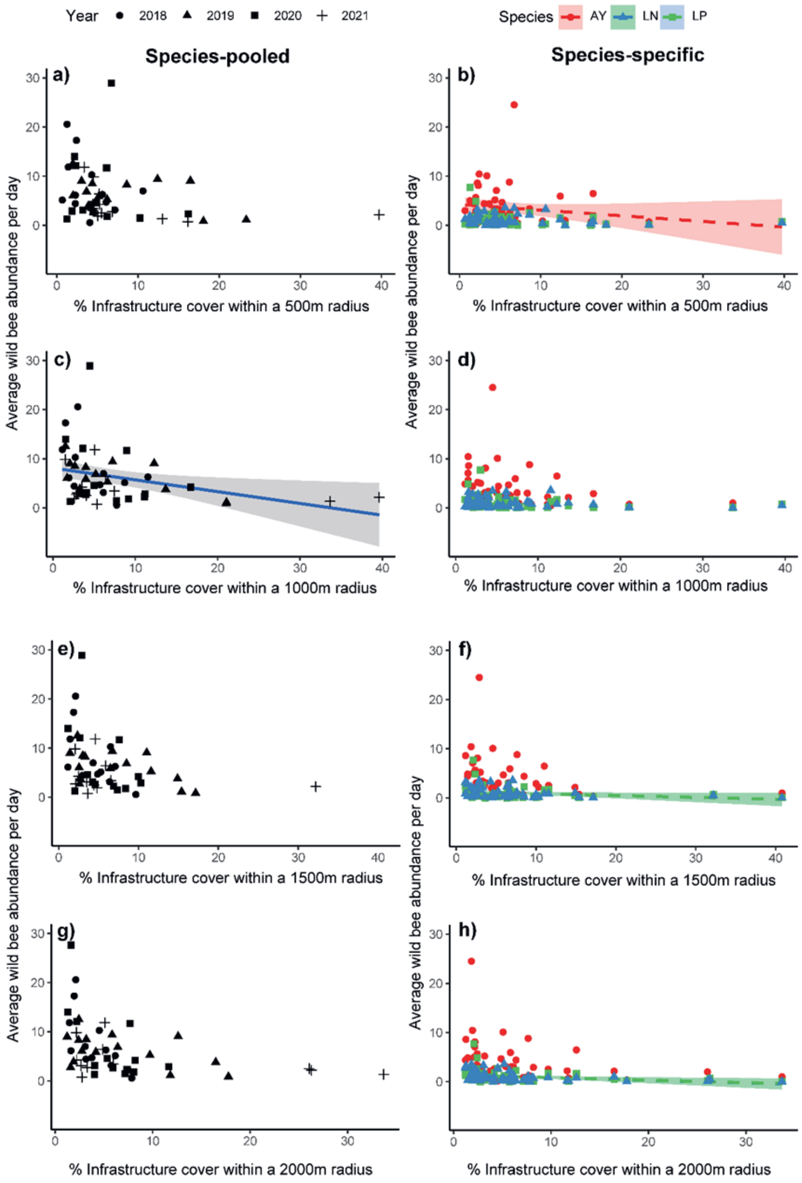

Figure S3.1 Response of total wild bee abundance (left) and three most abundant wild bee species abundance (right) to infrastructure cover at four spatial scales based on the circle analysis. Different symbols in the panels on the left represent data from different years. Different colors in the panels on the right represent different species: AY = *Andrena yamagishi* (red), LP = *Lasioglossum pseudannulipes* (blue), and LN = *Lasioglossum niveocinctum* (green). Solid and dashed lines indicate significant ($P < 0.05$) and marginally significant relationships ($P < 0.1$).

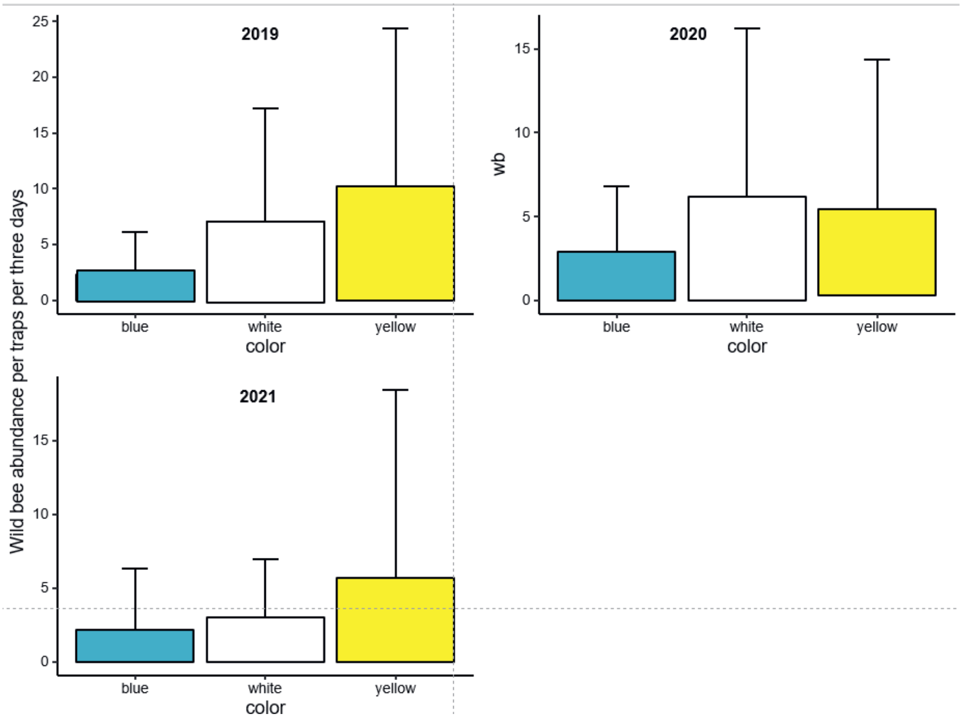

Figure S3.2 Average abundance of wild bees per traps per three days in Korla fragrant pear orchards in 2019-2021. Error bars indicate standard error of the means.

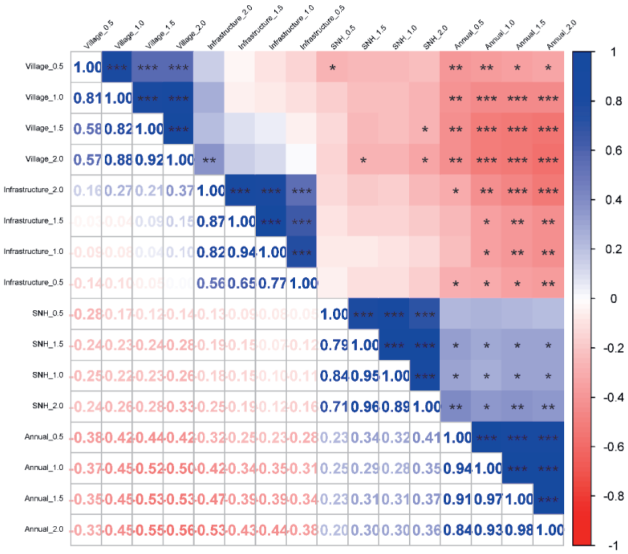

Figure S3.3 Values of Spearman correlation coefficients between the explanatory variables for cumulative landscape sectors (i.e. concentric circles with 0.5, 1.0, 1.5, and 2.0 radius, **circle level**) * *P*-value < 0.05; ** *P*-value < 0.01; *** *P*-value < 0.001.

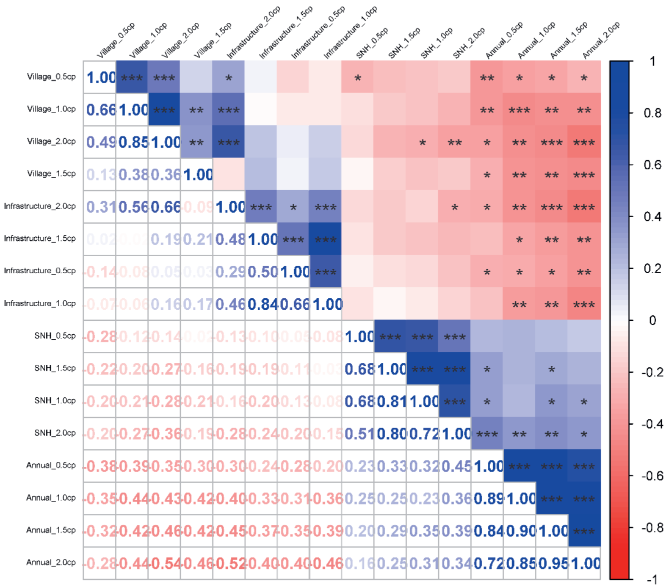

Figure S3.4 Values of Spearman correlation coefficients between the explanatory variables for individual landscape sectors (i.e. a 0.5 km radius circle and rings for increasing size for the other three spatial scales, **ring level**) * *P*-value < 0.05; ** *P*-value < 0.01; *** *P*-value < 0.001.

Chapter 4

Apricot trees affect the distribution of bees in Korla fragrant pear (*Pyrus sinkiangensis*) at the orchard level, but not at the landscape level

Qian Li[1,2,3], Bing Liu[1], Felix J. J. A. Bianchi[3], Wopke van der Werf[2,] and Yanhui Lu[1]

[1] *State Key Laboratory for Biology of Plant Diseases and Insect Pests, Institute of Plant Protection, Chinese Academy of Agricultural Sciences, Beijing, 100193, China;*

[2] *Centre for Crop Systems Analysis, Wageningen University & Research, Wageningen, The Netherlands;*

[3] *Farming Systems Ecology, Wageningen University & Research, Wageningen, The Netherlands*

Abstract

Pollinating insects rely on floral resources for survival and reproduction. Early flowering plants may offer food resources for pollinators when floral resources are scarce, but they may also distract pollinators from pollination-dependent crops. Here we assessed how the abundance of bees and the pollination success of Korla fragrant pear (*Pyrus sinkiangensis*) is influenced by early flowering apricot trees within the orchards or in the landscape at large, and how this influence is moderated by apricot flowering time. The abundance of bees was measured using colored pan traps and pollination success was assessed by recording the initial fruit set and seed set. The density of apricot trees and land use types in radii of 0.5, 1.0, 1.5, and 2.0 km around focal pear orchards were assessed by landscape survey. The abundance of wild bees and honeybees was significantly higher in pear orchards with interspersed apricot trees than in mono-pear orchards. Pear trees adjacent to an apricot tree row (5 m) had significantly higher wild bee abundance than pear trees at further distances (15 m, 30 m, 50 m, and 100 m). However, the positive effect of apricot trees on bee abundance of pear trees was only observed during apricot blooming, and the presence of apricot trees within or adjacent to pear orchards did not influence pear pollination success. The density of apricot trees in the surrounding landscape of pear orchards did not influence bee abundance and fruit set in pear orchards. Overall, our findings indicate that apricot trees in pear orchards can enhance bee abundance, but these effects only occur at relatively small spatial scales and during a short time span, and therefore do not result in marked differences in pollination success.

Keywords: pollinator, fruit production, diversification, early flowering crops, mixed cropping, spatial scales

4.1 Introduction

Many vegetable and fruit crops depend on insects for pollination, and these pollinator-dependent crops represent 35 percent of the global crop production (IPBES, 2016). As a consequence, there is increasing concern about the widespread decline in pollinator abundance and diversity (Biesmeijer et al., 2006; Potts et al., 2016; Powney et al., 2019) and the associated risk for pollination deficits and consequent yield losses (Kremen et al., 2002; Potts et al., 2010; Garratt et al., 2014; Reilly et al., 2020). The decline in flowering plants in agricultural landscapes is believed to be an important factor in pollinator declines (Roulston and Goodell, 2011; Goulson et al., 2015; IPBES, 2016). Increasing the amount of floral resources (e.g. flowering crop species or wild plants) may therefore have potential to mitigate the decline of wild pollinators (Jönsson et al., 2015; Scheper et al., 2015; Shaw et al., 2020).

The abundance of pollinators is generally positively associated with the availability of flower resources (Russo et al., 2013; Blaauw and Isaacs, 2014), but this does not mean that the establishment of flowering plants will necessarily increase the pollination of a target crop (Diekötter et al., 2010; Holzschuh et al., 2011). This is because flowering plants may act as “pollinator magnets” that attract pollinators, especially when these plants are more attractive to pollinators than the target crop, and thereby initiate a competition for pollinators with the target crop, i.e., the “aggregation” hypothesis (Ventruini et al., 2017). On the other hand, flower resources may also support the reproduction and survival of pollinator populations, which may result in higher pollinator abundance in the surroundings, i.e., the “exporter” hypothesis (Morandin and Kremen, 2013; Kremen et al., 2019). Depending on the dominance of the “exporter” and “aggregation” mechanisms or neutral effect, the presence of alternative floral resources may enhance or compromise pollinator visitation of a target crop. Many factors influence whether flowering plants have positive or negative effects on a specific crop species, such as the characteristics of the (crop) plant species, the distance between alternative floral resources and the target crop (Montero-Castaño et al., 2016), pollinator foraging behavior (Marzinzig et al., 2018; Bänsch et al., 2020) and the dispersal capacity of pollinators (Steffan-Dewenter et al., 2002; Zurbuchen et al., 2010). Moreover, the responses of pollinators to floral resources may be scale-specific (Westphal et al., 2006; Kovács-Hostyánszki et al., 2013; Montero-Castaño et al., 2016). Thus, pollinator responses to floral resources can be complex and are still incompletely understood.

Korla fragrant pear (*Pyrus sinkiangensis*; hereafter "pear") is a high-value fruit crop, and its production is concentrated in irrigated oasis areas in the arid plains of Xinjiang, China (e.g. Korla region, Aksu region). Like most Rosaceae, the flowers of Korla fragrant pear are self-incompatible and depend on insect pollination or artificial pollination to ensure a sufficient fruit set (Li et al., 2022). However, pear flowers are often not attractive to pollinators because they have a relatively low volume of nectar per flower (Faoro and Orth, 2011). Moreover, pear production landscapes in the Korla region can be hostile environments for pollinators because of the high agrochemical use to control weeds, pests, and diseases, the limited amount of semi-natural habitats that may potentially offer nesting sites for wild bees, and the limited availability of floral resources before and after the pear flowering season. While pear pollination can be ensured by introducing managed honeybees and artificial pollination (e.g. hand pollination or pollen spraying), artificial pollination requires substantial labor and/or capital investment (Partap and Ya, 2012).

Apricot trees (*Prunus armeniaca* L.) flower in late March, approximately one week earlier than pear, providing flower resources for insect pollinators in early spring. Apricot and pear trees are the most common flowering plants in pear production areas in Xinjiang in the early season, in combination with much scarcer other rosaceous trees, such as peach and plum. Due to the relatively low value of apricots, apricot trees are usually not grown in monocultures, but scattered apricot trees are relatively common in or adjacent to pear orchards, home gardens, and roadsides. Apricot flowers are more attractive to bees than pear flowers (Lan et al., 2021), therefore apricot trees within or around pear orchards could potentially influence pollinator communities and pollination success in pear orchards via the “exporter” and “aggregation” mechanisms. However, it is not clear whether these mechanisms can explain spatial patterns of pollinator abundance in pear orchards and the associated pear pollination success, and if so, at what spatial scales.

Here we assessed how the presence of early flowering apricot trees within orchards or in the landscape surrounding orchards influence the abundance of bees and pollination success on pear trees, and how this influence is moderated by apricot flowering. First, we studied how the presence of interspersed apricot trees in pear orchards influenced the abundance of wild bees and honeybees, fruit set, and seed set in pear orchards (Experiment 1, Figure 4.1a). Second, we studied the effect of apricot tree rows at the edge of pear orchards on the abundance of wild bees and honeybees, fruit set, and seed set in pear orchards at different distances from the apricot trees (Experiment 2, Figure 4.1b and 4.2). Third, we assessed whether bee abundance, fruit set, and seed set in pear orchards are influenced by the density of apricot trees in the landscape around the orchards (Experiment 3, Figure 4.1c). We hypothesized that 1) pear orchards with interspersed apricot trees would have a higher bee abundance and higher pollination success than mono-pear orchards; 2) the abundance of bees and pollination success in pear trees declines with increasing distance from apricot trees; 3) the density of apricot trees in the surrounding landscape of pear orchards is a meaningful predictor of bee abundance in pear orchards; 4) apricot trees only influence bee abundance on pear trees during apricot blooming, but not after; and 5) pollination success of pear is positively associated with bee abundance.

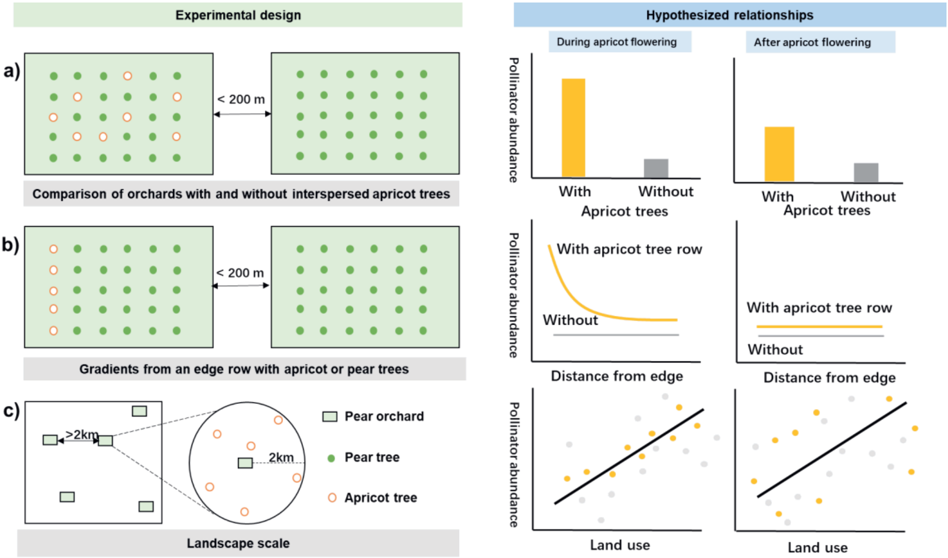

Figure 4.1 Experimental design and hypothesized relationships of three experiments in Korla fragrant pear orchards. The green squares indicate pear orchards, the green dots indicate pear trees, and the white dots indicate apricot trees. Experiment 1: the influence of apricot trees on the abundance of honeybees and wild bees in mixed and mono-pear orchards (a); Experiment 2: the influence of apricot tree row on the abundance of honeybees and wild bees on pear trees in strip apricot-pear orchards and mono-pear orchards (b); Experiment 3: the influence of apricot trees in the surrounding landscape of focal pear orchards (c). For the hypothesized relationships, we also expected that the pollination success (fruit set and seed set) of pear flowers is positively related to the presence of apricot trees in the three experiments (not shown in the Figure). The orange circles in panel c indicated the predicted pollinator abundance by the model included with apricot, and the gray circles indicated the predicted pollinator abundance by the model not included with apricot.

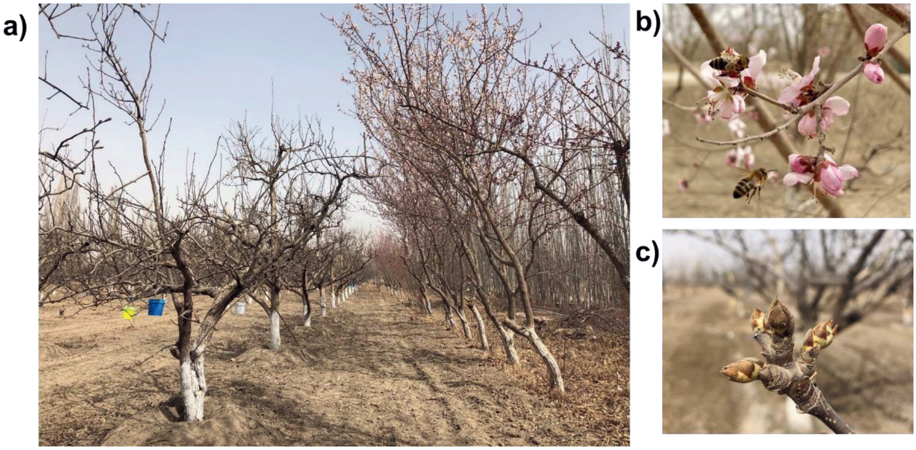

Figure 4.2 Pear orchard used in experiment 2. The orchard has pear trees on the left and an apricot tree row on the right (a), a close-up of apricot flowers (b), and a close-up of pear flower buds (c) in early spring in Korla, Xinjiang, China. The photos were taken on 31 March 2019.

4.2 Materials and methods

4.2.1 Study area

The study was conducted in the Korla region, Xinjiang, north-west China (E 85.48°, N 41.45°), which represents more than 60% of the pear cultivation area in Xinjiang (Xinjiang statistical yearbook, 2019). The total area of arable land in the Korla region is 1 x 10^5 ha, of which 26% consists of Korla fragrant pear, 65% of cotton, as well as some other fruit trees (e.g., apricot, peach, and jujube), and other crops (e.g., maize, sugar beet, alfalfa, and vegetables) (Xinjiang statistical yearbook, 2019). The region has a cold arid desert climate (Kottek et al., 2006), with an average annual precipitation of 60 mm and an average annual temperature of 11 $^{\circ}$C. Crop production relies on irrigation from the Kongque River, which originates from the nearby Tianshan mountain range.

Korla fragrant pear blooms for approximately two weeks in early April and pears are harvested in September. Pears are frequently treated with insecticides and fungicides throughout the growing season, except from one week before flowering until the end of flowering to avoid direct impacts on pollinators. Boron-based growth regulators are applied during flowering to enhance the fruit set (Perica et al., 2001). Mature pear trees are approximately 5 m high and are typically grown in rows at approximately 5 m distance between trees within the rows and 6 m between rows. Korla fragrant pear *(Pyrus sinkiangensis)* orchards usually contain Dangshan pear (*Pyrus bretschneideri*) trees as pollinizer to allow cross-pollination.

Selected pear orchards were 15-20 years old and had little or no flowering ground cover during the pear flowering period. There were no honeybee hives in the orchards and the orchards were not artificially pollinated. The experiments were conducted in 2019 and 2020, with different orchards selected in each year.

4.2.2 Experiment 1: Orchards with and without interspersed apricot trees

To assess the effect of the presence of interspersed apricot trees on pear pollination, we compared the abundance of wild bees and honeybees, fruit set, and seed set in mixed apricot-pear and mono-pear orchards in 2020 (Figure 4.1a; Table S4.1). Four sites were selected. The distance between the sites was at least 500 m. At each site, we selected two paired orchards, one with apricot trees interspersed between pear trees (treatment), and one with only pear trees (mono-pear control). The distance between the orchards was not more than 200 m. The mixed apricot-pear orchards contained at least 6% apricot trees in the sampling area (see below).

The bee abundance in each focal orchard was measured using colored pan traps (Zou et al., 2017) during pear flower blooming in early spring. Pan trap stations were established in four pear trees that were arranged on the corners of a 50 x 50 m square in the middle of the orchard if orchards were larger than 1 ha and a 20 x 20 m square otherwise. Trees with pan traps were located at least 10 m from the edge of the orchard. Each pan trap station consisted of three cups (12.1 cm diameter, 13 cm height) that were painted ultraviolet (UV) yellow (SANO, type No. 1005), UV blue (SANO, type No. 1004), and UV white (SANO, type No. 1010) on the inside and outside, and traps were fixed on three different branches of the same tree at a height of 1.5 m above ground. The traps were installed in the peak flowering period of apricot trees, which coincided with the onset of pear flowering, and were removed after pear flowering ended. Cups were filled with 600 ml water and a few drops of detergent. Cups were emptied and refilled four times at approximately 3-day intervals (range 2-4 days). A total of four sampling rounds were conducted from 31/03/2020 to 12/04/2020. Sampling round 1 coincided with the peak and late apricot blooming period, and sampling rounds 2, 3, and 4 took place after apricot blooming and during the early stages and peak period of pear blooming.

Samples of each focal orchard in four sampling rounds were pooled for analysis. We grouped pollinators into two taxa: honeybees (*Apis mellifera*) and wild bees (including Halictidae, Sphecidae, and Melittidae). The number of other potential pollinators, such as butterflies, moths, and hoverflies, was too low to conduct a meaningful analysis.

The initial fruit set was assessed in terms of the proportion of fruitlets per flower cluster at the end of April. Ten trees were selected per orchard in an “X” pattern and marked with red strings at the middle of the tree trunk, and 12 flower clusters per tree were selected and marked (three flower clusters x four cardinal directions) during pear blooming. The number of flowers per marked cluster was standardized to three flowers by carefully removing excess flowers by hand. The number of fruitlets per marked cluster was recorded one week after the end of flowering. The fruit set per orchard was calculated as the average proportion of fruitlets that developed from the initial number of marked flowers per cluster. The number of fruitlets was determined before thinning.

The seed set (number of mature seeds per pear) was assessed in early September before harvest. In each orchard five pear trees were selected in an “X” and from each tree six random pears were taken, for a total of 30 pears per orchard. The average number of seeds of 30 pears per orchard was used for the analysis of seed set.

4.2.3 Experiment 2: Gradients from an edge row with apricot or pear trees

To assess the relationship between pear pollination and the distance from the apricot tree row at the orchard edge, we compared the abundance of wild bees and honeybees, fruit set, and seed set in pear trees at five different distances (5, 15, 30, 50, and 100 m) from the edge row of apricot trees (strip-apricot pear orchard) and the edge row of pear trees (mono-pear orchard) in 2020 (Figure 4.1b; Table S4.2). Four sites (different from those of Experiment 1) were selected, which were located at least 500 m from each other. Within each site, we selected one pear orchard with a row of apricot trees at the edge and no other apricot trees in the orchard (treatment) and another pear orchard without apricot trees (control). The paired orchards were located not more than 200 m away from each other. For the assessment of bee abundance, we established pan trap stations on three trees per distance, at approximately 10 m distance within the row, for each of the five distances from the apricot/pear edge row. Three trees per distance were selected to assess fruit set (for a total of 3 trees x 12 flower clusters per tree = 36 flower clusters per distance) at the end of April. The fruit set was assessed by assessing the proportion of fruitlets per standardized flower clusters. Five additional trees were selected per distance to collect 30 fruits (6 fruits/tree) in early September, before harvest, to assess seed set. Procedures for sampling of bee abundance and assessment of pollination success were the same as in Experiment 1.

4.2.4 Experiment 3: apricot trees at the landscape scale

To assess how the density of apricot trees in the surrounding landscape influenced pear pollination, we assessed wild bee abundance, fruit set, and seed set in new 28 mono-pear orchards (15 in 2019 and another 13 in 2020) (Figure 4.1c; Table S4.3). The distance between orchards in the same year was at least 2 km. The abundance of wild bees and honeybees in 2019 and 2020, fruit set in 2020, and seed set in 2019 and 2020 were measured in each focal pear orchard using the same procedure as in Experiment 1, except for the procedure of fruit set assessment in 2019. In 2019, the fruit set was assessed by counting the number of fruitlets per flower cluster. Five pear trees were selected in an “X” pattern in each orchard and 12 flower clusters per tree were selected (three flower clusters x four cardinal directions). The fruit set for each orchard was calculated as the total number of fruitlets of the 60 flower clusters.

The number of apricot trees in radii of 0.5, 1.0, 1.5, and 2.0 km around focal pear orchards was assessed at the end of March 2019 and 2020 when the apricot trees can be easily recognized by their pink flowers. The number of apricot trees around the focal orchards was recorded by landscape survey. We drove through the landscape with a car recording the number of apricot trees and their location on a printed map. Only the flowering apricot trees were counted, and the age of the apricot tree was not recorded. The land use types in the landscape sectors were assessed by ground observation in early September of 2019 and 2020 when the annual crops were nearly mature and could be easily identified. The landscape data were digitized in ArcGIS 10.8 to calculate the percentage of each land use type around focal orchards. A total of 16 land use types were recorded and classified into seven categories: annual crops (19.4 ± 2.9%, including cotton, sugar beet, maize, vegetables, and watermelon), perennial crops (50.4 ± 2.5%, including pear, jujube, peach, apricot, and walnut), semi-natural habitats (7.5± 0.5%, including tree and grass belts), barren land (7.8 ± 1.3%, including bare fallow fields and uncultured field), infrastructure (6.3 ± 0.9%, including roads and open space), village (7.8 ± 1.4%), and water (0.7 ± 0.1%) (Table S4.4 and S4.5). The apricot density was positively correlated with perennial crop, which was dominated by pear orchards (Figure S4.1).

4.2.5 Data analysis

We conducted three analyses. In the first analysis (Expt. 1), we used generalized mixed effects models (GLMs) to explore how the abundance of wild bees and honeybees, fruit set, and seed set (response variables) were influenced by scattered apricot trees (presence or absence; “treatment”), sampling round (four rounds) and their interaction (explanatory variables). “Site” (i.e. the landscape in which the two paired pear orchards were embedded) was included as a random effect. In addition, we explored the effect of apricot trees within pear orchards in subsets of data for each sampling round.

Second (Expt. 2), we used generalized linear models to explore how the abundance of wild bees and honeybees, fruit set, and seed set (response variables) were influenced by the apricot tree row (presence or absence; “treatment”), distance from the edge row (5, 15, 30, 50, and 100 m), sampling round (four rounds), and their interaction (explanatory variables). “Site” was included as a random effect. To avoid redundant models and spurious results, a multi-model inference procedure based on the bias-corrected Akaike’s information criterion (AICc, corrected for small sample sizes) was performed for each response variable. We calculated all potential models that were nested in the global model as candidate models, and then ranked and selected among all alternative candidate models (Burnham and Anderson, 2004). The model selection process revealed the relative importance of explanatory variables and the relationships between the response and explanatory variables. The relative importance of explanatory variables was quantified by the sum of the Akaike weights associated with each variable in the fitted models (Grueber et al., 2011). All candidate models were selected in the model averaging procedure, from which we derived the importance value and coefficient estimates for each variable. The full average results were used, i.e. a model without a given predictor would contribute a value of 0 to the calculation of the weighted mean coefficient across models of that predictor (Grueber et al., 2011). We further conducted follow-up analyses using separate models for each sampling round.

Third (Expt. 3), we explored whether variation in abundance of wild bees and honeybees, fruit set, and seed set (response variables) in pear orchards were influenced by the seven land use types and apricot density in the surrounding (tree/km^2; response variables) using generalized linear models. We compared the AICc value of models containing both the seven land use types and apricot density with models that only contained the seven land use types as explanatory variables (Burnham and Anderson, 2004). Due to a significant positive correlation between perennial crops and annual crops, we excluded the perennial crops from the model (Figure S4.1). To account for differences in the sampling days we included the log-transformed sampling days as an offset variable in the full model (Zuur et al., 2009). In ecological terms, this means that the response variable is now expressed as the number of wild bees captured per day. We conducted analyses based on apricot densities in concentric circles of 0-0.5, 0-1.0, 0-1.5, and 0-2.0 km radii around the focal field. The difference between both types of models was compared by the Chi-squared test. Variance inflation factor (VIF) values for the explanatory variables in each global model were calculated and were found to be less than four, indicating that covariation between explanatory variables was not a problem (Dormann et al., 2013).

For all analyses, we used a negative binomial error distribution to analyze the count data (including the abundance of wild bees and honeybees, and number of fruitlets). For the fruit set rate, we used a normal error distribution. Due to the substantial overdispersion of fruit set rate when fit in a binomial error distribution, the ratio between the number of fruitlets and the number of flowers per orchard was performed and fitted with a normal error distribution. Moreover, the seed set was non-integer which averaged 30 fruits per orchard, we also used a normal error distribution. The Models were validated using histograms of normalized residuals and plots of residuals against fitted values (Zuur et al., 2009). All statistical analyses were performed using R version 4.0.5 (R Core Team, 2018). We used the glmer or lmer function of the "lme4" package (Bates et al., 2015) for Experiments 1 and 2, and the glm or lm function of the "MASS" package (Ripley et al., 2018) for Experiment 3. Means and standard errors of the mean are reported throughout the text.

4.3 Results

4.3.1 Experiment 1: Orchards with and without interspersed apricot trees

A total of 786 wild bees (540 and 246 individuals in apricot-pear and mono-pear orchards, respectively) and 104 honeybees (49 and 55 individuals in apricot-pear and mono-pear orchards, respectively) were trapped in four sampling rounds in the four paired sites in 2020.

The abundance of wild bees declined significantly with the sampling round ($P < 0.001$), but was not significantly influenced by the treatment and the interaction between the treatment and sampling round (Figure 4.3a; Table S4.6). For the abundance of honeybees there was a significant treatment-sampling round interaction ($P = 0.025$) indicating that the honeybee abundance decreased over time in apricot-pear orchards, but not in mono-pear orchards (Figure 4.3b; Table S4.6). This suggests a waning effect of the apricot on honeybee abundance as the apricots stopped flowering while pear started flowering.

When analyzing the relationship for the period of apricot blooming (sampling round 1) and after apricot blooming (sampling rounds 2, 3, and 4) separately, the abundance of wild bees ($P < 0.001$) and honeybees ($P = 0.048$) was significantly higher in apricot-pear orchards than in mono-pear orchards during apricot blooming, but not after apricot blooming (Figure 4.3; Table S4.7 and S4.8). The fruit set and seed set of pears were not significantly influenced by the presence of apricot trees in orchards (Table S4.9).

4.3.2 Experiment 2. Gradients from an edge row with apricot or pear trees

We collected a total of 2580 wild bees (1425 and 1155 individuals in apricot row-pear orchards and mono-pear orchards, respectively) and 404 honeybees (234 and 170 individuals in apricot row-pear orchards and mono-pear orchards, respectively) in four paired sites in 2020.

Results of the model averaging procedure showed that the abundance of wild bees was decreased significantly with sampling round ($P = 0.043$), but was not significantly influenced by treatment, sampling distance and their interaction (Figure 4.4; Table S4.10 and S4.11). For the abundance of honeybees there was a significant interaction between treatment and sampling round ($P = 0.025$), indicating that the effect of the presence of an edge row of apricot depended on the sampling round (Figure 4.5; Table S4.12 and S4.13).

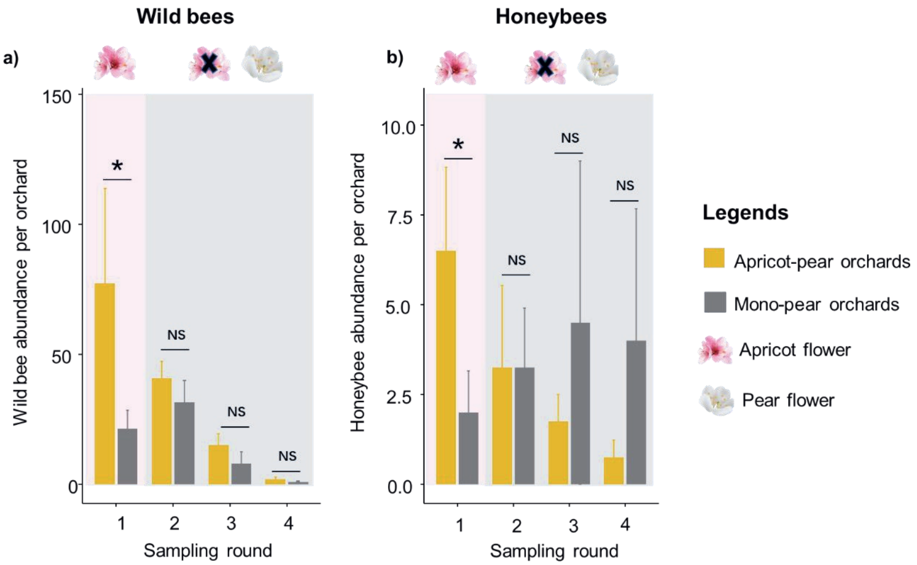

Figure 4.3 Wild bee abundance (a) and honeybee abundance (b) in apricot-pear (orange bars) and mono-pear orchards (grey bars) in four sampling rounds in 2020. Sampling round 1 coincided with apricot blooming while pear started blooming. Sampling rounds 2, 3, and 4 took place after apricot blooming and during the early and peak blooming of pear. Error bars represent the standard error of the mean. Asterisks (*) indicate significant differences ($P < 0.05$) and NS indicate non-significant differences ($P > 0.05$; Table S4.8).

During apricot blooming (sampling round 1), the abundance of wild bees and honeybees was significantly higher on pear trees adjacent to the apricot tree row (5 m) than on pear trees adjacent to the control pear row, but not at the subsequent three distances from the tree rows (15 m, 30 m, and 50 m) though it was again significant at 100 m ($P = 0.002$) (Figure 4.4 and 4.5; Table S4.14 and S4.15). After apricot blooming (sampling rounds 2, 3, and 4), the abundance of wild bees and honeybees was not significantly influenced by treatment and distance from the tree row (Figure 4.4 and 4.5; Table S4.14 and S4.15). The fruit set and seed set of pears were not significantly influenced by the treatment and distance from the tree row (Table S4.16 and S4.17).

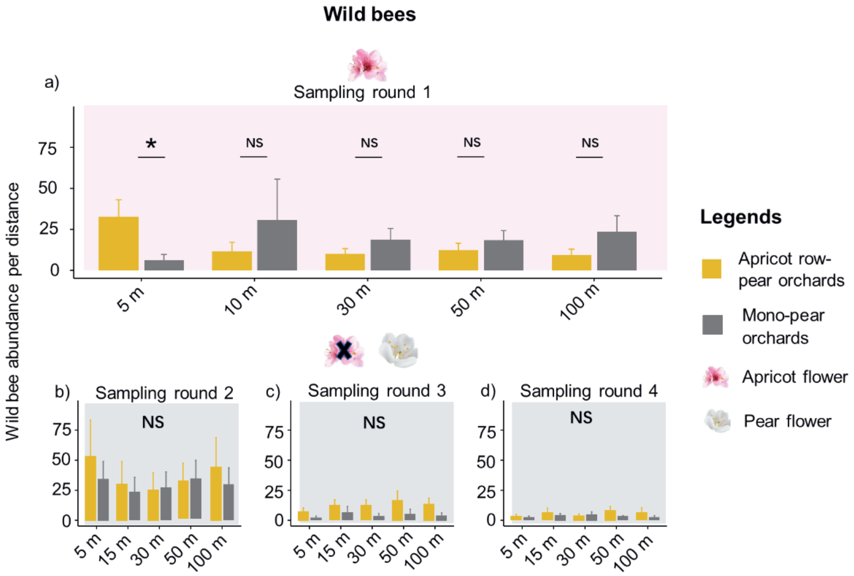

Figure 4.4 The abundance of wild bees during apricot blooming (a) and after apricot blooming (b, c, and d) in Korla fragrant pear trees at distances of 5, 15, 30, 50, and 100 m from apricot edge tree rows (orange bars) and pear tree rows (grey bars). Sampling round 1 coincided with apricot blooming when pear started blooming. Sampling rounds 2, 3, and 4 took place after apricot blooming and during the early and peak of pear blooming. Error bars represent the standard error of the mean. Asterisks (*) indicate the significant effect of treatment ($P < 0.05$) and NS indicate the non-significant effect of treatment ($P > 0.05$; Table S4.15).

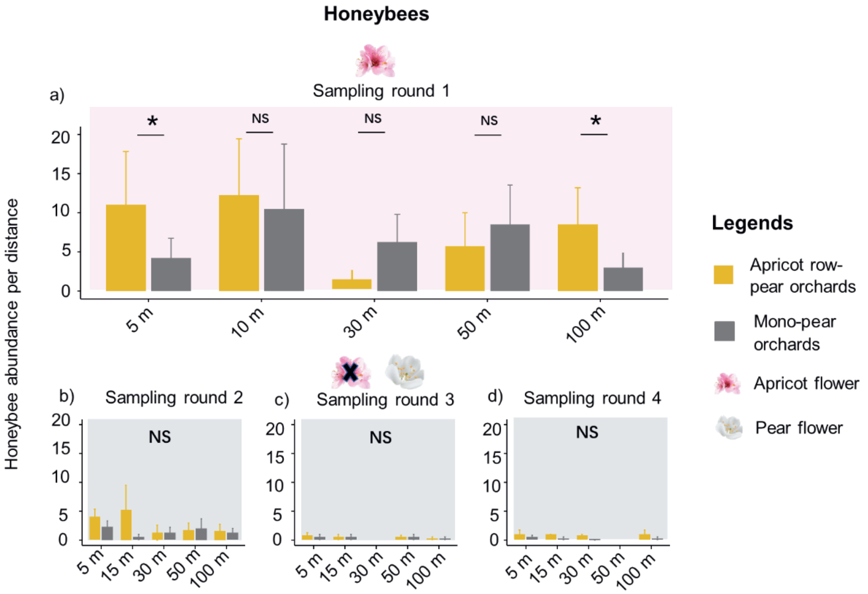

Figure 4.5 The abundance of honeybees during apricot blooming (a) and after apricot blooming/during pear blooming (b, c, and d) in Korla fragrant pear trees at distances of 5, 15, 30, 50, and 100 m from apricot edge tree rows (orange bars) or pear tree rows (grey bars). Sampling round 1 coincided with apricot blooming and pear was not yet blooming. Sampling rounds 2, 3, and 4 took place after apricot blooming and during the early and peak of pear blooming. Error bars represent the standard error of the mean. Error bars represent the standard error of the mean. Asterisks (*) indicate the significant effect of apricot tree row (treatment) ($P < 0.05$) and NS indicate the non-significant effect of apricot tree row (treatment) ($P > 0.05$; Table S4.15).

4.3.3 Experiment 3: Apricot trees at the landscape scale

A total of 2309 wild bees and 600 honeybees were collected in 28 orchards during a 12-day sampling period in 2019 and another 12-day in 2020. We caught on average 82.5 ± 12.3 wild bees per orchard (range 13 - 289) and 21.4 ± 3.5 honeybees (range 0 - 75).

Comparison of models with apricot tree density and land use types as explanatory variables were not significantly different from models with only land use types, indicating that the presence of apricot trees had no additional predictive value on the abundance of honeybees and wild bees in radii of 0.5, 1.0, 1.5 and 2.0 km around pear orchards (Table 4.1, Table S4.18 and 4.19). Likewise, the fruit set of pears was not significantly influenced by the density of apricot trees in the surrounding landscape (Table S4.20 and 4.21). However, the seed set of pears was significantly and negatively influenced by the density of apricot trees at a scale of 0.5 (*P* = 0.004) and 1.0 km (*P* = 0.006), but not at larger spatial scales (Table S4.22). The seed set in 2019 was significantly higher than in 2020 (Table S4.22).

Table 4.1. Model comparison results between models with apricot and land use variables as explanatory variables (with apricot) and models with only land use variables as explanatory variables (without apricot) in cumulative landscape sectors of 0.5 km, 1.0 km, 1.5 km, and 2.0 km radii (Table S4.18 and 4.19). The response variables were abundance of wild bees and honeybees assessed during four sampling rounds. The difference between both types of models was compared by Chi-squared tests.

Scales (km)	Wild bee abundance			Honeybee abundance		
	AICc With apricot	AICc Without apricot	Pr (Chi)	AICc With apricot	AICc Without apricot	Pr (Chi)
1) Sampling round 1						
0.5	252.20	250.77	0.447	165.82	164.89	0.302
1.0	256.11	254.16	0.822	162.32	160.43	0.742
1.5	251.58	249.67	0.765	163.22	161.85	0.427
2.0	248.87	247.32	0.500	157.57	155.57	0.975
2) Sampling round 2						
0.5	268.74	266.74	0.985	184.92	183.14	0.693
1.0	257.90	277.58	1.000	177.67	177.58	0.168
1.5	256.49	255.88	0.237	180.07	178.25	0.675
2.0	253.74	254.05	0.128	175.00	173.18	0.672
3) Sampling round 3						
0.5	200.50	198.90	0.527	132.92	133.09	0.140
1.0	180.99	119.72	1.000	134.90	133.72	0.368
1.5	184.83	185.27	0.181	118.76	117.08	0.567
2.0	184.83	182.27	0.118	123.32	121.44	0.716
4) Sampling round 4						
0.5	120.73	119.23	0.478	146.13	145.03	0.343
1.0	114.38	114.08	0.193	140.79	135.22	1.000
1.5	123.62	121.98	0.547	150.98	148.98	0.977
2.0	121.99	120.83	0.360	148.07	147.54	0.225

4.4 Discussion

We assessed the influence of apricot as an early flowering tree species on the abundance of bees and pollination success in Korla fragrant pear at three spatial scales. Here we report five key findings: i) scattered apricot trees in pear orchards increased the bee abundance in pear orchards during apricot flowering, but not after apricot flowering; ii) during apricot blooming, the abundance of wild bees and honeybees was higher in pear trees adjacent to apricot tree rows at the edge of the orchard than adjacent to other pear trees, but this effect did not extend further than 5 m; iii) the higher bee abundance during apricot blooming did not lead to higher pollination success; iv) apricot trees in the surroundings of pear orchards did not influence wild and honeybee abundance in pear orchards.

4.4.1 Effect of apricot trees on the abundance of wild bees and honeybees in pear orchards

The abundance of wild bees and honeybees was higher in mixed apricot-pear orchards than in mono-pear orchards, but only during the apricot blooming time (Figure 4.4a and 4.4b, Expt. 1). This response of wild bees and honeybees aligns with the general hypothesis that a diversified plant community may attract more pollinators than species-poor plant communities (Campbell et al., 2017; Albrecht et al., 2020). Flowering apricot trees within focal pear orchards thus appear to act as “magnets” that attract and arrest wild bees in the orchard from the surrounding area (Diekötter et al., 2010; Montero- Castaño et al., 2016). However, since this bee attraction effect was only observed during apricot blooming this suggests that this is an instantaneous aggregation effect and that it does not lead to retention of bees for the pollination of pear trees after apricot flowering. These findings suggest that establishing apricot trees in pear orchards may facilitate wild bees and honeybees in pear orchards, but this effect only occurs during the few days that flowering of apricot and pear coincide.

4.4.2 Spatially confined spillover effects of bees around apricot trees

During apricot blooming, we found that apricot tree rows only increased the abundance of wild bees and honeybees on adjacent pear trees and not in pear trees at greater distances (Figure 4.5a and 4.6a, Expt. 2). These results are in line with studies that report aggregation of pollinators to flowers-rich habitats (Kleijn et al., 2018; Kohler et al., 2007; Morandin and Kremen 2013; Nicholson and Wright et al., 2017; Zamorano et al. 2020) and declining pollinator abundance with distance from flower-rich habitats (Albrecht et al., 2020). In apricot row-pear orchards, the wild bee abundance-distance relationship was relatively steep (Figure 4.5a), indicating that apricot trees arrest bees in a relatively small area with a radius of approximately five meters. Therefore, to maximize benefits from the bee attraction effect of apricot trees the spatial distribution of apricot trees in pear orchards should be taken into consideration.

4.4.3 Increased bee abundance by apricot did not lead to increased pollination

In contrast with our hypothesis, the higher bee abundance near apricot trees did not result in a higher fruit or seed set in pears. This finding does not align with other studies that report increased pollination services in target crops associated with enhanced abundance of wild bees and honeybees near flowering habitats (Blaauw and Isaacs, 2014, Holzschuh et al., 2012; Földesi et al., 2015). The absence of increased pollination success in our study could be explained by several reasons. First, the bee aggregation effect of apricot trees was only local and short-term, and therefore it may not have had a meaningful effect on fruit and seed set. Second, the Korla fragrant pear pollination largely depends on pollination by honeybees (Li et al., 2022), and the abundance of honeybees in our study orchards was relatively low because the orchards did not contain beehives and there are no feral honeybees in the study region. Third, pear flowers are not attractive for wild bees (Monzón, et al., 2004), and therefore a higher wild bee abundance associated with apricot trees does not mean that the wild bees will also visit pear flowers. Thus, our results suggest that the increased wild bee abundance associated with apricot trees do not lead to a meaningful improvement of pollination in the pear crop.

4.4.4 Apricot trees in the surrounding landscape do not influence pollinator abundance in pear orchards

Opposite to our hypothesis, the presence of apricot trees in the surrounding landscape did not influence pollinator abundance and pollination success in pear orchards, except for a negative effect on seed set at the scale of 0.5 and 1.0 km (Table S4.22, Expt. 3). The lack of effect of apricot trees in the surrounding landscape in pear orchards may be explained by the following two factors. First, the apricot trees in the surrounding landscape may have been too few and too far to have a measurable effect on the abundance of wild bees and honeybees in pear orchards. Second, honeybee abundance strongly depends on the location and number of honeybee hives, which depends on decision-making by beekeepers and not on the presence of apricot trees in the surrounding landscape. The negative effect of apricot in the surrounding landscape on the seed set of pears was unexpected and is hard to explain based on the current dataset. The seed set is commonly determined by bee abundance and flower handling behavior by bees (Russo et al., 2017), but we have not detected any improved bee abundance by apricot in the surrounding landscape (Table 4.1) and data on flower visitation by bees was not assessed in this study. Overall, while apricot flowers are more attractive for bees than pear flowers, the associated aggregation effect occurs at the local scale and not at the landscape scale.

4.5 Conclusions

Korla fragrant pear requires cross-pollination to secure satisfactory fruit production, but pollinator abundance may be too low to provide the required pollination services in our study region. Our findings indicate that the presence of apricot trees, as an early flowering crop, increased the abundance of wild bees and honeybees in Korla fragrant pear orchards, however, this effect was only local and short-term and did not lead to improved pollination success. This suggests that pollination of Korla fragrant pear can be more effectively achieved by using honeybees (Li et al., 2022). The effectiveness of honeybees can be potentially enhanced by using synthetic Nasonov gland pheromone to attract honeybees to the pear trees (Li et al., 2023). When attempting to enhance Korla fragrant pear pollination using flowering plants, it is necessary to consider the overall effects of such plants on the life cycle of potential pollinators, as well as the flower preferences of pollinators. Establishing meaningful areas of habitats that provide floral resources in early spring, such as apricot trees, in combination with a reduction in insecticide use may offer scope to stimulate pollinator communities in intensively managed agricultural landscapes and to conserve wild bee diversity. However, pollination services in Korla fragrant pear are guaranteed most efficiently by promoting the use of honeybees.

Acknowledgments

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Supplementary Information

Table S4.1 Information on Korla fragrant pear orchards used for Experiment 1 (comparison of orchards with and without interspersed apricot trees).

Year	Site	Latitude（N）	Longitude (E)	Size (ha)	Pollinator sampling period
2020	1	85.95306	41.81750	2.02	2020/3/31-4/12
2020	1	85.95333	41.81611	0.59	2020/3/31-4/12
2020	2	86.02111	41.73028	0.81	2020/3/31-4/12
2020	2	86.02139	41.72972	0.83	2020/3/31-4/12
2020	3	86.06000	41.75833	0.53	2020/3/31-4/12
2020	3	86.05990	41.75777	0.94	2020/3/31-4/12
2020	4	85.90073	41.69684	0.66	2020/3/31-4/12
2020	4	85.90138	41.69560	0.74	2020/3/31-4/12

Table S4.2 Information on the Korla fragrant pear orchards used for Experiment 2 (with and without an apricot edge row).

Year	Site	Latitude（N）	Longitude (E)	Size (ha)	Pollinator sampling period
2020	1	85.97528	41.81194	1.38	2020/4/1-4/13
2020	1	85.97412	41.81304	0.91	2020/4/1-4/13
2020	2	85.98108	41.81216	1.04	2020/4/1-4/13
2020	2	85.98331	41.81198	1.39	2020/4/1-4/13
2020	3	86.04075	41.80201	0.64	2020/4/1-4/13
2020	3	86.04249	41.80200	0.72	2020/4/1-4/13
2020	4	85.99261	41.81174	1.31	2020/4/1-4/13
2020	4	85.99377	41.81112	1.15	2020/4/1-4/13

Table S4.3 Information on the Korla fragrant pear orchards used for Experiment 3 (effect of apricot trees at a landscape scale).

Year	Site	Latitude（N）	Longitude (E)	Size (ha)	Pollinator sampling period
2019	1	86.02761	41.75982	2.14	2019/3/31-4/12
2019	2	85.94621	41.75389	2.65	2019/3/31-4/12
2019	3	85.91435	41.75177	0.86	2019/3/31-4/12
2019	4	85.88438	41.69178	1.30	2019/3/31-4/12
2019	5	85.95025	41.70325	0.93	2019/3/31-4/12
2019	6	85.98694	41.72123	1.35	2019/3/31-4/12
2019	7	86.06130	41.74011	1.14	2019/3/31-4/12
2019	8	86.01051	41.79649	1.38	2019/3/31-4/12
2019	9	85.88758	41.82668	2.17	2019/3/31-4/12
2019	10	86.11975	41.63662	2.45	2019/3/31-4/12
2019	11	86.04022	41.62643	0.17	2019/3/31-4/12
2019	12	86.00981	41.62643	0.31	2019/3/31-4/12
2019	13	85.93809	41.65725	2.04	2019/3/31-4/12
2019	14	85.84494	41.73703	0.12	2019/3/31-4/12
2019	15	85.85335	41.72454	1.98	2019/3/31-4/12
2020	16	85.97509	41.81551	1.35	2020/4/2-4/14
2020	17	86.03091	41.79102	2.91	2020/4/2-4/14
2020	18	86.05868	41.75849	0.57	2020/4/2-4/14
2020	19	86.11034	41.78311	1.74	2020/4/2-4/14
2020	20	86.11048	41.72915	3.56	2020/4/2-4/14
2020	21	86.10119	41.66670	2.23	2020/4/2-4/14
2020	22	86.06877	41.69888	0.31	2020/4/2-4/14
2020	23	86.04189	41.66496	0.41	2020/4/2-4/14
2020	24	85.92201	41.67496	0.39	2020/4/2-4/14
2020	25	85.82571	41.68764	1.11	2020/4/2-4/14
2020	26	85.88408	41.74364	1.45	2020/4/2-4/14
2020	27	85.97350	41.76017	0.23	2020/4/2-4/14
2020	28	86.01960	41.73138	1.45	2020/4/2-4/14

Table S4.4 The detailed category and description of 16 land use types.

	Land use types	Category	Description
1	Cotton	Annual crop	Cotton
2	Pear	Perennial crop	Pear orchard
3	Apricot	Perennial crop	Apricot orchard
4	Peach	Perennial crop	Peach orchard
5	Jujube	Perennial crop	Jujube orchard
6	Grape	Perennial crop	Grape orchard
7	Maize	Annual crop	Maize
8	Vegetable	Annual crop	Cabbage, sugar beet, peanut, and greenhouse
9	Alfalfa	Annual crop	Alfalfa
10	Grass belt	Semi-natural habitat	The grass belt in the field margin
11	Tree belt	Semi-natural habitat	The tree belt in the field margin or roadside
12	Barren land	Wasteland	Fallow and uncultured land
13	Road	infrastructure	Concrete pavements and country roads without concrete
14	Open space	infrastructure	The space that with hardened pavement, such as a factory
15	Village	Village	The clustered human settlement or community, normally with fixed dwellings, gardens, and trees
16	Water	Water	River

Table S4.5 The percentage of each land use type and apricot density (trees/km^2) of focal pear orchards at four spatial scales in Korla, Xinjiang, China.

Scales	Land use types	Average (%)	SE (%)	Min (%)	Max (%)
500m	Annual crops	12.53	2.86	0.00	50.85
	Perennial crops	57.92	3.24	23.26	88.24
	Semi-natural habitats	8.98	1.11	0.00	27.35
	Barren land	5.24	1.03	0.00	24.66
	Infrastructure	6.71	1.06	1.26	23.34
	Village	8.06	2.05	0.00	46.08
	Water	0.57	0.25	0.00	4.94
1000m	Annual crops	16.11	3.08	0.09	67.30
	Perennial crops	52.84	2.61	24.03	76.01
	Semi-natural habitat	8.08	0.77	1.24	18.50
	Barren land	6.98	1.18	0.68	26.83
	Infrastructure	7.11	1.06	1.51	21.07
	Village	8.15	1.70	0.24	32.52
	Water	0.72	0.19	0.00	2.71
1500m	Annual crops	18.04	2.94	0.55	60.65
	Perennial crops	51.98	2.37	29.69	76.90
	Semi-natural habitat	7.51	0.59	2.08	13.98
	Barren land	7.38	1.32	0.45	35.07
	Infrastructure	6.47	0.85	1.17	17.15
	Village	7.91	1.42	0.45	32.92
	Water	0.71	0.17	0.00	3.31
2000m	Annual crops	19.43	2.92	0.41	58.95
	Perennial crops	50.42	2.48	29.06	73.82
	Semi-natural habitat	7.53	0.54	2.74	13.93
	Barren land	7.85	1.33	0.75	31.83
	Infrastructure	6.25	0.86	1.22	17.77
	Village	7.84	1.44	1.11	35.91
	Water	0.68	0.15	0.00	2.51

Table S4.6 Results of GLMM analysis with negative binomial error distribution for the samplings in paired apricot-pear and mono-pear orchards **(Expt. 1)**. The response variables were the abundance of wild bees and honeybees, and the explanatory variables were treatment (mixed apricot-pear orchard and mono-pear orchard) and sampling rounds (four rounds). Paired pear orchard was included as a random variable. Mono-pear orchard and sampling round 1 served as controls. Significant ($P < 0.05$) relationships were indicated in bold and marginally significant ($0.1 < P < 0.05$) relationships were indicated in italic.

Response variables	Explanatory variables	Estimate	Std.Error	Z value	Pr (>|t|)
Wild bee abundance	Intercept	4.75	0.59	8.08	**<0.001**
	Treatment	0.83	0.73	1.13	0.258
	Sampling round	-1.00	0.22	-4.50	**<0.001**
	Treatment x Sampling round	-0.08	0.29	-0.28	0.783
Honeybee abundance	Intercept	0.56	0.85	0.66	0.508
	Treatment	1.81	0.98	1.85	*0.064*
	Sampling round	0.09	0.26	0.35	0.728
	Treatment x Sampling round	-0.84	0.37	-2.25	**0.025**

Table S4.7 Mean and standard error of the abundance of wild bees and honeybees per orchard in four paired apricot-pear and mono-pear orchards in four sampling rounds **(Expt. 1)**.

Treatment	Wild bees		Honeybees	
	Mean	SE	Mean	SE
1) During apricot blooming - Sampling round 1				
Mixed apricot-pear orchard	77.20	36.50	6.50	2.33
Mono-pear orchard	21.20	7.20	2.33	1.15
2) After apricot blooming - Sampling round 2				
Mixed apricot-pear orchard	40.80	6.46	3.25	2.29
Mono-pear orchard	31.50	8.33	3.25	1.65
3) After apricot blooming - Sampling round 3				
Mixed apricot-pear orchard	15.00	4.38	1.75	0.75
Mono-pear orchard	8.00	4.53	4.50	4.50
4) After apricot blooming - Sampling round 4				
Mixed apricot-pear orchard	2.00	0.71	0.75	0.48
Mono-pear orchard	0.75	0.25	4.00	3.67

Table S4.8 Results of sampling round-specific GLMM analyses with negative binomial error distribution for paired apricot-pear and mono-pear orchards **(Expt. 1)**. The response variables were the abundance of wild bees and honeybees, and the explanatory variable was treatment (apricot-pear orchard and mono-pear orchard). Paired pear orchard was included as a random variable. Mono-pear orchard served as control. Significant (*P* < 0.05) relationships were indicated in bold, and marginally significant (0.1 < *P* < 0.05) relationships were indicated in italic.

Response variables	Estimate	Std. Error	Z value	Pr (>|t|)
1) During apricot blooming -Sampling round 1				
Wild bee abundance	1.23	0.24	5.03	**<0.001**
Honeybee abundance	1.18	0.60	1.98	**0.048**
2) After apricot blooming - Sampling round 2				
Wild bee abundance	0.26	0.27	0.95	0.340
Honeybee abundance	0.00	0.85	0.00	1.000
3) After apricot blooming - Sampling round 3				
Wild bee abundance	0.63	0.66	0.96	0.340
Honeybee abundance	-0.95	1.19	-0.79	0.429
4) After apricot blooming - Sampling round 4				
Wild bee abundance	0.98	0.68	1.45	0.147
Honeybee abundance	-1.67	1.32	-1.27	0.204

Table S4.9 Results of GLMM analysis for the pollination success in paired apricot-pear and mono-pear orchards **(Expt. 1)**. The response variables were the fruit set in 2020 and seed set in 2020, and the explanatory variable was treatment (apricot-pear orchard and mono-pear orchard). Paired pear orchard was included as a random variable. Mono-pear orchard served as controls. Significant (*P* < 0.05) relationships were indicated in bold.

Response variables	Estimate	Std. Error	Z value	Pr(>|t|)
1) Fruit set in 2020				
Intercept	0.09	0.02	4.66	**0.017**
Treatment	-0.01	0.01	-1.81	0.168
2) Seed set in 2020				
Intercept	5.93	0.64	9.30	**<0.001**
Treatment	-0.08	0.69	-0.11	0.920

Table S4.10 Most parsimonious models (ΔAICc < 2) resulting from model selection of all combinations of terms from global models that assessed the effect of treatment (apricot tree row), sampling round, sampling distance, and their interaction (explanatory variables) on **the abundance of wild bees**. K, number of parameters of each model; LogLik, log-likelihood of the model; AICc, Akaike's Information Criterion corrected for small sample size; ΔAICc, the difference in AICc value between the best ranked models; Weight, Akaike weight, which can be interpreted as the conditional probabilities for each candidate model **(Expt. 2)**.

	Model	df	logLiK	AICc	delta	weight
1	Treatment+sampling round+treatment:sampling rounds	6	-544.639	1101.8	0	0.215
2	Treatment+samping distance+sampling round+treatment: sampling rounds+treatment:sampling distance+sampling distance:sampling round+treatment:sampling rounds: sampling distance	10	-540.303	1102.1	0.26	0.189
3	Sampling round+treatment:sampling rounds	4	-547.021	1102.3	0.47	0.17
4	Treatment+sampling distance+sampling round+treatment: sampling rounds	7	-544.525	1103.8	1.96	0.081

Table S4.11 Results of multi-model inference analysis to determine the model with treatment (apricot tree row), sampling rounds, sampling distance and their interaction as explanatory variables effect on **the abundance of wild bees** (response variable). The average model was taken from the total candidate models. Z value is the estimate of each coefficient divided by its standard error **(Expt. 2)**.

Explanatory variables	Estimate	Std. Error	Z value	Pr(>|z|)
Intercept	3.438	0.662	5.165	**0.000**
Treatment	0.720	0.965	0.745	0.456
Sampling round	-0.416	0.205	2.025	**0.043**
Treatment x Sampling round	-0.300	0.388	0.773	0.440
Sampling distance	0.016	0.134	0.121	0.904
Treatment x Sampling distance	-0.121	0.260	0.466	0.641
Sampling distance x Sampling round	-0.008	0.051	0.166	0.868
Treatment x Sampling distance x Sampling distance	0.044	0.100	0.443	0.658

Table S4.12 Most parsimonious models (ΔAICc < 2) resulting from model selection of all combinations of terms from global models that assessed the effect of treatment, sampling round, sampling distance, and their interaction (explanatory variables) on **the abundance of honeybees**. K, number of parameters of each model; LogLik, log-likelihood of the model; AICc, Akaike's Information Criterion corrected for small sample size; ΔAICc, the difference in AICc value between the best ranked models; Weight, Akaike weight, which can be interpreted as the conditional probabilities for each candidate model **(Expt. 2)**.

	Model	df	logLiK	AICc	delta	weight
1	Treatment+sampling distance+sampling round+treatment:sampling round	7	-256.12	527	0	0.385
2	Treatment +sampling round+treatment:sampling rounds	6	-257.934	528.4	1.44	0.187
3	Treatment+sampling distance+sampling round+treatment:sampling rounds +treatment:sampling distance	8	-255.886	528.7	1.75	0.161

Table S4.13 Results of multi-model inference analysis to determine the model with treatment (apricot tree row), sampling round, sampling distance and their interaction as explanatory variables effect on **the abundance of honeybees** (response variable). The average model was taken from the total candidate models. Z value is the estimate of each coefficient divided by its standard error **(Expt. 2)**.

Explanatory variables	Estimate	Std. Error	Z value	Pr(>|z|)
Intercept	2.921	0.717	4.043	**0.000**
Treatment	-0.500	0.673	0.738	0.461
Sampling distance	-0.091	0.138	0.654	0.513
Sampling round	-1.243	0.234	5.274	**<0.001**
Treatment x Sampling round	0.651	0.288	2.250	**0.025**
Treatment x Sampling distance	-0.032	0.113	0.281	0.779
Sampling distance x Sampling round	-0.009	0.045	0.206	0.837
Treatment x Sampling distance x Sampling distance	0.001	0.026	0.053	0.958

Table S4.14 Mean and standard error of the abundance of wild bees and honeybees per orchard in four paired apricot row-pear and mono-pear orchards in five sampling distances and in four sampling rounds **(Expt. 2)**.

Distance (m)	Treatment	Wild bees		Honeybees	
		Mean	SE	Mean	SE
1) During apricot blooming -sampling round 1					
5	Strip apricot-pear orchard	32.50	10.38	11.00	6.82
	Mono-pear orchard	6.25	3.28	4.25	2.50
15	Strip apricot-pear orchard	11.50	5.68	12.25	7.22
	Mono-pear orchard	30.75	24.79	10.50	8.27
30	Strip apricot-pear orchard	10.00	3.08	1.50	1.19
	Mono-pear orchard	18.75	6.84	6.25	3.57
50	Strip apricot-pear orchard	12.25	4.33	5.75	4.25
	Mono-pear orchard	18.50	5.69	8.50	5.07
100	Strip apricot-pear orchard	9.25	3.47	8.50	4.73
	Mono-pear orchard	23.50	9.84	3.00	1.91
2) After apricot blooming -sampling round 2					
5	Strip apricot-pear orchard	53.50	29.85	4.00	1.35
	Mono-pear orchard	34.50	14.71	2.25	1.03
15	Strip apricot-pear orchard	30.50	18.31	5.25	4.27
	Mono-pear orchard	23.75	12.03	0.50	0.50
30	Strip apricot-pear orchard	25.75	13.84	1.25	1.25
	Mono-pear orchard	27.50	12.68	1.25	0.95
50	Strip apricot-pear orchard	31.50	14.45	1.75	1.18
	Mono-pear orchard	33.25	15.09	2.00	1.68
100	Strip apricot-pear orchard	44.75	23.81	1.50	1.19
	Mono-pear orchard	30.25	13.29	1.25	0.75
3) After apricot blooming -sampling round 3					
5	Strip apricot-pear orchard	7.75	2.95	0.75	0.48
	Mono-pear orchard	2.50	1.32	0.50	0.50
15	Strip apricot-pear orchard	12.75	4.77	0.50	0.50
	Mono-pear orchard	7.00	4.42	0.50	0.50
30	Strip apricot-pear orchard	13.00	4.24	0.00	0.00
	Mono-pear orchard	3.75	2.06	0.00	0.00
50	Strip apricot-pear orchard	17.00	7.29	0.50	0.29
	Mono-pear orchard	5.25	4.27	0.50	0.50
100	Strip apricot-pear orchard	13.75	4.85	0.25	0.25
	Mono-pear orchard	4.00	2.38	0.25	0.25
4) After apricot blooming -sampling round 4					
5	Strip apricot-pear orchard	3.75	1.11	1.00	0.71
	Mono-pear orchard	3.00	0.71	0.50	0.29
15	Strip apricot-pear orchard	7.00	3.39	1.00	0.00
	Mono-pear orchard	4.50	1.26	0.25	0.25
30	Strip apricot-pear orchard	4.00	1.58	0.75	0.25
	Mono-pear orchard	5.00	2.42	0.00	0.00
50	Strip apricot-pear orchard	8.75	2.66	0.00	0.00
	Mono-pear orchard	3.75	0.48	0.00	0.00
100	Strip apricot-pear orchard	7.00	3.67	1.00	0.71
	Mono-pear orchard	3.00	1.08	0.25	0.25

Table S4.15 Distance-specific results of GLM analysis with negative binomial error distribution for the samplings in paired apricot row-pear and mono-pear orchards **(Expt. 2)**. The response variables were the abundance of wild bees and honeybees, and the explanatory variables were treatment (mixed apricot-pear orchard and mono-pear orchard). Mono-pear orchard served as control. Significant (*P* < 0.05) relationships were indicated in bold, and marginally significant (0.1 < *P* < 0.05) relationships were indicated in italic.

Distance (m)	Response variables	Estimate	Std. Error	Z value	Pr (>|z|)
1) During apricot blooming (sampling round 1)					
5	Wild bees	1.65	0.49	3.34	**<0.001**
	Honeybees	0.95	0.81	1.17	0.241
15	Wild bees	-0.98	0.79	-1.24	0.216
	Honeybees	0.15	1.15	0.13	0.893
30	Wild bees	-0.63	0.42	-1.51	0.132
	Honeybees	-1.43	0.99	-1.44	0.151
50	Wild bees	-0.41	0.39	-1.06	0.291
	Honeybees	-0.39	0.99	-0.40	0.693
100	Wild bees	-0.93	0.50	-1.86	*0.063*
	Honeybees	1.04	0.34	3.10	**0.002**
2) During apricot blooming (sampling round 2)					
5	Wild bees	0.44	0.60	0.73	0.466
	Honeybees	0.58	0.49	1.18	0.237
15	Wild bees	0.25	0.73	0.35	0.730
	Honeybees	2.35	1.29	1.83	*0.067*
30	Wild bees	-0.07	0.82	-0.08	0.936
	Honeybees	<0.001	1.42	0.00	1.000
50	Wild bees	-0.05	0.73	-0.07	0.941
	Honeybees	-0.13	1.17	-0.11	0.909
100	Wild bees	0.39	0.69	0.57	0.570
	Honeybees	0.18	1.03	0.18	0.860
3) During apricot blooming (sampling round 3)					
5	Wild bees	1.13	0.59	1.92	*0.055*
	Honeybees	0.41	1.04	0.39	0.697
15	Wild bees	0.60	0.68	0.88	0.379
	Honeybees	<0.001	1.52	0.00	1.000
30	Wild bees	1.24	0.69	1.81	*0.070*
	Honeybees	<0.001	1.52	0.00	1.000
50	Wild bees	1.18	0.77	1.54	0.125
	Honeybees	<0.001	1.00	0.00	1.000
100	Wild bees	1.23	0.61	2.03	**0.042**
	Honeybees	<0.001	1.41	0.00	1.000
4) During apricot blooming (sampling round 4)					
5	Wild bees	0.22	0.39	0.58	0.565
	Honeybees	0.69	0.93	0.75	0.454
15	Wild bees	0.44	0.48	0.92	0.358
	Honeybees	1.39	1.12	1.24	0.215
30	Wild bees	-0.22	0.59	-0.38	0.707
	Honeybees	0.22	0.21	0.001	0.999
50	Wild bees	0.85	0.38	2.25	**0.025**
	Honeybees	0.22	0.21	0.001	0.999
100	Wild bees	0.85	0.61	1.39	0.165
	Honeybees	1.39	1.24	1.12	0.262

Table S4.16 Mean and standard error of the fruit set rate and seed set in 2020 per orchard in four paired apricot row-pear and mono-pear orchards in five sampling distances **(Expt. 2)**.

Distance (m)	Treatment	Mean	SE
1) Fruit set rate in 2020			
5	Strip apricot-pear orchard	0.079	0.018
	Mono-pear orchard	0.113	0.036
15	Strip apricot-pear orchard	0.123	0.039
	Mono-pear orchard	0.074	0.021
30	Strip apricot-pear orchard	0.100	0.039
	Mono-pear orchard	0.058	0.013
50	Strip apricot-pear orchard	0.095	0.021
	Mono-pear orchard	0.065	0.017
100	Strip apricot-pear orchard	0.093	0.019
	Mono-pear orchard	0.090	0.025
2) Seed set in 2020			
5	Strip apricot-pear orchard	6.1	0.191
	Mono-pear orchard	5.22	0.886
15	Strip apricot-pear orchard	6.25	0.403
	Mono-pear orchard	5.65	0.287
30	Strip apricot-pear orchard	6.80	0.665
	Mono-pear orchard	5.68	0.405
50	Strip apricot-pear orchard	6.38	0.103
	Mono-pear orchard	5.42	0.320
100	Strip apricot-pear orchard	6.45	0.087
	Mono-pear orchard	5.58	0.325

Table S4.17 Results of LMM analysis for the pollination success in paired apricot row-pear and mono-pear orchards **(Expt. 2)**. The response variables were the fruit set rate in 2020 and seed set in 2020 and the explanatory variables was treatment (mixed apricot-pear orchard and mono-pear orchard). Paired pear orchard was included as a random variable. Mono-pear orchard was served as controls. Significant (*P* < 0.05) relationships were indicated in bold.

Response variables	Estimate	Std. Error	Z value	Pr(>|t|)
1) Fruit set rate in 2020				
Intercept	0.082	0.022	3.727	**0.008**
Treatment	0.017	0.020	0.854	0.399
Distance	<0.001	<0.001	-0.215	0.831
Treatment x Distance	<0.001	<0.001	0.010	0.992
2) Seed set in 2020				
Intercept	5.454	0.309	17.680	**<0.001**
Treatment	0.849	0.380	2.233	**0.033**
Distance	0.001	0.001	0.271	0.788
Treatment x Distance	0.001	0.001	0.125	0.902

Table S4.18 Results of multi-model inference analysis to compare the model with apricot and landscape context and the model with only landscape context on **the abundance of wild bees** in four sampling rounds for cumulative landscape sectors at four spatial scales **(Expt. 3)**. For each scale, the average model was taken from the total candidate models. Z value is the estimate of each coefficient divided by its standard error.

Scales	Estimate	Std. Error	Adjusted SE	Z value	Pr(>|z|)
0-0.5 km					
1) *Model with apricot- sampling round 1*					
Intercept	2.236	1.340	1.342	1.666	*0.096*
Waste land	-0.134	0.203	0.207	0.646	0.518
Year 2020	0.409	0.508	0.517	0.793	0.428
Water	-0.186	0.237	0.241	0.770	0.442
SNH	0.089	0.174	0.178	0.501	0.616
Urban	-0.122	0.216	0.220	0.557	0.578
Annual	-0.052	0.164	0.167	0.309	0.758
Village	-0.026	0.140	0.144	0.178	0.859
Apricot	-0.019	0.101	0.105	0.177	0.859
2) *Model without apricot- sampling round 1*					
Intercept	2.222	1.346	1.348	1.649	*0.099*
Waste land	-0.137	0.204	0.208	0.655	0.512
Year 2020	0.424	0.512	0.520	0.815	0.415
Water	-0.189	0.238	0.242	0.782	0.434
SNH	0.092	0.177	0.181	0.511	0.610
Urban	-0.117	0.210	0.213	0.551	0.582
Annual	-0.051	0.162	0.166	0.308	0.758
Village	-0.022	0.134	0.138	0.160	0.873
AICc (with apricot)=252.20; AICc (without apricot)=250.77; Pr(>F) = 0.447					
3) *Model with apricot- sampling round 2*					
Intercept	1.882	1.246	1.248	1.508	0.131
Waste land	-0.128	0.191	0.195	0.656	0.512
Annual	0.114	0.184	0.187	0.609	0.542
Urban	-0.083	0.160	0.163	0.506	0.613
SNH	0.072	0.150	0.153	0.471	0.638
Year 2020	-0.147	0.319	0.326	0.450	0.653
Water	0.022	0.095	0.09808	0.224	0.823
Apricot	-0.011	0.080	0.08385	0.129	0.897
	0.013	0.094	0.09784	0.128	0.898
4) *Model without apricot- sampling round 2*					
Intercept	1.885	1.247	1.249	1.509	0.131
Waste land	-0.130	0.192	0.196	0.665	0.506
Annual	0.116	0.185	0.188	0.616	0.538
Urban	-0.080	0.156	0.160	0.502	0.616
SNH	0.074	0.152	0.154	0.477	0.633
Year 2020	-0.145	0.318	0.32411	0.449	0.654
Water	0.022	0.095	0.0987	0.225	0.822
Village	0.014	0.095	0.09849	0.140	0.888
AICc (with apricot)=268.74; AICc (without apricot)=266.74; Pr(>F) = 0.985					
5) *Model with apricot- sampling round 3*					
Intercept	0.740	1.319	1.321	0.560	0.575
Annual	0.141	0.229	0.233	0.606	0.544
Water	0.092	0.177	0.181	0.511	0.609
Year 2020	-0.341	0.496	0.504	0.676	0.499

Urban	-0.148	0.231	0.236	0.626	0.531
SNH	0.082	0.170	0.173	0.473	0.636
Waste land	-0.023	0.117	0.121	0.186	0.853
Village	-0.008	0.107	0.112	0.074	0.941
Apricot	-0.026	0.110	0.114	0.223	0.823
6) *Model without apricot- sampling round 3*					
Intercept	0.744	1.320	1.322	0.562	0.574
Annual	0.143	0.229	0.233	0.612	0.540
Water	0.094	0.177	0.182	0.516	0.606
Year 2020	-0.340	0.494	0.503	0.677	0.498
Urban	-0.140	0.224	0.228	0.613	0.540
SNH	0.082	0.170	0.173	0.474	0.635
Waste land	-0.023	0.118	0.122	0.191	0.849
Village	-0.006	0.106	0.111	0.056	0.955
AICc (with apricot)=200.50; AICc (without apricot)=198.90; Pr(>F) = 0.527					
7）*Model with apricot- sampling round 4*					
Intercept	0.669	1.360	1.361	0.492	0.623
Year 2020	-2.426	0.464	0.482	5.028	**<0.001**
Apricot	0.225	0.149	0.152	1.483	0.138
Village	0.117	0.179	0.182	0.640	0.522
SNH	0.031	0.073	0.075	0.413	0.680
Water	0.031	0.073	0.075	0.416	0.677
Waste land	0.030	0.086	0.089	0.337	0.736
Annual	-0.010	0.059	0.061	0.171	0.864
Urban	0.008	0.060	0.063	0.127	0.899
8）Model without apricot- sampling round 4					
Intercept	0.662	1.362	1.363	0.486	0.627
Year 2020	-2.342	0.466	0.485	4.831	**<0.001**
Village	0.053	0.128	0.132	0.398	0.691
SNH	0.032	0.083	0.085	0.374	0.708
Water	0.030	0.080	0.082	0.369	0.712
Waste land	0.034	0.097	0.100	0.340	0.734
Annual	-0.015	0.068	0.071	0.215	0.830
Urban	-0.010	0.060	0.063	0.156	0.876
AICc (with apricot)=120.73; AICc (without apricot)=119.23 Pr(>F) =0.478					
0-1.0 km					
9）Model with apricot- sampling round 1					
Intercept	2.099	1.391	1.393	1.506	0.132
Year 2020	0.573	0.581	0.590	0.972	0.331
Waste land	-0.133	0.215	0.219	0.608	0.544
Urban	-0.162	0.232	0.236	0.684	0.494
SNH	0.093	0.183	0.187	0.495	0.620
Water	-0.041	0.131	0.135	0.306	0.759
Annual	0.005	0.125	0.130	0.038	0.970
Village	-0.016	0.111	0.116	0.136	0.892
Apricot	-0.002	0.102	0.107	0.015	0.988
10）Model without apricot- sampling round 1					
Intercept	2.091	1.392	1.394	1.500	0.134
Year2020	0.579	0.577	0.586	0.988	0.323
Waste land	-0.135	0.216	0.220	0.616	0.538
Urban	-0.162	0.232	0.236	0.689	0.491
SNH	0.090	0.179	0.183	0.493	0.622
Water	-0.041	0.131	0.135	0.307	0.759
Annual	0.005	0.126	0.131	0.037	0.970
Village	-0.016	0.112	0.117	0.138	0.890
AICc (with apricot)=256.11; AICc (without apricot)=254.16; Pr(>F) = 0.822					
11）Model with apricot- sampling round 2					

Intercept	1.816	1.246	1.247	1.456	0.146
SNH	0.266	0.239	0.242	1.098	0.272
Urban	-0.315	0.234	0.238	1.325	0.185
Waste land	-0.212	0.218	0.222	0.954	0.340
Apricot	-0.089	0.164	0.167	0.534	0.594
Annual	0.113	0.185	0.188	0.603	0.546
Year 2020	-0.063	0.224	0.230	0.276	0.783
Water	-0.003	0.070	0.073	0.035	0.972
Village	0.000	0.077	0.080	0.004	0.997
12）Model without apricot- sampling round 2					
Intercept	0.794	1.287	1.288	0.617	0.538
Waste land	-0.439	0.298	0.305	1.438	0.151
Water	-0.289	0.280	0.285	1.012	0.311
SNH	-0.124	0.213	0.217	0.573	0.567
Village	-0.116	0.213	0.217	0.536	0.592
Annual	-0.030	0.123	0.127	0.238	0.812
Urban	0.010	0.087	0.091	0.109	0.913
Year 2020	0.041	0.232	0.240	0.171	0.864
AICc (with apricot)=257.90; AICc (without apricot)=177.58; Pr(>F) = 0.992					
13）Model with apricot- sampling round 3					
Intercept	0.275	1.246	1.247	0.220	0.826
Apricot	-0.520	0.282	0.288	1.804	*0.071*
SNH	0.254	0.241	0.245	1.038	0.299
Urban	-0.809	0.252	0.260	3.107	**0.002**
Village	-0.062	0.146	0.150	0.412	0.680
Waste land	0.049	0.140	0.144	0.341	0.733
Year 2020	-0.187	0.372	0.378	0.494	0.621
Water	0.044	0.118	0.121	0.363	0.716
Annual	0.034	0.141	0.144	0.235	0.814
14）Model without apricot- sampling round 3					
Intercept	-0.575	1.306	1.308	0.440	0.660
Water	-0.352	0.319	0.325	1.082	0.279
SNH	0.073	0.174	0.178	0.410	0.682
Village	-0.034	0.132	0.137	0.247	0.805
Annual	0.042	0.136	0.141	0.298	0.765
Urban	-0.009	0.102	0.107	0.082	0.935
Year2020	0.013	0.236	0.245	0.053	0.958
Waste land	-0.009	0.112	0.117	0.079	0.937
AICc (with apricot)= 180.99; AICc (without apricot)=119.72; Pr(>F) = 0.995					
15）Model with apricot- sampling round 4					
Intercept	0.744	1.366	1.367	0.544	0.586
Year 2020	-2.595	0.603	0.623	4.165	**<0.001**
Urban	-0.104	0.145	0.148	0.702	0.483
Village	0.156	0.225	0.229	0.680	0.496
Apricot	0.074	0.151	0.155	0.479	0.632
Waste land	0.063	0.143	0.147	0.431	0.667
SNH	0.029	0.086	0.088	0.329	0.742
Annual	-0.014	0.078	0.081	0.175	0.861
Water	0.000	0.053	0.056	0.008	0.994
16）Model without apricot- sampling round 4					
Intercept	-0.178	1.522	1.529	0.116	0.908
Year 2020	1.114	0.965	0.982	1.135	**<0.001**
Village	-0.171	0.328	0.336	0.510	0.610
Waste land	-0.063	0.209	0.216	0.291	0.771
Urban	-0.054	0.202	0.209	0.257	0.797
Water	-0.065	0.259	0.265	0.244	0.807
SNH	-0.051	0.202	0.209	0.243	0.808

Annual	-0.038	0.218	0.226	0.170	0.865
AICc (with apricot)= 114.38; AICc (without apricot)=114.08; Pr(>F) =0.193					
0-1.5 km					
17） *Model with apricot- sampling round 1*					
Intercept	2.288	1.281	1.283	1.784	0.074
SNH	0.327	0.253	0.259	1.265	0.206
Urban	-0.252	0.258	0.263	0.957	0.339
Apricot	0.052	0.164	0.168	0.312	0.755
Waste land	-0.067	0.159	0.163	0.413	0.680
Year 2020	0.259	0.460	0.467	0.553	0.580
Water	0.008	0.102	0.105	0.077	0.939
Annual	0.013	0.136	0.141	0.090	0.928
Village	-0.025	0.114	0.118	0.209	0.834
18） *Model without apricot- sampling round 1*					
Intercept	2.294	1.287	1.289	1.780	*0.075*
SNH	0.293	0.235	0.241	1.217	0.224
Urban	-0.258	0.261	0.266	0.971	0.332
Waste land	-0.074	0.163	0.167	0.444	0.657
Year 2020	0.289	0.469	0.476	0.608	0.543
Water	0.009	0.104	0.108	0.087	0.931
Annual	0.008	0.135	0.139	0.057	0.954
Village	-0.025	0.116	0.121	0.210	0.834
AICc (with apricot)=251.58; AICc (without apricot)=249.67; Pr(>F) = 0.765					
19） *Model with apricot- sampling round 2*					
Intercept	1.950	1.276	1.277	1.527	0.127
Annual	0.238	0.252	0.255	0.931	0.352
SNH	0.189	0.198	0.201	0.941	0.347
Waste land	-0.292	0.234	0.238	1.226	0.220
Urban	-0.195	0.221	0.224	0.872	0.383
Apricot	-0.083	0.162	0.165	0.504	0.615
Village	-0.047	0.130	0.133	0.357	0.721
Year 2020	-0.055	0.240	0.246	0.225	0.822
Water	0.014	0.078	0.081	0.175	0.861
20）Model without apricot- sampling round 2					
Intercept	1.879	1.264	1.265	1.485	0.138
Annual	0.285	0.253	0.257	1.109	0.267
SNH	0.230	0.200	0.203	1.130	0.258
Waste land	-0.256	0.226	0.230	1.113	0.266
Urban	-0.149	0.200	0.203	0.735	0.462
Village	-0.039	0.122	0.125	0.313	0.755
Year 2020	-0.077	0.255	0.261	0.294	0.769
Waster	0.013	0.079	0.082	0.159	0.874
AICc (with apricot)=256.49; AICc (without apricot)=255.88; Pr(>F) = 0.237					
21）Model with apricot- sampling round 3					
Intercept	0.530	1.289	1.290	0.411	0.681
Apricot	-0.301	0.304	0.309	0.973	0.330
SNH	0.387	0.261	0.266	1.451	0.147
Urban	-0.301	0.310	0.314	0.960	0.337
Annual	0.336	0.348	0.352	0.954	0.340
Village	-0.087	0.195	0.199	0.435	0.664
Water	0.088	0.174	0.177	0.498	0.618
Year 2020	-0.136	0.366	0.372	0.364	0.716
Waste land	0.018	0.099	0.103	0.173	0.863
22）Model without apricot- sampling round 3					
Intercept	0.526	1.297	1.298	0.405	0.685
Annual	0.480	0.349	0.353	1.358	0.175
SNH	0.413	0.269	0.274	1.509	0.131

Water	0.136	0.209	0.212	0.641	0.522
Waste land	0.037	0.120	0.124	0.303	0.762
Urban	-0.161	0.258	0.261	0.619	0.536
Year 2020	-0.234	0.453	0.460	0.509	0.610
Village	-0.070	0.185	0.189	0.370	0.711
AICc (with apricot)=184.83; AICc (without apricot)=182.27; Pr(>F) = 0.118					
23）Model with apricot- sampling round 4					
Intercept	0.693	1.364	1.365	0.508	0.612
Year 2020	-2.406	0.512	0.533	4.515	**<0.001**
Urban	-0.068	0.121	0.124	0.551	0.581
Village	0.045	0.136	0.141	0.322	0.747
Waste land	0.033	0.114	0.119	0.282	0.778
Apricot	0.018	0.099	0.104	0.171	0.864
SNH	0.012	0.067	0.071	0.166	0.868
Annual	-0.007	0.080	0.083	0.079	0.937
Water	0.005	0.058	0.061	0.075	0.940
24）Model without apricot- sampling round 4					
Intercept	0.684	1.363	1.364	0.501	0.616
Year 2020	-2.385	0.496	0.516	4.623	**<0.001**
Urban	-0.071	0.123	0.126	0.566	0.572
Village	0.045	0.136	0.141	0.321	0.748
Waste land	0.032	0.111	0.115	0.276	0.783
SNH	0.011	0.067	0.070	0.161	0.872
Annual	-0.007	0.082	0.085	0.084	0.933
Water	0.004	0.058	0.061	0.069	0.945
AICc (with apricot)=123.62; AICc (without apricot)=121.98; Pr(>F) = 0.547					
0-2.0 km					
25）Model with apricot- sampling round 1					
Intercept	2.250	1.253	1.254	1.794	*0.073*
SNH	0.327	0.273	0.279	1.175	0.240
Urban	-0.192	0.241	0.245	0.782	0.434
Water	0.160	0.226	0.230	0.696	0.487
Apricot	0.050	0.154	0.157	0.320	0.749
Year 2020	0.110	0.305	0.312	0.353	0.724
Waste land	-0.025	0.105	0.109	0.229	0.819
Annual	0.011	0.122	0.126	0.084	0.933
Village	0.012	0.100	0.104	0.112	0.911
26）Model without apricot- sampling round 1					
Intercept	2.294	1.243	1.245	1.843	*0.065*
SNH	0.299	0.258	0.263	1.139	0.255
Urban	-0.204	0.245	0.249	0.817	0.414
Water	0.161	0.226	0.230	0.702	0.483
Year2020	0.127	0.311	0.317	0.399	0.690
Waste land	-0.028	0.106	0.110	0.252	0.801
Annual	0.010	0.123	0.128	0.082	0.935
Village	0.011	0.101	0.105	0.109	0.913
AICc (with apricot)=248.87; AICc (without apricot)=247.32; Pr(>F) = 0.500					
27）Model with apricot- sampling round 2					
Intercept	2.085	1.286	1.287	1.621	0.105
Annual	0.247	0.247	0.250	0.988	0.323
Apricot	-0.169	0.207	0.210	0.802	0.423
Waste land	-0.534	0.204	0.210	2.542	**0.011**
Urban	-0.108	0.180	0.183	0.593	0.553
SNH	0.136	0.188	0.191	0.713	0.476
Year 2020	-0.006	0.202	0.208	0.030	0.976
Village	-0.014	0.096	0.099	0.136	0.892
Water	-0.001	0.061	0.064	0.022	0.983

28）Model without apricot- sampling round 2					
Intercept	1.770	1.241	1.242	1.425	0.154
Annual	0.291	0.254	0.257	1.131	0.258
SNH	0.209	0.206	0.209	1.001	0.317
Waste land	-0.482	0.208	0.214	2.253	**0.024**
Urban	-0.043	0.119	0.122	0.351	0.726
Village	-0.012	0.100	0.104	0.119	0.906
Water	0.000	0.066	0.069	0.001	0.999
Year 2020	-0.049	0.200	0.205	0.238	0.812
AICc (with apricot)=253.74; AICc (without apricot)=254.05; Pr(>F) = 0.128					
29）Model with apricot- sampling round 3					
Intercept	0.661	1.292	1.293	0.511	0.609
Annual	0.373	0.365	0.369	1.013	0.311
Apricot	-0.669	0.293	0.299	2.235	**0.025**
Urban	-0.358	0.343	0.346	1.035	0.301
SNH	0.086	0.170	0.173	0.494	0.621
Waste land	-0.059	0.140	0.144	0.406	0.685
Village	-0.011	0.116	0.121	0.090	0.928
Year 2020	-0.031	0.252	0.259	0.118	0.906
Water	0.006	0.080	0.083	0.075	0.940
30）Model without apricot- sampling round 3					
Intercept	0.487	1.287	1.289	0.378	0.706
Annual	0.632	0.345	0.350	1.803	*0.071*
SNH	0.154	0.230	0.233	0.661	0.509
Water	0.055	0.132	0.135	0.408	0.683
Year2020	-0.284	0.447	0.454	0.625	0.532
Waste land	-0.006	0.090	0.094	0.059	0.953
Village	-0.009	0.130	0.135	0.068	0.946
Urban	-0.082	0.211	0.215	0.380	0.704
AICc (with apricot)=186.18; AICc (without apricot)=186.55; Pr(>F) = 0.124					
31）Model with apricot- sampling round 4					
Intercept	0.691	1.364	1.365	0.506	0.613
Year 2020	-2.431	0.527	0.547	4.442	**<0.001**
Urban	-0.088	0.135	0.138	0.640	0.522
Village	0.141	0.212	0.216	0.654	0.513
Water	-0.013	0.067	0.070	0.187	0.851
Annual	0.001	0.088	0.091	0.009	0.992
Waste land	-0.008	0.086	0.090	0.090	0.928
Apricot	-0.016	0.090	0.094	0.167	0.868
SNH	-0.005	0.070	0.074	0.074	0.941
32）Model with apricot- sampling round 4					
Intercept	0.701	1.363	1.364	0.514	0.607
Year 2020	-2.452	0.518	0.538	4.559	**<0.001**
Urban	-0.087	0.134	0.136	0.635	0.525
Village	0.144	0.213	0.218	0.663	0.507
Water	-0.012	0.065	0.068	0.176	0.860
Annual	0.001	0.088	0.091	0.012	0.991
Waste	-0.007	0.085	0.090	0.081	0.936
SNH	-0.005	0.070	0.074	0.066	0.947
AICc (with apricot)=121.99; AICc (without apricot)=120.83; Pr(>F) = 0.360					

Table S4.19 Results of multi-model inference analysis to determine the model with apricot and landscape context as explanatory variables and the model with landscape context as explanatory variables effect on **the abundance of honeybees** in four sampling rounds for cumulative landscape sectors at four spatial scales **(Expt. 3)**. For each scale, the average model was taken from the total candidate models. Z value is the estimate of each coefficient divided by its standard error.

Scales	Estimate	Std. Error	Adjusted SE	Z value	Pr(>|z|)
0-0.5 km					
1) Model with apricot- sampling round 1					
Intercept	0.385	1.293	1.295	0.297	0.766
Annual	-0.808	0.310	0.319	2.535	**0.011**
SNH	0.157	0.207	0.212	0.741	0.458
Water	-0.649	0.326	0.334	1.940	*0.052*
Apricot	0.024	0.100	0.104	0.230	0.818
Waste land	-0.014	0.089	0.093	0.149	0.881
Village	0.018	0.103	0.107	0.170	0.865
Urban	0.017	0.112	0.115	0.151	0.880
Year2020	0.020	0.226	0.234	0.087	0.931
2) Model without apricot- sampling round 1					
Intercept	0.394	1.293	1.295	0.304	0.761
Annual	-0.808	0.307	0.316	2.562	**0.010**
SNH	0.158	0.207	0.212	0.747	0.455
Water	-0.651	0.324	0.332	1.957	*0.050*
Waste land	-0.014	0.089	0.093	0.153	0.878
Village	0.015	0.097	0.101	0.150	0.880
Urban	0.015	0.105	0.109	0.134	0.894
Year2020	0.023	0.229	0.237	0.095	0.924
AICc (with apricot)=165.82; AICc (without apricot)=164.89; Pr(>F) = 0.302					
3) *Model with apricot- sampling round 2*					
Intercept	0.987	1.275	1.277	0.773	0.440
Village	-0.168	0.252	0.257	0.655	0.513
Water	-0.119	0.209	0.213	0.558	0.577
Waste land	-0.128	0.218	0.223	0.575	0.565
SNH	-0.104	0.194	0.199	0.525	0.599
Urban	0.079	0.174	0.178	0.445	0.656
Apricot	0.025	0.111	0.115	0.222	0.825
Year2020	0.090	0.293	0.301	0.299	0.765
Annual	-0.005	0.122	0.127	0.041	0.967
4) *Model without apricot- sampling round 2*					
Intercept	0.987	1.276	1.278	0.772	0.440
Village	-0.177	0.255	0.260	0.679	0.497
Water	-0.122	0.211	0.215	0.566	0.571
Waste land	-0.130	0.219	0.224	0.580	0.562
SNH	-0.109	0.198	0.202	0.538	0.591
Urban	0.078	0.172	0.176	0.446	0.656
Year2020	0.094	0.297	0.305	0.306	0.759
Annual	-0.007	0.123	0.128	0.054	0.957
AICc (with apricot)=184.92; AICc (without apricot)=183.14; Pr(>F) = 0.693					
5) *Model with apricot- sampling round 3*					
Intercept	-0.496	1.267	1.270	0.391	0.696
Apricot	-0.430	0.299	0.3064	1.402	0.161
Water	-0.959	0.559	0.581	1.650	*0.099*
Village	-0.068	0.155	0.159	0.430	0.667
Year2020	0.160	0.352	0.360	0.445	0.656

Annual	0.027	0.108	0.111	0.244	0.807
Waste land	-0.013	0.087	0.091	0.142	0.887
SNH	0.014	0.084	0.088	0.156	0.876
Urban	0.012	0.093	0.097	0.122	0.903
6) *Model without apricot- sampling round 3*					
Intercept	-0.533	1.285	1.289	0.413	0.679
Water	-0.954	0.564	0.585	1.632	0.103
Annual	0.049	0.142	0.146	0.333	0.739
Village	-0.028	0.118	0.123	0.225	0.822
Urban	0.039	0.128	0.132	0.293	0.770
SNH	0.018	0.095	0.099	0.181	0.857
Waste land	-0.008	0.097	0.102	0.082	0.935
Year2020	0.079	0.287	0.296	0.269	0.788
AICc (with apricot) = 132.92; AICc (without apricot) = 133.09; Pr(>F) = 0.140					
7）*Model with apricot- sampling round 4*					
Intercept	-0.03673	1.46044	1.46616	0.025	0.980
Year2020	0.749	0.855	0.869	0.862	0.388
SNH	-0.460	0.536	0.543	0.846	0.398
Waste land	-0.180	0.319	0.326	0.550	0.582
Urban	-0.178	0.334	0.341	0.522	0.601
Water	-0.069	0.209	0.215	0.319	0.750
Apricot	0.032	0.182	0.188	0.167	0.867
Annual	-0.012	0.180	0.187	0.063	0.950
Village	-0.024	0.167	0.174	0.140	0.889
8) Model without apricot- sampling round 4					
Intercept	-0.058	1.464	1.470	0.039	0.969
Year2020	0.775	0.857	0.871	0.890	0.374
SNH	-0.473	0.541	0.548	0.862	0.389
Waste land	-0.186	0.323	0.330	0.564	0.573
Urban	-0.184	0.337	0.344	0.533	0.594
Water	-0.070	0.210	0.217	0.322	0.747
Annual	-0.013	0.181	0.188	0.069	0.945
Village	-0.026	0.168	0.175	0.149	0.881
AICc (with apricot)=146.13; AICc (without apricot)=145.03; Pr(>F) = 0.343					
0-1.0 km					
9）Model with apricot- sampling round 1					
Intercept	0.0146	1.2889	1.29087	0.011	0.991
Annual	-0.779	0.415	0.422	1.843	*0.065*
SNH	0.223	0.274	0.280	0.798	0.425
Water	-0.517	0.322	0.328	1.578	0.115
Waste land	-0.332	0.343	0.349	0.953	0.341
Village	0.114	0.234	0.237	0.478	0.633
Year2020	-0.105	0.323	0.331	0.317	0.751
Urban	0.016	0.130	0.134	0.118	0.906
Apricot	-0.010	0.093	0.098	0.105	0.916
10）Model without apricot- sampling round 1					
Intercept	0.0101	1.28885	1.2908	0.008	0.994
Annual	-0.780	0.415	0.422	1.848	*0.065*
SNH	0.228	0.275	0.280	0.815	0.415
Water	-0.518	0.321	0.327	1.584	0.113
Waste land	-0.333	0.343	0.349	0.954	0.340
Village	0.115	0.235	0.238	0.483	0.629
Year 2020	-0.109	0.326	0.334	0.326	0.744
Urban	0.016	0.130	0.133	0.121	0.904
AICc (with apricot)=162.32; AICc (without apricot)=160.43; Pr(>F) = 0.427					
11）Model with apricot- sampling round 2					
Intercept	0.804	1.285	1.286	0.625	0.532

Waste land	-0.440	0.299	0.306	1.436	0.151
Water	-0.290	0.282	0.287	1.009	0.313
SNH	-0.130	0.219	0.223	0.582	0.561
Village	-0.115	0.212	0.216	0.530	0.596
Apricot	-0.017	0.103	0.107	0.156	0.876
Annual	-0.030	0.123	0.127	0.237	0.813
Urban	0.009	0.087	0.091	0.099	0.921
Year2020	0.043	0.235	0.243	0.176	0.860
12）Model without apricot- sampling round 2					
Intercept	0.794	1.287	1.288	0.617	0.538
Waste land	-0.439	0.298	0.305	1.438	0.151
Water	-0.289	0.280	0.285	1.012	0.311
SNH	-0.124	0.213	0.217	0.573	0.567
Village	-0.116	0.213	0.217	0.536	0.592
Annual	-0.030	0.123	0.127	0.238	0.812
Urban	0.010	0.087	0.091	0.109	0.913
Year2020	0.041	0.232	0.240	0.171	0.864
AICc (with apricot)=177.67; AICc (without apricot)=177.58; Pr(>F) = 0.168					
13）Model with apricot- sampling round 3					
Intercept	-0.470	1.290	1.292	0.364	0.716
Apricot	-0.256	0.293	0.298	0.857	0.391
Water	-0.448	0.326	0.333	1.343	0.179
Urban	-0.031	0.124	0.129	0.238	0.812
SNH	0.049	0.148	0.153	0.321	0.748
Annual	0.034	0.126	0.131	0.258	0.797
Village	-0.026	0.119	0.124	0.214	0.831
Year2020	0.072	0.295	0.303	0.238	0.812
Waste land	-0.011	0.105	0.110	0.099	0.921
14）Model without apricot- sampling round 3					
Intercept	-0.575	1.306	1.308	0.440	0.660
Water	-0.352	0.319	0.325	1.082	0.279
SNH	0.073	0.174	0.178	0.410	0.682
Village	-0.034	0.132	0.137	0.247	0.805
Annual	0.042	0.136	0.141	0.298	0.765
Urban	-0.009	0.102	0.107	0.082	0.935
Year2020	0.013	0.236	0.245	0.053	0.958
Waste land	-0.009	0.112	0.117	0.079	0.937
AICc (with apricot)=134.90; AICc (without apricot)=133.72; Pr(>F) = 0.368					
15）Model with apricot- sampling round 4					
Intercept	-0.470	1.290	1.292	0.364	0.716
Apricot	-0.256	0.293	0.298	0.857	0.391
Water	-0.448	0.326	0.333	1.343	0.179
Urban	-0.031	0.124	0.129	0.238	0.812
SNH	0.049	0.148	0.153	0.321	0.748
Annual	0.034	0.126	0.131	0.258	0.797
Village	-0.026	0.119	0.124	0.214	0.831
Year 2020	0.072	0.295	0.303	0.238	0.812
Waste land	-0.011	0.105	0.110	0.099	0.921
16）Model without apricot- sampling round 4					
Intercept	-0.178	1.522	1.529	0.116	0.908
Year2020	1.114	0.965	0.982	1.135	0.257
Village	-0.171	0.328	0.336	0.510	0.610
Waste land	-0.063	0.209	0.216	0.291	0.771
Urban	-0.054	0.202	0.209	0.257	0.797
Water	-0.065	0.259	0.265	0.244	0.807
SNH	-0.051	0.202	0.209	0.243	0.808
Annual	-0.038	0.218	0.226	0.170	0.865

AICc (with apricot)=140.79; AICc (without apricot)=135.22; Pr(>F) =1.000					
0-1.5 km					
17） *Model with apricot- sampling round 1*					
Intercept	0.029	1.294	1.296	0.022	0.982
Village	0.668	0.380	0.386	1.730	*0.084*
Waste land	-0.855	0.438	0.449	1.904	*0.057*
Annual	-0.260	0.337	0.342	0.759	0.448
Urban	0.035	0.133	0.137	0.253	0.800
SNH	0.067	0.157	0.161	0.415	0.678
Water	-0.051	0.141	0.145	0.352	0.725
Apricot	0.013	0.106	0.110	0.119	0.906
Year2020	-0.080	0.300	0.309	0.258	0.796
18） *Model without apricot- sampling round 1*					
Intercept	0.028	1.293	1.295	0.022	0.983
Village	0.666	0.378	0.384	1.734	*0.083*
Waste land	-0.862	0.434	0.446	1.933	*0.053*
Annual	-0.264	0.338	0.343	0.772	0.440
Urban	0.035	0.133	0.137	0.255	0.799
SNH	0.064	0.153	0.157	0.411	0.681
Water	-0.052	0.143	0.146	0.356	0.722
Year2020	-0.071	0.282	0.290	0.246	0.806
AICc (with apricot)=163.22; AICc (without apricot)=161.85; Pr(>F) = 0.427					
19） *Model with apricot- sampling round 2*					
Intercept	0.725	1.291	1.293	0.561	0.575
Waste land	-0.361	0.308	0.315	1.146	0.252
Water	-0.322	0.290	0.296	1.091	0.275
SNH	-0.173	0.230	0.235	0.737	0.461
Urban	0.016	0.098	0.102	0.161	0.872
Annual	-0.026	0.111	0.115	0.227	0.820
Village	0.006	0.104	0.109	0.055	0.956
Apricot	0.014	0.107	0.111	0.130	0.897
Year2020	0.026	0.223	0.231	0.113	0.910
20）Model without apricot- sampling round 2					
Intercept	0.740	1.291	1.292	0.573	0.567
Waste land	-0.367	0.307	0.314	1.168	0.243
Water	-0.324	0.291	0.296	1.097	0.273
SNH	-0.177	0.230	0.234	0.757	0.449
Urban	0.016	0.098	0.102	0.158	0.874
Annual	-0.027	0.112	0.116	0.236	0.814
Village	0.006	0.106	0.110	0.057	0.955
Year2020	0.030	0.220	0.228	0.129	0.897
AICc (with apricot)=180.07; AICc (without apricot)=178.25; Pr(>F) = 0.675					
21）Model with apricot- sampling round 3					
Intercept	-0.496	1.299	1.301	0.381	0.703
Water	-0.340	0.326	0.333	1.021	0.307
Apricot	-0.065	0.169	0.174	0.370	0.711
SNH	0.035	0.127	0.132	0.268	0.789
Annual	0.059	0.167	0.172	0.342	0.732
Year2020	0.042	0.269	0.279	0.152	0.879
Urban	0.013	0.121	0.126	0.103	0.918
Village	0.031	0.133	0.138	0.225	0.822
Waste land	-0.006	0.111	0.116	0.048	0.962
22）Model without apricot- sampling round 3					
Intercept	-0.530	1.303	1.305	0.406	0.684
Water	-0.324	0.320	0.326	0.992	0.321
SNH	0.040	0.132	0.137	0.293	0.769
Annual	0.065	0.174	0.178	0.366	0.714

Year2020	0.024	0.247	0.257	0.095	0.924
Urban	0.016	0.125	0.130	0.123	0.902
Village	0.030	0.134	0.138	0.215	0.830
Waste land	-0.004	0.112	0.117	0.032	0.975
AICc (with apricot)=118.76; AICc (without apricot)=117.08; Pr(>F) = 0.567					
23）Model with apricot- sampling round 4					
Intercept	0.035	1.399	1.404	0.025	0.980
Apricot	0.457	0.438	0.447	1.022	0.307
Year2020	0.439	0.806	0.819	0.536	0.592
Village	-0.067	0.229	0.236	0.284	0.777
Waste land	0.019	0.169	0.176	0.107	0.915
Water	-0.033	0.171	0.178	0.188	0.851
SNH	-0.044	0.193	0.200	0.219	0.827
Urban	-0.008	0.169	0.176	0.048	0.962
Annual	-0.017	0.178	0.186	0.090	0.928
24）Model without apricot- sampling round 3					
Intercept	-0.118	1.519	1.525	0.077	0.939
Year2020	1.064	0.957	0.975	1.092	0.275
Village	-0.093	0.281	0.288	0.324	0.746
SNH	-0.098	0.244	0.250	0.392	0.695
Water	-0.063	0.212	0.219	0.287	0.774
Waste land	-0.023	0.166	0.173	0.133	0.894
Annual	-0.024	0.208	0.216	0.109	0.913
Urban	-0.026	0.204	0.212	0.124	0.901
AICc (with apricot)=153.98; AICc (without apricot)=148.98; Pr(>F) = 0.977					
0-2.0 km					
25）Model with apricot- sampling round 1					
Intercept	0.085	1.297	1.298	0.065	0.948
Annual	-0.575	0.407	0.414	1.391	0.164
SNH	0.152	0.247	0.252	0.604	0.546
Village	0.542	0.382	0.389	1.393	0.164
Waste land	-0.839	0.380	0.390	2.149	**0.032**
Water	-0.140	0.207	0.211	0.662	0.508
Urban	-0.096	0.221	0.225	0.427	0.669
Apricot	-0.004	0.104	0.108	0.039	0.969
Year 2020	-0.034	0.231	0.239	0.142	0.887
26）Model without apricot- sampling round 1					
Intercept	0.075	1.296	1.298	0.058	0.954
Annual	-0.576	0.401	0.408	1.413	0.158
SNH	0.157	0.249	0.254	0.618	0.537
Village	0.546	0.381	0.388	1.409	0.159
Waste land	-0.842	0.378	0.388	2.169	**0.030**
Water	-0.141	0.207	0.211	0.667	0.505
Urban	-0.096	0.219	0.223	0.430	0.668
Year 2020	-0.035	0.228	0.235	0.148	0.882
AICc (with apricot) = 157.57; AICc (without apricot) = 155,57; Pr(>F) = 0.975					
27）Model with apricot- sampling round 2					
Intercept	0.706	1.274	1.276	0.553	0.580
Waste land	-0.536	0.280	0.288	1.861	*0.063*
Water	-0.549	0.259	0.266	2.061	**0.039**
SNH	-0.081	0.167	0.171	0.477	0.634
Annual	-0.036	0.113	0.117	0.303	0.762
Village	0.033	0.122	0.126	0.259	0.795
Urban	0.007	0.085	0.089	0.076	0.940
Year2020	0.037	0.212	0.219	0.170	0.865
Apricot	0.013	0.102	0.106	0.124	0.901
28）Model without apricot- sampling round 2					

Intercept	0.727	1.272	1.273	0.571	0.568
Waste land	-0.542	0.276	0.284	1.909	*0.056*
Water	-0.555	0.255	0.262	2.121	**0.034**
SNH	-0.083	0.168	0.171	0.486	0.627
Annual	-0.037	0.115	0.119	0.310	0.757
Village	0.034	0.124	0.128	0.266	0.791
Urban	0.007	0.086	0.090	0.074	0.941
Year 2020	0.040	0.206	0.213	0.187	0.852
AICc (with apricot)=175.00; AICc (without apricot)=173.18; Pr(>F) = 0.672					
29）Model with apricot- sampling round 3					
Intercept	-0.461	1.300	1.302	0.354	0.723
Annual	0.056	0.163	0.169	0.333	0.739
SNH	0.089	0.195	0.200	0.443	0.658
Water	-0.061	0.168	0.172	0.353	0.724
Urban	-0.025	0.132	0.138	0.181	0.856
Apricot	-0.016	0.124	0.129	0.123	0.902
Waste land	-0.004	0.111	0.116	0.039	0.969
Year2020	0.028	0.252	0.262	0.105	0.917
Village	0.016	0.131	0.136	0.120	0.905
30）Model without apricot- sampling round 3					
Intercept	-0.469	1.301	1.303	0.360	0.719
Annual	0.058	0.165	0.170	0.339	0.735
SNH	0.091	0.196	0.201	0.454	0.650
Water	-0.059	0.165	0.170	0.346	0.729
Urban	-0.024	0.132	0.138	0.177	0.859
Waste land	-0.004	0.111	0.116	0.032	0.975
Year2020	0.024	0.243	0.253	0.093	0.926
Village	0.016	0.132	0.137	0.120	0.904
AICc (with apricot)=123.32; AICc (without apricot)=121.44; Pr(>F) = 0.716					
31）Model with apricot- sampling round 4					
Intercept	-0.038	1.434	1.439	0.026	0.979
Apricot	0.462	0.464	0.473	0.978	0.328
Village	-0.226	0.410	0.416	0.542	0.588
Year2020	0.602	0.921	0.933	0.646	0.518
Waste land	0.047	0.204	0.210	0.223	0.824
SNH	-0.018	0.217	0.224	0.082	0.935
Urban	-0.037	0.214	0.221	0.168	0.867
Water	-0.045	0.197	0.203	0.219	0.827
Annual	-0.030	0.200	0.208	0.144	0.885
32）Model with apricot- sampling round 4					
Intercept	-0.272	1.546	1.553	0.175	0.861
Year 2020	1.246	1.028	1.045	1.193	0.233
Village	-0.267	0.465	0.472	0.567	0.571
Water	-0.098	0.252	0.258	0.379	0.704
SNH	-0.091	0.249	0.255	0.358	0.720
Waste land	0.000	0.171	0.178	0.002	0.998
Urban	-0.054	0.258	0.264	0.203	0.840
Annual	-0.028	0.214	0.222	0.126	0.900
AICc (with apricot)=148.07; AICc (without apricot)=147.54; Pr(>F) = 0.225					

Table S4.20 Results of multi-model inference analysis to determine the model with apricot and landscape context as explanatory variables and the model with landscape context as explanatory variables effect on the **fruit set in 2019** for cumulative landscape sectors at four spatial scales **(Expt. 3)**. For each scale, the average model was taken from the total candidate models. Z value is the estimate of each coefficient divided by its standard error.

Scales	Estimate	Std. Error	Adjusted SE	Z value	Pr(>|z|)
1) 0-0.5 km (Model with apricot)					
Intercept	2.098	1.365	1.367	1.535	0.125
Apricot	-0.046	0.118	0.125	0.368	0.713
SNH	0.016	0.078	0.084	0.186	0.853
Water	0.018	0.081	0.088	0.201	0.841
Annual	0.015	0.080	0.087	0.178	0.859
Urban	0.012	0.078	0.085	0.145	0.885
Village	0.006	0.068	0.075	0.081	0.936
Waste land	0.001	0.067	0.074	0.017	0.986
2）0-0.5 km (Model without apricot)					
Intercept	2.102	1.365	1.367	1.538	0.124
SNH	0.016	0.080	0.087	0.189	0.850
Water	0.018	0.083	0.090	0.200	0.842
Annual	0.017	0.084	0.091	0.190	0.849
Urban	0.015	0.082	0.089	0.168	0.866
Village	0.007	0.071	0.078	0.088	0.930
Waste land	0.002	0.070	0.077	0.022	0.982
AICc (with apricot)=140.98; AICc (without apricot)=142.91; Pr(>F)=0.786					
3）0-1.0 km (Model with apricot)					
Intercept	2.099	1.365	1.367	1.536	0.125
Waste land	-0.046	0.124	0.131	0.349	0.727
Urban	0.025	0.100	0.107	0.236	0.813
Annual	0.020	0.092	0.099	0.202	0.840
SNH	0.012	0.074	0.081	0.142	0.887
Apricot	-0.014	0.083	0.089	0.157	0.875
Village	-0.004	0.080	0.087	0.051	0.959
Water	0.001	0.067	0.074	0.009	0.993
4）0-1.0 km (Model with apricot)					
Intercept	2.099	1.365	1.367	1.536	0.125
Waste land	-0.045	0.121	0.128	0.350	0.726
Urban	0.027	0.103	0.110	0.247	0.805
Annual	0.019	0.092	0.099	0.194	0.846
SNH	0.012	0.076	0.083	0.149	0.881
Village	-0.002	0.073	0.080	0.024	0.981
Water	0.001	0.068	0.075	0.014	0.989
AICc (with apricot)=139.90; AICc (without apricot)=138.13; Pr(>F)=0.637					
5）0-1.5 km (Model with apricot)					
Intercept	2.102	1.365	1.367	1.538	0.124
Waste land	-0.021	0.089	0.096	0.221	0.825
Urban	0.024	0.102	0.109	0.219	0.827
Annual	0.017	0.094	0.101	0.167	0.867
Apricot	0.011	0.074	0.081	0.133	0.894
Village	0.004	0.069	0.076	0.050	0.961
Water	-0.004	0.068	0.075	0.056	0.956
SNH	0.003	0.067	0.074	0.043	0.965
6）0-1.5 km (Model without apricot)					

Intercept	2.102	1.365	1.367	1.538	0.124
Waste land	-0.022	0.090	0.097	0.229	0.819
Urban	0.024	0.103	0.110	0.218	0.827
Annual	0.018	0.096	0.103	0.173	0.863
Village	0.003	0.070	0.077	0.043	0.965
Water	-0.005	0.069	0.076	0.061	0.951
SNH	0.003	0.068	0.075	0.041	0.967
AICc (with apricot)=144.41; AICc (without apricot)=142.73; Pr(>F)=0.569					
7）0-2.0 km (Model with apricot)					
Intercept	2.101	1.365	1.367	1.537	0.124
Apricot	0.036	0.109	0.116	0.308	0.758
SNH	0.018	0.083	0.090	0.196	0.844
Urban	0.026	0.107	0.115	0.225	0.822
Annual	0.014	0.093	0.100	0.144	0.886
Water	-0.005	0.069	0.076	0.069	0.945
Village	-0.004	0.071	0.078	0.052	0.959
Waste land	0.002	0.069	0.077	0.032	0.975
8）0-2.0 km (Model without apricot)					
Intercept	2.103	1.365	1.367	1.538	0.124
SNH	0.015	0.080	0.087	0.177	0.860
Urban	0.022	0.102	0.109	0.200	0.842
Annual	0.017	0.096	0.104	0.163	0.871
Water	-0.007	0.071	0.078	0.091	0.927
Village	-0.006	0.072	0.080	0.078	0.937
Waste land	0.000	0.069	0.076	0.006	0.995
AICc (with apricot)=141.98; AICc (without apricot)=142.48; Pr(>F)=0.114					

Table S4.21 Results of multi-model inference analysis to determine the model with apricot and landscape context as explanatory variables and the model with landscape context as explanatory variables effect on **fruit set in 2020** for cumulative landscape sectors at four spatial scales **(Expt. 3)**. For each scale, the average model was taken from the total candidate models. Z value is the estimate of each coefficient divided by its standard error.

Scales	Estimate	Std. Error	Adjusted SE	Z value	Pr(>|z|)
2) 0-0.5 km (Model with apricot)					
Intercept	-1.062	1.151	1.151	0.923	0.356
Village	0.021	0.017	0.018	1.159	0.246
Apricot	-0.015	0.017	0.017	0.839	0.401
SNH	-0.008	0.013	0.013	0.596	0.551
Urban	-0.003	0.009	0.009	0.353	0.724
Annual	0.000	0.004	0.004	0.037	0.971
Waste land	0.001	0.005	0.005	0.127	0.899
Water	0.000	0.003	0.004	0.033	0.973
2）0-0.5 km (Model without apricot)					
Intercept	-1.062	1.151	1.151	0.923	0.356
Village	0.031	0.014	0.015	2.094	0.036
SNH	-0.001	0.005	0.006	0.206	0.837
Annual	0.001	0.004	0.005	0.145	0.884
Waste land	0.001	0.005	0.006	0.143	0.887
Urban	0.000	0.003	0.004	0.019	0.985
Water	-0.000	0.004	0.004	0.012	0.991
AICc (with apricot)=-48.53; AICc (without apricot)=-38.42; Pr(>F)=**0.039**					
3）0-1.0 km (Model with apricot)					
Intercept	-1.062	1.151	1.151	0.923	0.356
Apricot	-0.006	0.012	0.012	0.470	0.638
Urban	0.004	0.010	0.011	0.398	0.691
Village	0.004	0.010	0.010	0.368	0.713
Water	-0.001	0.007	0.007	0.205	0.838
Waste land	0.001	0.005	0.006	0.116	0.908
SNH	-0.001	0.006	0.007	0.151	0.880
Annual	-0.001	0.006	0.007	0.099	0.922
4）0-1.0 km (Model with apricot)					
Intercept	-1.062	1.151	1.151	0.923	0.356
Urban	0.005	0.011	0.011	0.431	0.667
Village	0.004	0.010	0.010	0.371	0.711
Water	-0.001	0.006	0.007	0.192	0.848
Waste land	0.001	0.006	0.006	0.136	0.892
SNH	-0.001	0.005	0.006	0.092	0.927
Annual	-0.000	0.006	0.006	0.041	0.968
AICc (with apricot)=-34.40; AICc (without apricot)=-33.86; Pr(>F)=0.346					
5）0-1.5 km (Model with apricot)					
Intercept	-1.062	1.151	1.151	0.923	0.356
Water	0.007	0.013	0.014	0.540	0.589
Urban	0.006	0.012	0.012	0.453	0.650
SNH	0.000	0.005	0.006	0.078	0.937
Annual	0.000	0.005	0.006	0.014	0.988
Apricot	0.000	0.005	0.006	0.088	0.930
Waste land	-0.001	0.006	0.006	0.131	0.896
Village	0.000	0.005	0.005	0.018	0.986
6）0-1.5 km (Model without apricot)					

Intercept	-1.062	1.151	1.151	0.923	0.356
Water	0.008	0.013	0.014	0.550	0.582
Urban	0.006	0.012	0.012	0.455	0.649
SNH	-0.000	0.005	0.006	0.076	0.940
Annual	0.000	0.005	0.006	0.020	0.984
Waste land	-0.001	0.006	0.006	0.132	0.895
Village	0.000	0.005	0.005	0.017	0.986
AICc (with apricot)=-33.65; AICc (without apricot)=-33.58; Pr(>F)=0.395					
7）0-2.0 km (Model with apricot)					
Intercept	-1.062	1.151	1.151	0.923	0.356
Urban	0.010	0.015	0.016	0.629	0.530
Water	0.001	0.006	0.007	0.172	0.863
Waste land	-0.002	0.007	0.008	0.247	0.805
Annual	0.000	0.007	0.008	0.053	0.958
Village	0.000	0.005	0.006	0.031	0.975
SNH	0.000	0.006	0.006	0.040	0.968
Apricot	0.000	0.005	0.006	0.041	0.967
8）0-2.0 km (Model without apricot)					
Intercept	-1.062	1.151	1.151	0.923	0.356
Urban	0.010	0.015	0.016	0.637	0.524
Water	0.001	0.006	0.007	0.175	0.861
Waste land	-0.002	0.007	0.008	0.247	0.805
Annual	0.000	0.007	0.008	0.059	0.953
Village	0.000	0.005	0.006	0.031	0.975
SNH	0.000	0.006	0.006	0.044	0.965
AICc (with apricot)=-33.99; AICc (without apricot)=-34.74; Pr(>F)=0.509					

Table S4.22 Results of multi-model inference analysis to determine the model with apricot and landscape context as explanatory variables and the model with landscape context as explanatory variables effect on **seed set in 2019 and 2020** for cumulative landscape sectors at four spatial scales **(Expt. 3)**. For each scale, the average model was taken from the total candidate models. Z value is the estimate of each coefficient divided by its standard error.

Scales	Estimate	Std. Error	Adjusted SE	Z value	Pr(>|z|)
1） 0-0.5 km (Model with apricot)					
Intercept	7.292	1.375	1.377	5.295	**<0.001**
Year	-2.859	0.416	0.433	6.599	**<0.001**
Apricot	-0.587	0.196	0.205	2.865	**0.004**
Waste land	0.076	0.148	0.152	0.501	0.616
Water	0.068	0.140	0.144	0.474	0.636
Village	0.050	0.132	0.136	0.365	0.715
Urban	-0.014	0.089	0.094	0.153	0.878
SNH	-0.004	0.074	0.078	0.050	0.960
Annual	0.004	0.086	0.090	0.042	0.966
2）0-0.5 km (Model without apricot)					
Intercept	7.386	1.384	1.387	5.327	**<0.001**
Year	-3.060	0.481	0.501	6.111	**<0.001**
Village	0.183	0.240	0.246	0.744	0.457
Waste land	0.083	0.171	0.176	0.473	0.636
Water	0.050	0.137	0.142	0.353	0.724
Urban	0.029	0.121	0.125	0.232	0.817
Annual	0.024	0.127	0.132	0.178	0.859
SNH	0.004	0.091	0.096	0.039	0.969
AICc (with apricot)=91.05; AICc (without apricot)=84.73; Pr(>F)=**0.019**					
3）0-1.0 km (Model with apricot)					
Intercept	7.030	1.379	1.381	5.090	**<0.001**
Year	-2.293	0.467	0.485	4.724	**<0.001**
Apricot	-0.654	0.227	0.236	2.772	**0.006**
SNH	0.044	0.127	0.131	0.337	0.736
Annual	0.044	0.134	0.139	0.316	0.752
Water	0.022	0.095	0.099	0.227	0.820
Village	-0.016	0.093	0.098	0.165	0.869
Waste land	0.021	0.096	0.100	0.207	0.836
Urban	0.027	0.111	0.115	0.238	0.812
4）0-1.0 km (Model without apricot)					
Intercept	7.265	1.386	1.389	5.231	**<0.001**
Year	-2.800	0.514	0.534	5.245	**<0.001**
SNH	0.216	0.252	0.258	0.839	0.401
Waste land	0.088	0.182	0.187	0.474	0.636
Urban	0.146	0.234	0.239	0.610	0.542
Annual	0.104	0.226	0.232	0.451	0.652
Water	0.055	0.148	0.152	0.358	0.720
Village	-0.008	0.109	0.114	0.069	0.945
AICc (with apricot)=83.96; AICc (without apricot)=87.15; Pr(>F)=*0.064*					
5）0-1.5 km (Model with apricot)					
Intercept	7.014	1.396	1.399	5.012	**<0.001**
Year	-2.268	0.616	0.636	3.564	**<0.001**
Apricot	-0.133	0.230	0.235	0.564	0.573
Village	-0.266	0.285	0.291	0.914	0.361
Water	0.106	0.182	0.186	0.571	0.568

Annual	0.156	0.298	0.303	0.515	0.607
SNH	0.109	0.191	0.195	0.559	0.576
Urban	0.176	0.277	0.282	0.623	0.533
Waste land	-0.002	0.093	0.098	0.020	0.984
6）0-1.5 km (Model without apricot)					
Intercept	7.070	1.391	1.395	5.070	**<0.001**
Year	-2.383	0.585	0.604	3.947	**<0.001**
Village	-0.254	0.285	0.291	0.875	0.382
Water	0.110	0.185	0.190	0.582	0.561
Annual	0.192	0.321	0.326	0.588	0.557
SNH	0.139	0.206	0.211	0.657	0.511
Urban	0.207	0.296	0.301	0.688	0.491
Waste land	0.006	0.089	0.093	0.068	0.946
AICc (with apricot)=85.47; AICc (without apricot)=84.55; Pr(>F)=0.396					
7）0-2.0 km (Model with apricot)					
Intercept	7.105	1.392	1.396	5.091	**<0.001**
Year	-2.459	0.588	0.608	4.045	**<0.001**
Annual	0.247	0.364	0.370	0.666	0.505
SNH	0.156	0.229	0.234	0.666	0.506
Urban	0.249	0.337	0.343	0.728	0.467
Village	-0.096	0.199	0.205	0.469	0.639
Apricot	-0.082	0.198	0.203	0.404	0.686
Waste land	-0.045	0.141	0.145	0.307	0.759
Water	0.021	0.106	0.110	0.191	0.849
8）0-2.0 km (Model without apricot)					
Intercept	7.139	1.389	1.392	5.129	**<0.001**
Year	-2.530	0.559	0.578	4.379	**<0.001**
Annual	0.271	0.375	0.382	0.710	0.477
SNH	0.181	0.237	0.242	0.750	0.453
Urban	0.277	0.346	0.352	0.785	0.432
Village	-0.093	0.197	0.202	0.459	0.646
Waste land	-0.029	0.115	0.120	0.241	0.810
Water	0.025	0.110	0.114	0.214	0.830
AICc (with apricot)=-33.99; AICc (without apricot)=-34.74; Pr(>F)=0.509					

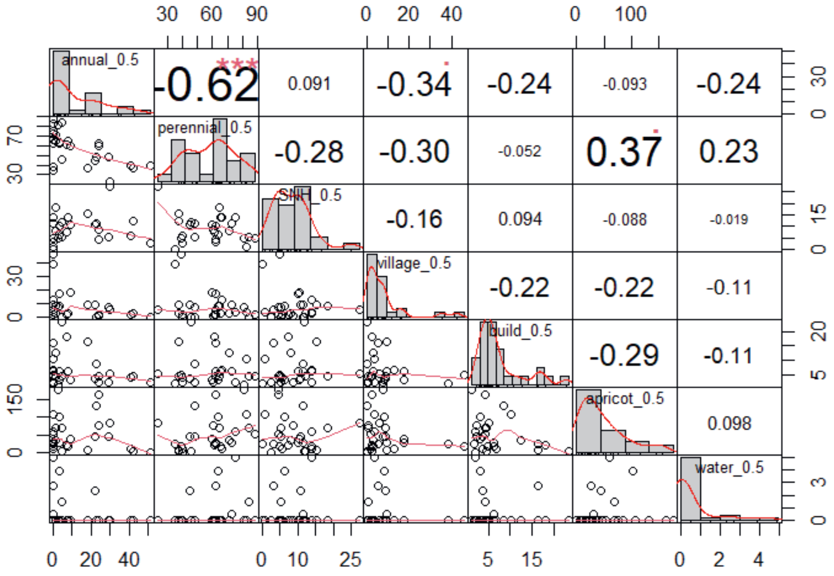

Figure S4.1 Values of Spearman correlation coefficients between the explanatory variables at 0.5 km landscape scale * *P*-value < 0.05; ** *P*-value < 0.01; *** *P*-value < 0.001.

Chapter 5

Synthetic Nasonov gland pheromone enhances abundance and visitation of honeybee, *Apis mellifera*, in Korla fragrant pear, *Pyrus sinkiangensis*

Qian Li[1,2,3], Mengxiao Sun[1,2,3], Yangtian Liu[1], Bing Liu[1], Wopke van der Werf[2], Felix J. J. A. Bianchi[3] and Yanhui Lu[1]

[1] *State Key Laboratory for Biology of Plant Diseases and Insect Pests, Institute of Plant Protection, Chinese Academy of Agricultural Sciences, Beijing, 100193, China;*

[2] *Centre for Crop Systems Analysis, Wageningen University & Research, Wageningen, The Netherlands;*

[3] *Farming Systems Ecology, Wageningen University & Research, Wageningen, The Netherlands*

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Abstract

Korla fragrant pear (*Pyrus sinkiangensis* Yü) depends on cross-pollination by honeybees (*Apis mellifera*) but may suffer from low honeybee visitation. We assessed whether honeybee abundance and visitation frequency are enhanced by using synthetic Nasonov gland pheromone (NGP), which is naturally produced by worker bees to stimulate the aggregation of bees to food resources or nesting sites. The response of honeybees to synthetic NGP was firstly assessed using Y-tube olfactometer tests in the laboratory, and subsequently in the field, by placing NGP lures on Korla fragrant pear trees in orchards with and without beehives. Honeybee abundance was assessed using colored pan traps while honeybee visits were assessed by visual observations on pear flowers. Y-tube olfactometer tests showed a significant preference of honeybees for NGP. In pear orchards with beehives, honeybee abundance was 2.5-fold higher on trees with NGP lures than on trees without NGP, and 2.2-fold higher in orchards in which all trees contained NGP lures than in orchards without NGP lures. Such positive effects were not observed in orchards without beehives. Flower visitation by honeybees was significantly higher in trees with NGP lures than without NGP lures, irrespective of the presence (5.7-fold higher) or absence of beehives (27.6-fold higher). In mixed pear-apricot orchards, honeybee abundance was higher in pear trees with NGP lures than without lures. Our results show that NGP lures attract honeybees to flowering pear trees in monoculture pear and mixed pear-apricot orchards, and that this effect is greatest in orchards with beehives.

Keywords: behavior manipulation, pheromone, attractant, pollination, pollinator, floral resource

5.1 Introduction

The production of many kinds of fruit depends on insects for pollination (Kleijn et al., 2015; Sawe et al., 2020; Hünicken et al., 2021), but there are growing concerns about the decline of the abundance and diversity of wild insect pollinators in many parts in the world (Powney et al., 2019; LeBuhn and Vargas Luna, 2021; Wagner et al., 2021; Outhwaite et al., 2022). Some fruit crops, such as pear, depend heavily on managed European honeybees (*Apis mellifera* L.) because the flowers are less attractive for wild bees because of the low sugar content of the nectar (Delaplane and Mayer, 2000). Yet, even with honeybees fruit production can be constrained by pollination limitation (Aizen and Harder, 2009; Aizen et al., 2019; Osterman et al., 2021; Mashilingi et al., 2022). Therefore, there is a need for approaches that can further enhance the activity of honeybees for crop pollination, particularly in regions where there is a shortage of pollinators.

Pheromones are chemicals that are released by individuals for communication within the same species (Shorey, 1976). The Nasonov gland pheromone (hereafter “NGP”) is released by worker honeybees from their abdominal glands to stimulate aggregation and orient other bees to food resources or nest sites (Pickett et al., 1980; Free et al., 1981; 1984; Williams et al., 1981). NGP has been chemically characterized and synthesized. It consists of geraniol, (E)-citral, nerolic acid, (Z)-citral, nerol, geranic acid, and (E,E)-farnesol (Pickett et al., 1980). Synthetic NGP triggers a similar response in honeybees as the naturally produced pheromone (Williams et al., 1981) and it attracts honeybees at a distance of approximately 10 cm (Butler, 1970). Despite this relatively small range, attraction of honeybees to NGP has been observed under field conditions (Williams et al., 1981; Schmidt, 1994; Schmidt, 2001) and honeybee attractants based on NGP have been used to enhance fruit crop pollination in apple (Mayer et al., 1989a), sweet orange (Malerbo-Souza et al., 2004), guava (Anita et al., 2012) and kiwifruit (Jailyang et al., 2022).

Korla fragrant pear (*Pyrus sinkiangensis* Yü) is a local variety of pear which is usually intensively managed with high pesticide inputs and is typically grown in landscapes dominated by Korla fragrant pear orchards in Xinjiang, China. Like most rosaceous plants, Korla fragrant pear is a self-incompatible species that requires cross pollination by insects with a compatible cultivar to set fruit (De Franceschi et al., 2012). There is a large pollination deficit in Korla fragrant pear and this deficit can be mitigated by using beehives with managed honeybees, *Apis mellifera* (Li et al., 2022). While Korla fragrant pear is usually grown in monocultures, it is also grown in mixed pear-apricot orchards. These mixed orchards usually have a low density of apricot trees to produce apricots for self-consumption. Apricot, *Prunus armeniaca* L., is an early flowering tree species which flowers one week before pear. The apricot flowers are more attractive to honeybees than pear flowers (Lan et al., 2021) and therefore the presence of apricot trees can increase honeybee abundance in pear orchards (Li et al., unpublished data). It is unclear to what extent NGP lures can increase honeybee abundance and pear flower visitation in pear trees in monoculture pear and mixed pear-apricot orchards.

Here, we assessed the effect of NGP on honeybee aggregation and flower visitation in Korla fragrant pear orchards, and assessed how this was influenced by placing honeybee hives in the orchard. These assessments were conducted in four complementary experiments. First, we assessed the attractiveness of NGP lures to honeybees under controlled conditions to ascertain the biological activity of the used source of NGP. Second, we assessed how NGP lures deployed on individual pear trees influenced honeybee abundance and visitation in orchards with or without beehives. Third, we assessed how NGP lures deployed on all pear trees in an orchard influenced the abundance of honeybees in orchards with or without beehives. Fourth, we assessed how NGP lures influence honeybee abundance in mixed apricot-pear orchards. We hypothesized that 1) honeybees should show a preference for the NGP under controlled conditions, 2) honeybee abundance and pear flower visitation rate should be higher on pear trees with NGP lures and in orchards with honeybee hives, 3) the aggregation effect of NGP on honeybee abundance in orchards where all pear trees have NGP lures should be consistent with the effect where NGP lures are deployed on individual pear trees, and 4) honeybee abundance should be higher on pear trees with NGP lures than pear trees without NGP lures in mixed pear-apricot orchards.

5.2 Materials and methods

5.2.1 Study site and NGP source

The field study was conducted in Korla fragrant pear orchards in four counties around the city of Korla, Xinjiang, northwest China (E 85.48°, N 41.45°) in 2021 (Table S5.1, S5.2 and S5.3). The region has an average annual temperature of 13.4 °C and an average annual precipitation of 87 mm. The criteria of experimental orchards selection were 1) orchards had an in-row spacing of approximately 5 m and approximately 6 m between rows; 2) pear trees were 15-20 years old; 3) no chemical pesticides were applied from one week before flowering until the end of flowering. Most orchards consisted of Korla fragrant pear trees with some interspersed Dangshan pear trees (*Pyrus communis* L.) used as pollinizer to ensure cross-pollination. All orchards had conventional management with regular pesticide applications after the pear flowering period. We recorded whether orchards contained beehives or not.

We used the commercial product Polynate® as NGP lures (i.e., yellow plastic "rings" in Figure 5.1), which were obtained from Bioglobal Co. in Shenzhen, China (http://www.bioglobal.com.cn/product/detail/99.html). Following product recommendation, three lures were established per Korla fragrant pear tree (which is equivalent to one lure per 10 m^2).

Figure 5.1 Korla fragrant pear tree with three “Polynate” rings containing the Nasonov gland pheromone and yellow, blue, and white pan traps to sample the pollinator community around the tree.

5.2.2 Experiment 1: Y-tube olfactometer trials

To verify the honeybee preference to NGP released from Polynate, we studied the behavioral responses of honeybees to NGP using a Y-tube olfactometer. The olfactometer consisted of a 3 cm diameter, clear glass tube, made of a 15 cm long central tube that branched into two 15 cm lateral arms with a 60° angle between the arms. The Y-tube was placed in a 100 × 100 × 60 cm chamber, illuminated with two 40 W fluorescent lamps (light intensity 2000 lx) and maintained at 25 ± 1 °C and 60 ± 5% RH. A vacuum pressure pump (Beijing Institute of Labor Instrument, Beijing, China) pushed air through activated charcoal and an Erlenmeyer flask filled with distilled water. The airflow through each of the olfactometer arms was maintained at 300 ml/min and entered the apparatus via a Teflon tube. One arm was connected with a glass conical flask place with the NGP source and other arm was connected with a glass conical flask place without NGP. Honeybees were obtained from a colony of a local beekeeper on the day of the bioassay, using bees that were approximately 20 days old. Before the behavioral bioassay, honeybees were starved for 4 h individually in a transparent glass container (1.5 cm diameter, 5 height).

Individual honeybees were introduced at the base of the main arm of the olfactometer via a 10 cm long glass vial and given 5 min to respond. A choice for the NGP or control treatment was recorded when honeybees passed the Y-junction by 3 cm for at least 5 seconds. If a honeybee did not make a choice within 5 min, it was recorded as “no choice.” Each honeybee was used only once. After each trial, the Y-tube was replaced with a clean one, and the used Y-tube was cleaned with acetone and then air dried overnight at room temperature. The NGP source was changed every four hours. In total, 100 individual honeybees were tested. All bioassays were conducted between 08:00 and 18:00.

5.2.3 Experiment 2: Tree-level effects of NGP on honeybee abundance and pear flower visitation

To assess the effect of NGP on honeybee abundance at the tree level, we selected nine pear monoculture orchards, of which two orchards contained beehives and seven orchards did not (Figure 5.2a). The minimum distance between two focal orchards was 0.92 km. In each orchard, two blocks with same size (approximately 48 m x 20 m) were selected and each block contained around 45 trees (9 rows x 5 trees per row). One block was selected to assess honeybee abundance and another block to assess honeybee visitation rates. The two blocks were at least 20 m apart. Within each block, 6 trees were selected out of 45 trees, of which three pear trees received NGP lures (three lures per tree at 1.5-2.0 m height following product recommendation) and three trees did not (Figure 5.2a). The distance between selected trees was 24 m between rows and 20 m within rows.

The abundance of honeybees was monitored using pan trap stations, which were placed in the six trees of one of the blocks (Figure 5.2a). The pan traps stations and NGP lures were installed at the same time. Each pan trap station consisted of three cups (12.1 cm diameter, 13 cm height) that were painted with ultraviolet (UV) yellow (SANO, type No. 1005), UV blue (SANO, type No. 1004), or UV white (SANO, type No. 1010) on the in and outside. Pans were placed on three different branches of the same tree. Cups were filled with 600 ml water and a few drops of detergent. Cups were emptied and refilled three times, at approximately 3-day intervals, for a total sampling period of 9 days. The abundance of honeybees per tree (3 rounds and 3 cups) were pooled together for the analysis.

Honeybee visits to pear flowers were assessed on the three trees with and three trees without NGP lures in the other block (Figure 5.2a). Of each tree, a 1-cm diameter branch was selected at 1.5 m height and a group of 100 open flowers was marked for observation of flower visitation. The number of honeybees that visited the marked branch during a 10-minute interval was recorded, and this was replicated four times on newly selected flower areas between 10:00-11:30, 12:00-13:30, 14:00-15:30 and 16:00-17:30 on different days (Table S5.1). A visit was recorded when a honeybee touched the stigma of a pear flower, and when the same honeybee visited another new flower it was recorded as another visit. All observations were conducted during dry weather conditions with temperature ranging between 10℃ and 22℃ and wind speeds below 29 km/h. The number of honeybee visits during the four observation periods per tree were pooled for the analysis.

5.2.4 Experiment 3: Orchard level effects of NGP on honeybee abundance

To assess the effect of NGP on honeybee abundance at the orchard level, we selected 18 new orchards, in nine pairs of two orchards. Paired orchards were located less than 200 m apart, and the minimum distance between two focal orchard pairs was 1.03 km. Two of these orchard pairs consisted of orchards with beehives (4 orchards) while seven pairs (14 orchards) did not have beehives (Figure 5.2b). Of each orchard pair, one was randomly selected to have NGP lures in all the trees as described previously, while the trees in other orchard did not receive NGP lures and served as a control.

Honeybee abundance was monitored by placing 5 pan trap stations in a “X” pattern in 5 trees in an approximately 54 x 45 m block in the middle of the orchard. The block contained around 100 trees (10 rows x 10 trees per row). Five trees were selected in the four corners and center of the block, respectively. Pan trap stations were always located 2 trees away from the edge of the orchard (around 10-12 m). The methodology for NGP lures and pan trap installation and honeybee collection were similar as described in section 2.3, and honeybees were sampled over a period of 9 days (Table S5.2).

5.2.5 Experiment 4: Effect of NGP on honeybee abundance in mixed pear-apricot orchards

To assess the effect of NGP on honeybee abundance in mixed pear-apricot orchards, we selected four pear orchards with a row of apricot trees at the edge of the orchard, and pear trees in the rest of the orchard (Figure 5.2c). One orchard contained beehives, and the other three orchards did not. The minimum distance between two focal orchards was 1.45 km. In each apricot-pear orchard two blocks with same size (approximately 12 x 50 m) were established at a distance of 50 m. Trees in one block received NGP lures and the other block served as a control (Figure 5.2c). Each block contained around 30 pear trees (3 rows x 10 trees per row), of which 9 trees were selected at distances of 10 m, 30 m, and 50 m from the apricot tree row, three adjacent trees at each distance (Figure 5.2c). In the treatment block, the pan trap stations and NGP lures were established in the 9 selected trees, while in the control block only the pan trap stations were set up in 9 selected trees. The methodology for NGP lures and pan trap installation and collection were similar as described in section 2.3, and honeybees were sampled for 9 days (Table S5.3).

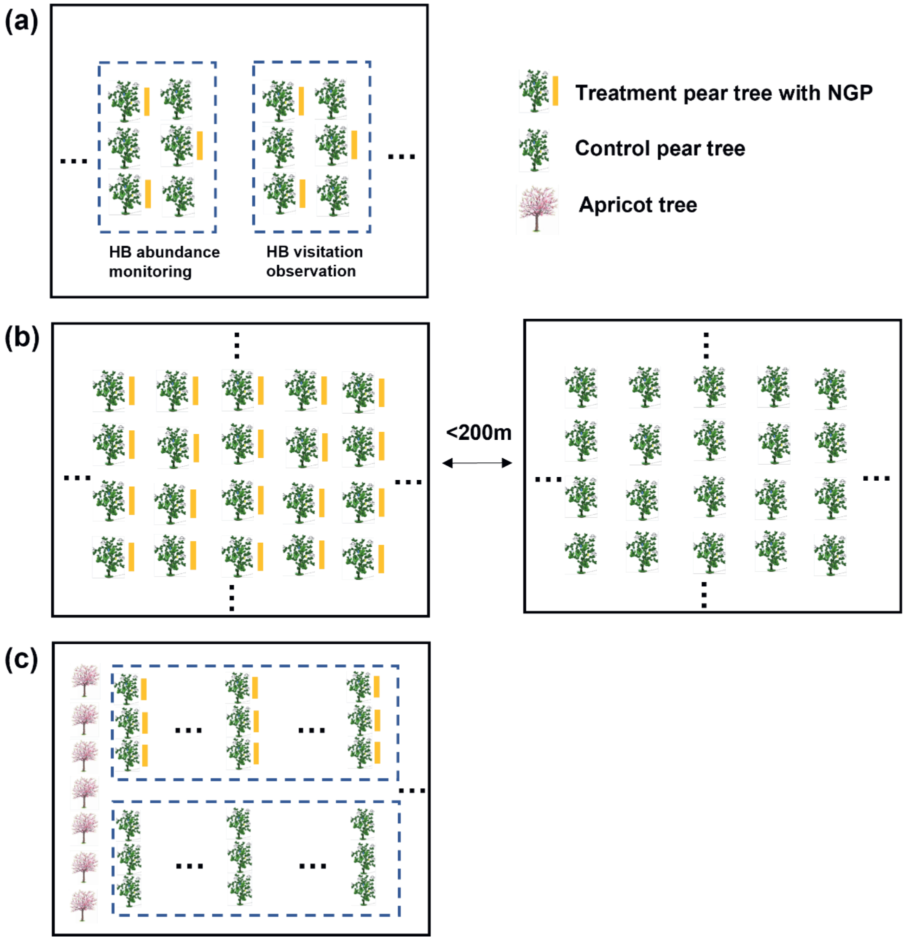

Figure 5.2 Experimental design of three field experiments in Korla fragrant pear orchards. The green trees with/without yellow bars indicate pear trees with/without NGP dispenser, the pink tree line in panel c indicates the apricot trees in a mixed pear-apricot orchard. The different panels show: (a) Experiment 2: tree-level effects of NGP on honeybee abundance and pear flower visitation in pear orchards; (b) Experiment 3: orchard-level effects of NGP on honeybee abundance in pear orchards; and (c) Experiment 4: effect of NGP on honeybee abundance in mixed pear-apricot orchards. For each experimental design, orchards with and without beehives were selected (not shown).

5.2.6 Data analysis

We conducted five analyses. In the first analysis (Expt 1), honeybee responses to NGP and control in the Y-tube olfactometer experiment was analyzed with a Chi-square goodness-of-fit test. In the second analysis (Expt 2), we explored how the abundance of honeybees in pan traps and the number of honeybee flower visits in pear trees (response variables) were influenced by “NGP” (NGP lures present or absent), “beehive” (beehives present or absent) and their interaction at single tree level using generalized linear mixed effects models with a negative binomial error distribution. “Orchard” was included as a random effect. We further explored the influence of NGP lures in subsets of data for orchards with and without beehives using the same model, but without the explanatory variable “beehive”. For orchards without beehives (n=7), we used a GLMM and for orchards with beehives (n=2) we used a GLM because the inclusion of random effects is not recommended for a low number of sites (Zuur et al., 2009). In the third analysis (Expt 2), we explored the relationship between the total honeybee flower visits per site (response variable) and total number of honeybees in pan traps per site (explanatory variable) using a linear mixed effect model. “Orchard pair” was included as a random effect. In the fourth analysis (Expt 3), we explored how the abundance of honeybee in pan traps (response variable) was influenced by “NGP” (orchards with or without NGP lures), “beehive” and their interaction at orchard level in the same way as in the second analysis. In the fifth analysis (Expt 4) we explored how honeybee abundance in mixed pear-apricot orchards (response variable) were influenced by “NGP”, “beehive” and “distance” (distance of sampled pear trees from the apricot tree row), and their interactions in the same way as in the second analysis. We used a model selection procedure using the "dredge" function to select the most parsimonious model based on the smallest AIC value. The honeybee abundance and honeybee flower visits were all analyzed at single tree level, and we assumed the individual trees in each block were independent. In addition, a data-analysis of experiment 4 was conducted using the total count for the 9 trees per block in each orchard (i.e., aggregating over the distances and replicate trees per distance). In this case, the datafile comprised 8 data records, with for each orchard one record for the total count of bees on the nine trees with NGP and one record for the total count of bees on the nine trees without NGP.

All models were validated using histograms of normalized residuals and plots of residuals against fitted values (Zuur et al., 2009). All calculations and analyses were conducted using R version 3.5.1 (R Core Team, 2018). We used the glmer function of the "lme4" package (Bates et al., 2015) and the dredge function of the "MuMIn" package (Bartón, 2017). Means and standard errors of the mean are reported throughout the text.

5.3 Results

5.3.1. Y-tube olfactometer trial

Out of 91 honeybees making a choice between NGP and the control arm of the Y-tube olfactometer, 68 chose NGP and 23 control, indicating significant preference for NGP ($\chi^2=22.253$, $P < 0.001$; Figure 5.3).

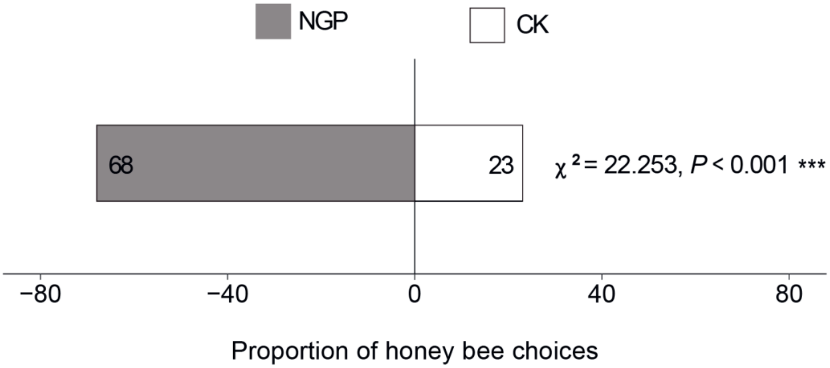

Figure 5.3 Preference of honeybees for the synthetic Nasonov gland pheromone (NGP) treatment and the blank control (CK) in a Y-tube olfactometer.

5.3.2 Experiment 2: Tree-level effects of NGP and beehives on honeybee abundance and pear flower visitation

There was a significant interaction between the NGP treatment and "beehives" (*P* = 0.033; Table S5.5). In pear orchards with beehives, the honeybee abundance in pear trees with NGP lures was 2.50-fold higher than in pear trees without NGP lures (9.17 ± 2.18 vs. 3.67 ± 1.43 individuals per tree, *P* = 0.024), while in pear orchards without beehives, honeybee abundance was not significantly different between trees that had NGP lures or not (0.62 ± 0.20 vs. 0.67 ± 0.21 individuals per tree, *P* = 0.876; Table S5.4 and S5.6; Figure 5.4a).

The number of pear flowers visited by honeybees was significantly higher in trees with NGP lures than control trees (*P* = 0.018), and significantly higher in orchards with beehives than without beehives (*P* = 0.014). The interaction between NGP lures and "beehive" was not significant (Table S5.5). In pear orchards with beehives, the number of pear flower visits in trees with NGP lures was 5.7-fold higher than in control trees (15.17 ± 5.55 vs. 2.67 ± 1.71 visits per 40 minutes, *P* = 0.028), while in pear orchards without beehives, the number of pear flower visits in trees with NGP lures was 27.6-fold higher than in control trees (1.38 ± 0.96 vs. 0.05 ± 0.05 visits per 40 minutes, *P* = 0.016; Figure 5.4b; Table S5.4 and S5.6).

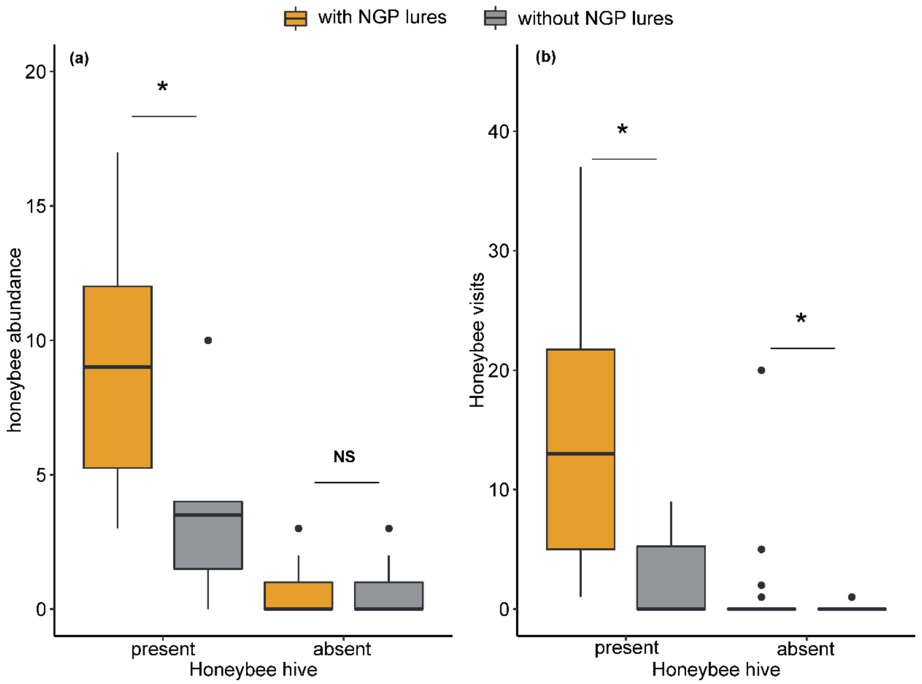

Figure 5.4 Honeybee abundance in pan traps in pear trees (a) and number of pear flower visits by honeybees in 40 minutes (b) in pear trees that contained three Nasonov gland pheromone (NGP) lures or not, and have beehives (2 orchards) or not (7 orchards) (Expt 2). Asterisks (* $P < 0.05$) and NS ($P > 0.05$) indicate significance levels of the effect of NGP for orchards with and without beehives, respectively (Table S5.6).

The honeybee flower visits were significantly positively associated with the honeybee abundance in pan traps ($P < 0.001$; Figure 5.5; Table S5.7).

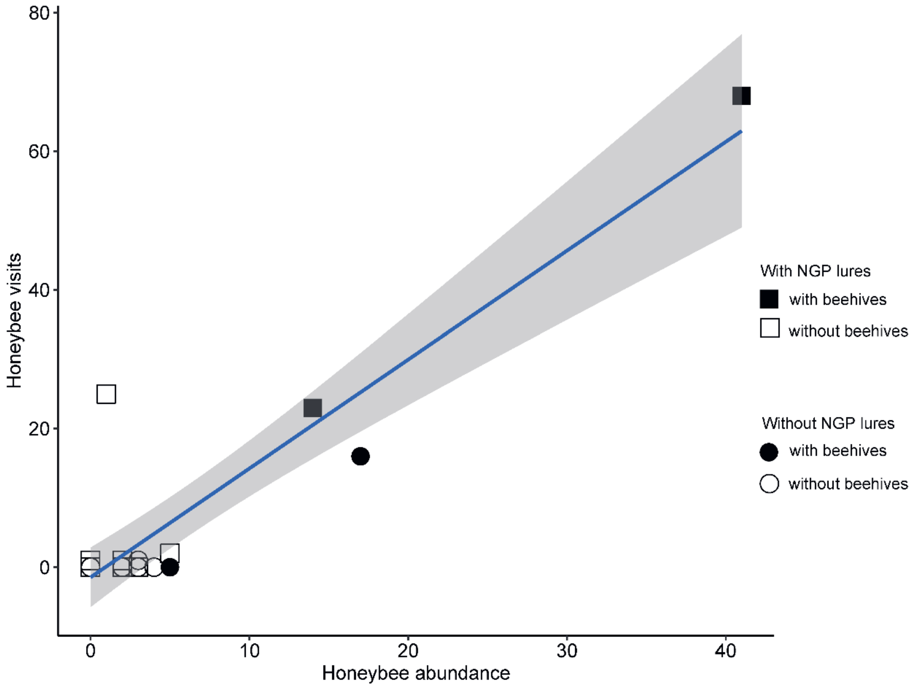

Figure 5.5 Relationship between the honeybee abundance in pan traps and the number of honeybee visits on pear flowers per orchard in Korla fragrant pear orchards (Expt 2). The regression line indicates a significant relationship (*P* < 0.05), and is based on a linear mixed effect model (Table S5.7).

5.3.3 Experiment 3: Orchard-level effects of NGP and beehives on honeybee abundance

The abundance of honeybees was not significantly influenced by the presence of NGP lures, but was significantly higher in orchards with beehives than without beehives (*P* < 0.001). The interaction between NGP and beehives was not significant (Table S5.9). However, when the abundance of honeybees was analyzed separately for the orchard pairs that contained beehives, the abundance of honeybees in orchards with NGP lures was significantly higher than in orchards without NGP lures (8.40 ± 1.51 vs. 3.80 ± 0.70 individuals per tree, *P* = 0.003; Table S5.8 and S10, Figure 5.6). In orchards without beehives, honeybee abundance was more than an order of magnitude lower, and the presence of NGP lures did not have a significant influence on the honeybee abundance (0.34 ± 0.11 (NGP) vs. 0.31 ± 0.10 (control) individuals per tree; *P* = 0.835; Table S5.8 and S10; Figure 5.6).

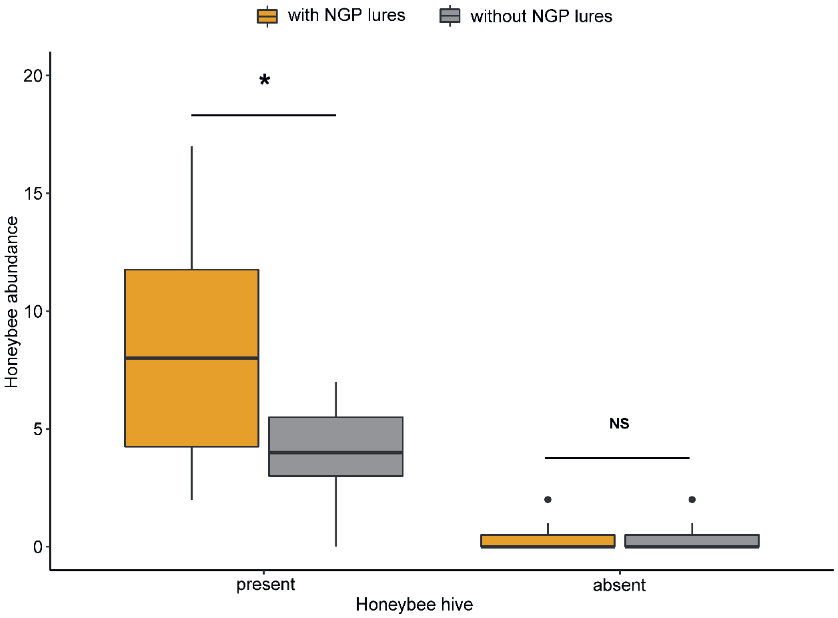

Figure 5.6 Honeybee abundance in pan traps per tree in pear orchards with or without beehives in which all trees have three Nasonov gland pheromone (NGP) lures or not, and have beehives or not (Expt 3). Asterisks (* $P < 0.05$) and NS ($P > 0.05$) indicate significance levels for the effect of NGP for orchards with and without beehives, respectively (Table S5.10).

5.3.4 Experiment 4: Effects of NGP and beehives on honeybee abundance in mixed pear-apricot orchards

Model selection indicated that the most parsimonious model contained the main effects “NGP” and “beehive”, without “distance” and the interaction between NGP and beehive. Honeybee abundance in the block with NGP lures in mixed pear-apricot orchards was significantly higher than in the blocks without NGP (*P* = 0.019), but not significantly different between orchards with and without beehives (Table S5.12). The analysis using the total count of bees per block of nine trees in each orchard confirmed the results of the analysis using single tree data: there was a significant effect of NGP (*P* = 0.007), no significant effect of presence of beehives (*P* = 0.143) and no significant interaction between NGP and beehives (*P* = 0.288) (Table S5.13). In the one mixed pear-apricot orchard with beehives, the honeybee abundance in the block with NGP lures was 2.2-fold higher than in the block without NGP lures (5.78 ± 0.55 vs 2.67 ± 0.55 individuals per tree, Figure 5.7). In the three mixed pear-apricot orchards without beehives, the honeybee abundance in the block with NGP lures was 1.6-fold higher than in the block without NGP lures (2.56 ± 0.43 vs 1.59 ± 0.30 individuals per tree; *P* = 0.049; Table S5.11 and S5.14; Figure 5.7).

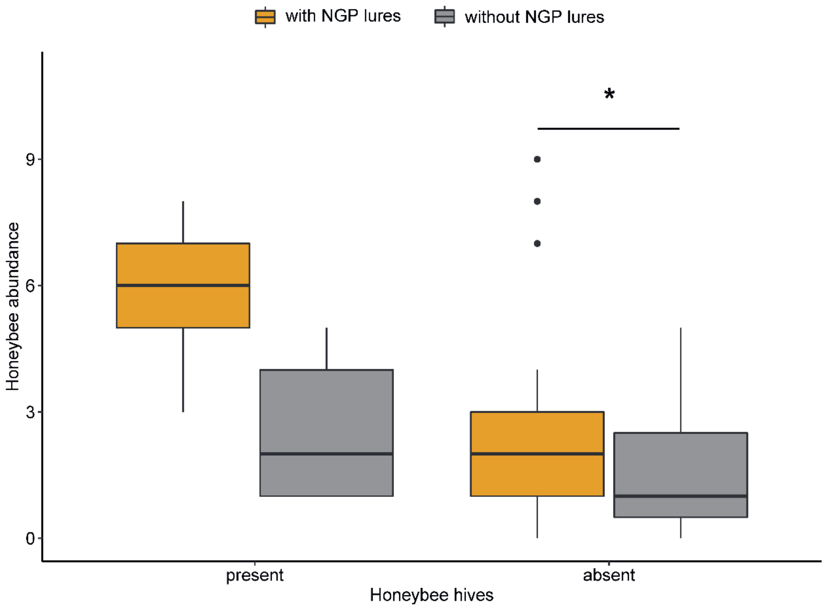

Figure 5.7 Honeybee abundance in pan traps per tree in pear orchards with an edge row of apricot trees in which pear trees contained three Nasonov gland pheromone (NGP) lures or not and have beehives or not (Expt 4). Asterisks (* $P < 0.05$) indicate significance levels for the effect of NGP for orchards without beehives (Table S5.13). The effect of NGP on honeybee abundance in the single orchard with beehives was not tested because of the lack of replication at the orchard level.

5.4 Discussion

This is the first study to assess the attractiveness of Nasonov gland pheromone lures to honeybees in Korla fragrant pear orchards in Xinjiang. We found that NGP in pear trees enhanced honeybee abundance in pan traps and pear flower visitation rates, and that this effect was most pronounced in pear orchards that contained beehives. NGP also resulted in higher honeybee abundance in mixed pear-apricot orchards. As insect pollination is a limiting factor in Korla fragrant pear (Li et al., 2022), these findings suggest that NGP has a potential to improve crop pollination by honeybees in this crop.

The Y-tube olfactometer trial confirmed the attractiveness of NGP lures for honeybees, and this was further confirmed in our field experiments in Korla fragrant pear orchards. Placing NGP lures in individual pear trees increased honeybee abundance by 2.5-fold and pear flower visitation by 5.2-fold, but only in orchards with beehives. This aligns with the findings of other studies. For instance, Schmidt (2001) showed that beehives marked with synthetic Nasonov pheromone were more attractive to honeybees and Mayer et al. (1989a, b) found that NGP increased honeybee visitation and fruit set in apple, cherry and pear in the USA. In China, the application of NGP lures increased the honeybee visitation frequency and fruit set in blueberry (Liu et al., 2016) and sweet cheery (Wang et al., 2021). However, in orchards without beehives pear flower visitation rates were low, despite the 27.6-fold higher flower visitation rates in trees with NGP lures than without NGP lures (1.38 ± 0.96 vs. 0.05 ± 0.05 visits per 40 minutes). Our findings at the individual tree level were consistent with our findings at the orchard level. When NGP lures were applied to all trees in pear orchards this lead to a 2.2-fold higher honeybee abundance in pan traps compared to orchards without NGP lures, but only when there were beehives in the orchard. When no beehives were present in the orchards the honeybee abundance was low, and most likely constrained fruit set (Li et al., 2022). Obviously, if there are no or only few honeybees present in the orchard, the use of NGP will not be meaningful (Delaplane and Mayer, 2000). Therefore, NGP should be used in combination with the establishment of beehives.

In mixed pear-apricot orchards, honeybee abundance was significantly higher in pear trees with NGP lures than without lures, and this was not influenced by the distance from the apricot tree row. While honeybees aggregate at apricot trees, honeybee densities quickly decline with increasing distance from apricot trees, such that only pear trees in the direct vicinity of apricot trees can benefit from increased honeybee visitation (Li et al., unpublished data). Here we show that the use of NGP in combination with the presence of early flowering apricot trees leads to a higher honeybee abundance in pan traps. We did not find a decrease of honeybee abundance at further distance from apricot trees. Possibly, the NGP lures functioned as stepping stones for honeybees, or arrested honeybees that happened to be nearby pear trees with NGP lures. While our experiment does not allow us to draw conclusions about the underlying mechanisms, our findings suggest that the use of NGP in combination with early flowering plant resources may be a promising approach to attract and retain honeybees in Korla fragrant pear orchards.

Here, we did not assess the influence of NGP lures on fruit set, yield, and the quality of pears. However, our results show that honeybee abundance in pan traps was strongly correlated with pear flower visitation rate, indicating that honeybee abundance in pan traps is a useful indicator for pear flower visitation. Furthermore, in a two-year study we showed that honeybee visitation rates were positively associated with initial fruit set and sugar content, but not fruit weight (Li et al., 2022). In addition, the effectiveness of NGP on fruit set and quality has also been reported in Guava and kiwifruit in India (Anita et al., 2012; Jailyang et al., 2022). Therefore, we expect that the use of NGP can improve Korla fragrant pear fruit set and quality.

While the use of NGP can increase the honeybee abundance and pear flower visitation, we cannot exclude the possibility that the use of NGP has side effects on the pollination system in and around the orchards where it is used. There may be at least two mechanisms. First, an enhanced aggregation of honeybees in pear orchards with NGP lures could possibly negatively affect the pollination of plants that flower at the same time as pear, i.e., competition among plant species for pollination by honeybees.

In the study region there are relatively few co-flowering plant species around pear orchards, besides apricot, peach, and plum. The low flower cover in early spring can be explained by weed management practices in pear orchards, and that the study region is an oasis area in an arid environment, where vegetation in absence of irrigation is sparse. Second, the use of NGP in pears also could increase competition for floral resources of pear among different pollinator groups. The increased visitation of honeybees to pear flowers could result in depletion of nectar in pear and/or increase the interference of different pollinator species (Weekers et al., 2022). However, even though wild pollinator species, such as wild bees, hoverflies, and other flies, are common in pear orchards, their pear visitation rates are relatively low as compared to honeybees (Li et al., 2022). Based on this preliminary evaluation, the risks of using NGP in pear orchards are likely to be limited as compared to the risks of, for instance, the high agrochemical input in these orchards. The use of NGP in combination with insecticide applications could potentially be very harmful for pear pollinators, and therefore NPG lures need to be removed after pear flowering before insecticide applications take place. Further study is needed for a more conclusive risk assessment for the use of NGP in orchards.

A limitation of the study in mixed pear-apricot orchards (Expt 4) was that these types of orchards are not so common in the study area and that we could only include a single pear-apricot orchard with beehives. While the lack of replication at the orchard level prevents drawing statistically underpinned conclusions, the observations in this orchard provided circumstantial evidence that the use of NGP in mixed pear-apricot orchards with honeybee hives can attract honeybees to pear trees even though honeybees prefer apricot flowers to pear flowers (Lan et al., 2021). However, a replicated study is needed to ascertain whether this a general pattern or not.

In conclusion, the honeybee attraction function of NGP has been shown in several crops and locations, and can therefore be considered robust. NGP has therefore potential to attract honeybees and increase honeybee visitation, fruit set and quality in pollination-limited fruit crops (Jayaramappa et al., 2011; Sivaram et al., 2013; Ma et al., 2015). Our current results show that NGP is not effective in orchards without beehives, and therefore NGP can best be used in combination with placing honeybee hives in orchards.

Acknowledgments

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Supplementary Information

Table S5.1 Information on the Korla fragrant pear orchards for the experiment at the single tree level in Korla, Xinjiang, China (Expt 2).

Site	Country	Beehives	Latitude (N)	Longitude (E)	Size (ha)	Pollinator sampling period	Flower visitation rate observation
1	Shanghu	without	41.82823	85.91315	0.23	2021/4/6-4/15	2021/4/13-4/16
2	Shanghu	without	41.81871	85.94775	0.41	2021/4/6-4/15	2021/4/13-4/16
3	Shanghu	without	41.81520	85.96791	0.76	2021/4/6-4/15	2021/4/13-4/16
4	Heshilike	without	41.73876	85.87264	0.50	2021/4/6-4/15	2021/4/13-4/16
5	Heshilike	without	41.73747	85.90566	0.42	2021/4/6-4/15	2021/4/13-4/16
6	Heshilike	without	41.74060	85.90782	0.61	2021/4/6-4/15	2021/4/13-4/16
7	Heshilike	without	41.74802	85.90393	0.43	2021/4/6-4/15	2021/4/13-4/16
8	Shayidong	with	41.74720	85.99685	1.27	2021/4/6-4/15	2021/4/13-4/16
9	Shayidong	with	41.75448	85.98887	1.17	2021/4/6-4/15	2021/4/13-4/16

Table S5.2 Information on the Korla fragrant pear orchards for the experiment at the orchard level in Korla, Xinjiang, China (Expt 3).

Site	Country	Beehives	NGP lures	Latitude (N)	Longitude (E)	Size (ha)	Pollinator sampling period
1	Shanghu	without	with	41.82848	85.91068	0.48	2021/4/6-4/15
1	Shanghu	without	without	41.82880	85.91046	0.64	2021/4/6-4/15
2	Shanghu	without	with	41.81956	85.94527	0.42	2021/4/6-4/15
2	Shanghu	without	without	41.82014	85.94659	0.56	2021/4/6-4/15
3	Shanghu	without	with	41.81544	85.95993	0.31	2021/4/6-4/15
3	Shanghu	without	without	41.81627	85.95959	0.34	2021/4/6-4/15
4	Heshilike	without	with	41.73851	85.87111	0.50	2021/4/6-4/15
4	Heshilike	without	without	41.73920	85.87099	0.36	2021/4/6-4/15
5	Heshilike	without	with	41.73610	85.90388	0.71	2021/4/6-4/15
5	Heshilike	without	without	41.73737	85.90359	0.77	2021/4/6-4/15
6	Heshilike	without	with	41.73891	85.90626	0.55	2021/4/6-4/15
6	Heshilike	without	without	41.74007	85.90591	0.53	2021/4/6-4/15
7	Heshilike	without	with	41.74694	85.90011	0.66	2021/4/6-4/15
7	Heshilike	without	without	41.74750	85.89803	0.47	2021/4/6-4/15
8	Shayidong	with	with	41.74709	85.99412	1.08	2021/4/6-4/15
8	Shayidong	with	without	41.74755	85.99290	0.65	2021/4/6-4/15
9	Shayidong	with	with	41.75183	85.98757	0.81	2021/4/6-4/15
9	Shayidong	with	without	41.75089	85.98765	0.54	2021/4/6-4/15

Table S5.3 Information on the Korla fragrant pear orchards with apricot tree lines in Korla, Xinjiang, China (Expt 4).

Site	Country	Beehives	Latitude (N)	Longitude (E)	Size (ha)	Pollinator sampling period
1	Awati	without	41.66792	86.08964	1.71	2021/4/7-4/16
2	Heshilike	without	41.73037	85.92260	0.68	2021/4/7-4/16
3	Shanghu	without	41.81258	85.98864	1.62	2021/4/7-4/16
4	Awati	with	41.67625	86.05322	1.92	2021/4/7-4/16

Table S5.4 Mean and standard error of honeybee abundance per tree in pan traps during a sampling period of 9 days and pear flower visits by honeybees in 40 minutes in pear trees with or without NGP lures in monoculture Korla fragrant pear orchards with (n = 2) and without beehives (n = 7) (Expt 2).

Beehives	NGP lures	Honeybee abundance		Pear flower visits	
		Mean	Standard error	Mean	Standard error
Yes	Yes	9.17	2.18	15.17	5.55
Yes	No	3.67	1.43	2.67	1.71
No	Yes	0.62	0.20	1.38	0.96
No	No	0.67	0.21	0.05	0.05

Table S5.5 Results of GLMM analysis with negative binomial error distribution for the observations at tree level in monoculture Korla fragrant pear orchards (Expt 2). Response variables were honeybee abundance per tree per 9 days and pear flower visits per 40 minutes, and the explanatory variables were NGP lures (presence or absence), beehives (presence or absence) and their interaction. Orchard was included as a random variable. Pear trees without NGP lures and in orchards without beehives served as controls.

Response variables	Explanatory variables	Estimate	Std. Error	Z value	Pr (>|z|)
Honeybee abundance	NGP lures	-0.07	0.39	-0.19	0.847
	Beehives	1.68	0.53	3.19	**0.001**
	NGP lures x Beehives	0.99	0.47	2.13	**0.033**
Pear flower visits	NGP lures	2.81	1.18	2.37	**0.018**
	Beehives	3.99	1.63	2.45	**0.014**
	NGP lures x Beehives	-0.58	1.53	-0.38	0.701

Table S5.6 Results of GLMM analysis with negative binomial error distribution for the observations at tree level in monocultural Korla fragrant pear orchards (Expt 2). Response variable were honeybee abundance per tree per 9 days and pear flower visits per 40 minutes in orchards with and without beehives, respectively. The explanatory variables were NGP lures (presence or absence). Orchard was included as a random factor. Pear trees without NGP lures served as control.

Beehives	Response variables	Explanatory variables	Estimate	Std. Error	Z value	Pr (>|z|)
Yes	HB abundance	NGP lures	0.92	0.40	2.27	**0.024**
Yes	Pear flower visits	NGP lures	1.74	0.79	2.19	**0.028**
No	HB abundance	NGP lures	-0.07	0.48	-0.16	0.876
No	Pear flower visits	NGP lures	3.37	1.40	2.42	**0.016**

Table S5.7 Results of LMM analysis with normal error distribution for observations at the tree level in monoculture Korla fragrant pear orchards (Expt 2). The response variable was pear flower visits per orchard and the explanatory variable was honeybee abundance per orchard. Orchard was included as a random factor.

Explanatory variable	Estimate	Std. Error	t value	*P* value
Honeybee abundance	1.60	0.19	8.59	**<0.001**

Table S5.8 Mean and standard error of honeybee abundance per tree per 9 days with or without NGP lures in monoculture Korla fragrant orchards at orchard level with (n=2) and without beehives (n=7) (Expt 3).

Beehives	NGP lures	Honeybee abundance	
		Mean	Standard error
Yes	Yes	8.40	1.51
Yes	No	3.80	0.70
No	Yes	0.34	0.11
No	No	0.31	0.10

Table S5.9 Results of GLMM with negative binomial error distribution for observations at orchard level in monoculture Korla fragrant pear orchards (Expt 3). The response variable was honeybee abundance per tree per 9 days, and the explanatory variables were NGP lures (presence or absence), beehives (presence or absence) and their interaction. Orchard was included as a random variable. Pear orchards without NGP lures and orchards without beehives served as controls.

Explanatory variables	Estimate	Std. Error	Z value	Pr (>|z|)
NGP lures	0.09	0.43	0.21	0.834
Beehives	2.56	0.55	4.69	**<0.001**
NGP lures x Beehives	0.71	0.46	1.54	0.124

Table S5.10 Results of GLMM with negative binomial error distribution for the observations at the orchard level in monoculture Korla fragrant pear orchards (Expt 3). Response variables were the honeybee abundance per tree per 9 days in orchards with or without beehives, respectively. The explanatory variable was NGP (presence or absence of NPG lures). Orchard was included as a random factor. Pear trees without NGP lures served as control.

Beehives	Explanatory variable	Estimate	Std. Error	Z value	Pr (>|z|)
Yes	NPG lures	0.79	0.26	3.00	**0.003**
No	NPG lures	0.09	0.42	0.21	0.835

Table S5.11 Mean and standard error of honeybee abundance per tree per 9 days on pear trees with or without NGP lures in mixed pear-apricot orchards with (n=1) and without beehives (n=3) (Expt 4).

Beehives	NGP lures	Honeybee abundance	
		Mean	Standard error
Yes	Yes	5.78	0.55
Yes	No	2.67	0.55
No	Yes	2.56	0.43
No	No	1.59	0.30

Table S5.12 Results of GLMM analysis with negative binomial error distribution for the observations in mixed pear-apricot orchards (Expt 4). The response variable was honeybee abundance per tree per 9 days and the explanatory variables were NGP (presence or absence of NGP lures) and beehives (presence or absence). Orchard was included as a random variable. Pear trees without NGP lures and orchards without beehives served as controls.

Explanatory variables	Estimate	Std. Error	Z value	Pr (>|z|)
NGP lures	0.48	0.20	2.35	**0.019**
Beehives	0.57	0.43	1.33	0.185

Table S5.13 Results of GLMM analysis with negative binomial error distribution for the observations in mixed pear-apricot orchards (Expt 4). The response variable was honeybee abundance in 9 trees per block per 9 days and the explanatory variables were NGP (presence or absence of NGP lures) and beehives (presence or absence). Orchard was included as a random variable. Pear trees without NGP lures and orchards without beehives served as controls.

Explanatory variables	Estimate	Std. Error	Z value	Pr (>|z|)
NGP lures	0.47	0.17	2.71	**0.007**
Beehives	0.57	0.39	1.47	0.143
NGP* Beehives	0.30	0.28	1.06	0.288

Table S5.14 Results of GLMM analysis with negative binomial error distribution for the observations in mixed pear-apricot orchards (Expt 4). The response variable was honeybee abundance per tree per 9 days in orchards without beehives, and the explanatory variable was NGP (presence or absence of NGP lures). Orchard was included as a random variable. Pear trees without NGP lures served as control.

Explanatory variable	Estimate	Std. Error	Z value	Pr (>|z|)
NGP lures	0.47	0.24	1.97	**0.049**

Chapter 6

General discussion

6. General discussion

The objective of this thesis was to assess the pollination deficit, pollinator communities, and the contribution of pollinators to the pollination of Korla fragrant pear (hereafter "KFP"), and explore possible management strategies to strengthen pollination services. A series of field studies were conducted involving both managed honeybees and wild bees, from the field to landscape level, and from habitat management to pollinator management. Although KFP is mostly grown in specific regions in Xinjiang, China (e.g., Korla and Aksu), these findings may also have relevance for the pollination of the common pear, *Pyrus communis*, which is grown worldwide. Furthermore, these findings are related to those obtained in other crops that are pollinator-dependent but not so attractive to pollinators.

In the current chapter, I will first provide a brief overview of the main results (6.1), then discuss how these results can be connected with existing literature to obtain new insights (6.2-6.6), indicate the limitations of this study (6.7), and conclude with an outlook (6.8) and final remarks (6.9).

6.1 Overview of main findings

In **Chapter 2**, I assessed the pollination deficit in KFP and the contribution of honeybees and wild bees to the fruit set and quality of KFP. I found that there is a large pollination deficit in KFP, and honeybees are the main contributors of KFP pollination, while wild bees contribute little. Second, as wild bees are often important pollinators and their diversity depends on the availability of food and nesting resources in the surrounding landscape, I surveyed the wild bee's diversity in KFP orchards and assessed how this diversity is affected by landscape context **(Chapter 3)**. I identified wild bees collected in pan traps to species level and found that one out of the three most abundant species showed positive responses to semi-natural habitats, but the other two species did not. I also reported the wild bee abundance on ten wild plant species and found that *Medicago sativa* and *Apocynum venetum* supported a higher wild bee abundance than the other wild plant species. Third, in **Chapter 4**, I assessed how honeybees and wild bees in KFP are affected by early-flowering apricot trees in and outside KFP orchards. Here I found that the presence of apricot trees in pear orchards can increase the abundance of honeybees and wild bees, but this effect is local and only lasts as long as apricot trees are flowering. Fourth, having shown that honeybees are important visitors of KFP flowers (**Chapter 2)**, I assessed whether the honeybee abundance and visitation frequency can be further enhanced by using synthetic Nasonov gland pheromone (hereafter "NGP") **(Chapter 5)**. I found that the abundance and visitation rate of honeybees can be increased by using NGP, however, this benefit is only significant when there are beehives in or near the orchards.

6.2 Explaining the pollination deficit in KFP

Cross-pollination is often a yield-limiting factor of crops. I found a 89% pollination deficit in KFP (**Chapter 2**). To figure out the reason for the pollination deficit in KFP, I further surveyed the pollinator community by pan-trapping and visual observation of flower visitation in orchards without beehives **(Chapters 2 and 3)**. The trapping results showed that there are indeed pollinators present in the water traps in KFP orchards, and wild bees are the dominant pollinator groups. However, the visual observation results showed that hardly any wild insects were observed on pear flowers and honeybee visits account for 66% of flower visits of pears **(Chapter 2)**. These results showed the low attractiveness of KFP flowers to wild bees and the difference in foraging preference between honeybees and wild bees in KFP.

All bee species rely on pollen and nectar as their source of sustenance, thus the quality and quantity of nectar and pollen in the flower of target crops could determine the foraging behavior of bees (Vaudo et al., 2015). Wild bees are reluctant to visit pear flowers, but honeybees do visit pear flowers **(Chapter 2)**. This could be explained by the different foraging behaviors between honeybees and wild bees. First, managed honeybee colonies can be trained to accept pear flowers by feeding inside or outside the hive with sugar syrup containing pear scent (Gemeda et al., 2018), or by using honeybee attractant that is based on Synthetic Nasonov gland pheromone **(Chapter 5).** Second, managed honeybees collect pear pollen for their larvae in their (Díaz et al., 2013), and the low nectar attractiveness is partly compensated by the relatively high amount of pollen (i.e., 1.2 mg per flower) and pollen quality (i.e., adequate polypeptide, amino-acid, and sterol concentrations) (McGregor, 1976; Free, 1993; Delaplane and Mayer, 2000). Third, wild bees assess the nectar quality of the flowers offered (Waddington and Gottlieb 1990; Banschbach 1994; Molet et al., 2009), which forms the basis of the decision whether to forage or not. For example. Quinet et al., (2016) reported that insect foraging behavior in pear and apple orchards can be mainly explained by the quality of the floral resources. This suggests that enhancing the contribution of wild bees to KFP pollination and lowering the dependency on honeybees would require improving the floral resource attractiveness of cultivars by breeding.

The low attractiveness of KFP flowers to wild bees aligns with reports of low attractiveness of common pear to wild pollinators in Argentina (Geslin et al., 2017). However, the common pear is not in all circumstances unattractive to wild bees. In a four-year study in England, Fountain et al. (2019) observed a total of 13 solitary bee species on the flowers of the common pear cultivar Conference, including three *Andrena* species (*A. haemorrhoa*, *A. nigroaenea*, and *A. nitida*). Bees of the genus *Andreana* were also abundant in my study, with *A. amagishi* accounting for 57% of the total catch (2044 out of 3594 individuals) **(Chapter 3)**. However, the three *Andrena* species reported by Fountain et al. (2019) were different than in my study **(Chapter 2 and 3)**. I observed a few visits of hoverflies, other Diptera, Vespula, and Coccinellidae on KFP, which were also observed on Conference pear (Fountian et al., 2019), but I never observed bumble bees in KFP. Together, these findings provide insight into the pollinator community composition on pear and indicate that the flower attractiveness to pollinators in the same crop could greatly vary in different locations and different varieties.

6.3 Habitat management strategies for wild bees

6.3.1 Field level

I found that the presence of apricot trees within or adjacent to pear orchards during pear blooming in early April can increase wild bee abundance in KFP orchards **(Chapter 4)**. During pear fruiting from May to August, wild plants such as *Medicago sativa* and *Apocynum venetum* in the margins of orchards can provide flowering resources to wild bees **(Chapter 3)**. Suitable habitats near KFP orchards are important to wild bees because the foraging distance of most wild bees is limited (Steffan-Dewenter et al., 2002; Zurbuchen et al., 2010). Nesting sites are critically important for wild bees to reproduce and overwinter, especially in landscapes which are dominated by intensively managed crops, such as KFP. However, flowering annual wild plants at the field edge are often mown by orchard owners, which may reduce the food availability for wild bees. Fruit trees may provide a more stable habitat for wild bees (Eeraerts et al., 2021; Wood et al., 2021) and provide floral resources to wild bees during bloom, and potentially wood cavities in twigs for nesting. Wild bees that nest in wood cavities (e.g., carpenter bees) account for ~30% of total wild bee species (Kremen et al., 2004), could make use of such nesting sites. Furthermore, undisturbed soil at the field edge may provide nesting sites to ground-nesting bees, which account for the other ~70% of wild bee species (Antoine and Forrest, 2020). These findings offer scope to develop pollinator-friendly strategies using perennial and annual flowering plants close to orchards, which could provide a more diversified and long-term habitat for pollinators than provided by only perennial or annual habitats.

6.3.2 Landscape level

I found that the cover of semi-natural habitats in the surrounding landscape **(Chapter 3),** but not of scattered apricot trees (**Chapter 4**), was positively associated with the total abundance of wild bees. However, I found that only one out of three dominant wild bee species responded positively to semi-natural habitats, whereas the other two species did not **(Chapter 3)**. The reason for the lack of positive response of the other two species is unclear, but could be due to their small body size and inability to utilize the habitats that exceed their maximum foraging distance. Alternatively, this lack of response may be explained by specialized food and nesting requirements. Not all floral and nesting resources can be used by wild bee species because wild bee species vary in diet breath and body size, which is related to movement capacity (Ogilvie et al., 2017). These findings suggest that future landscape studies could benefit from: (i) not only assessing the pollinator abundance and diversity, but also measuring the body size and identifying the pollen on their bodies (Grab et al., 2019; Warzecha et al., 2016); (ii) assessing the functionality of habitats in the surrounding landscape (e.g., the cover of bare grounds can be considered as potential nesting sites for ground-nesting bees) (Fahrig et al., 2011); and (iii) not only assessing relationships between landscape composition and pollinator abundance/diversity, but also considering landscape configuration (Bottero et al., 2023; Steckel et al., 2014).

6.4 Pollinators management strategies for honeybees

The most common pollinator management practice that farmers take to reduce the pollination deficit is to introduce managed bee colonies. I found that introducing managed honeybee hives increased the frequency of flower visits and fruit set of KFP **(Chapter 2)**, and that honeybees are attracted to early flowering apricot trees **(Chapter 4)**. Besides honeybees, bumble bees (Jacquemart et al., 2006; Zisovich et al., 2012) and the mason bee *Osima cornuta* (Maccagnani et al., 2003) are considered efficient pear pollinators that can increase fruit and seed set of pears. For example, bumblebees can deposit more pollen grains per pear flower than honeybees (Jacquemart et al., 2006) and can forage at lower temperatures than honeybees (Lundberg and Ranta 1980; Westerkamp 1991; Vicens and Bosch 2000). Bumblebee pollination promotes fruit and seed set, and results to a lower proportion of misshapen fruits than pollination by honeybees (Wei et al., 2002; Ladurner et al., 2004). Zisovich et al. (2012) found that combined pollination by honeybees and bumblebees increased the seed set in common pear from 1-3 seeds to 4-6 seeds compared to orchards only with honeybees. Thus, honeybees are not the only pollinators to compensate against a shortage of wild pollinators of pears, but other species may also be used (e.g., honeybees, bumble bees, and mason bees). Diversifying managed pollinators may contribute to more robust pollination of pears that is less dependent on a single bee species.

In addition to providing alternative managed bee species rather than honeybees alone, it is important to further improve the pollination efficiency of managed honeybee colonies. I found the abundance and visits of managed honeybees can be further enhanced by the synthetic Nasonov Gland pheromone (hereafter “NGP’) (**Chapter 5**). In pear orchards with an outer guard row of apricot trees, the use of NGP lure in pear trees can significantly increase the honeybee abundance on pear trees up to 50 m from the apricot tree rows **(Chapter 5)**. Thus, the use of NGP can further extend the positive effect of apricot trees from a small distance (i.e., 5 m away from the apricot tree row) **(Chapter 4)** to 50 m **(Chapter 5)**.

The timing of the introduction of beehives and the quality of honeybee colonies may have a large influence on the pollination efficiency of honeybees. First, flower visitation by honeybees depends strongly on the timing of the placement of beehives (Humphry-Baker, 1975; Mayer et al., 1986; Free, 1993). For example, Stern et al. (2004) found that introducing the honeybee colonies sequentially increased honeybee abundance on common pear trees and their mobility along tree rows, and consequently increased fruit set and yield by 50-80%. Second, Geslin et al. (2017) reported that honeybee colonies of high quality (i.e., healthy colonies with abundant and active workers) increased fruit weight of the common pear cultivar "Abate fetel" as compared to colonies with a lower quality. These findings indicate that the integrated management of managed bees and the use of pollinator attractants could improve the pollination efficiency of managed bees and partly mitigate the effects of global pollinator declines.

6.5 Reflection on methodologies, strengths, and limitations

In this thesis, I adopted several methods to sample pollinator communities, including pan traps, visual observation, and sweep net sampling. The pollinator communities arising from these three sampling methods provide a more comprehensive understanding of pollinator composition in Xinjiang KFP orchards and its contribution to KFP pollination. For example, the results of pan trapping and visual observation of flower visits are very different (**Chapter 2**). In pan traps, I collected lots of wild bees, but in visual observation of flower visits, almost no wild bees were observed. Thus, insect sampling should combine different methods, which may largely depend on the target taxa (e.g., flying insects, crawling insects, and ground-dwelling insects) and time and labor constraints (Zou et al., 2012).

My study has some limitations. In the study to assess the contribution of honeybees to KFP pollination (**Chapter 2)**, I selected pear orchards with and without managed honeybee hives according to the presence or absence of beehives in orchards, and did not randomize the honeybee treatment across comparable orchards. In this case, the difference in visitation rate, fruit set, and quality between orchards with and without beehives could not only be due to the presence or absence of managed beehives, but also come from the other potential factors that are associated with the decision of the farmer to place beehives (e.g., orchard size, density of beehives and quality of bee colonies). Also, the timing of the beehive introduction could result in a difference in KFP pollination. Nevertheless, I consider the results from **Chapter 2** convincing because I have conducted replicated the study in two years in a total of 41 orchards, and the statistical analysis was robust. In **Chapter 5**, I avoided this limitation by selecting orchard pairs and randomly assigning the NPG to one orchard. Also, in the mixed apricot-pear orchards (**Chapter 5**), I randomized the NPG treatment between blocks I the orchards. By randomization the potential confounding of the treatment with other factors is eliminated. Thus, I stress the importance of a robust design for field experiments to make sound inferences from these experiments.

6.6 Outlook on future research

6.6.1 Measuring the ecological requirements of pollinators

Numerous studies and the results from **Chapter 3** of this thesis showed that the wild bee community benefits from the cover of semi-natural habitats (Beduschi et al., 2018; Eeraerts et al., 2019). However, these results could be too general to be applied because the habitats needed by specific pollinator communities could be different. There is a need for more studies that incorporate direct measurements of the ecological requirements of pollinators, such as food and nesting sites (Fahrig et al., 2011). For nesting resources, Eeraerts and Isaacs (2023) surveyed three different types of semi-natural habitat (i.e., hollow roads, tree rows, and forest edges), and showed that different semi-natural habitat types provide a set of distinct, complementary nesting resources for wild bees. For flower resources, functional resource maps across seasons and habitats in specific regions can be useful for targeted pollinator conservation (Ammann et al., 2024). If possible, the assessment of flowering resources for bees based on different diet breadth of bees (i.e., polylectic, oligolectic, and threatened species) is also useful (Kuppler et al., 2023). Overall, this kind of information will allow for more targeted conservation programs that incorporate the full ecological needs of these species, allowing for tailored approaches that enhance populations of species providing pollination services in different settings.

6.6.2 Measuring the interaction between management practices and pollinators on pollination

In addition to landscape context, the management practices in orchards can influence pollinator communities and the associated pollination services. Therefore, it is important to consider pest and pollinator management together as both contribute to safeguarding satisfactory yields (Lundin et al., 2021). For example, the semi-natural habitats around KFP orchards **(Chapter 3)**, wild plants in the edges of KFP orchards **(Chapter 3)** and flowering apricot trees **(Chapter 4)** not only support wild bees, but may also support herbivores and natural enemies. In this case, the benefits and side-effects of these habitats on insect communities and their associated ecosystem services need to be re-evaluated. For example, semi-natural habitats not only are vital habitats to pollinators and natural enemies (Bartual et al., 2019), but also can support a high abundance of pests (Laterza et al., 2023). In this case, the crop production improved by wild bees that come from semi-natural habitats could be counteracted by the pests that also come from semi-natural habitats. This needs further study. In addition, Wu et al. (2021) reported that the positive relationship between bee abundance and seed number was counteracted by high soil nitrogen levels. Thus, it is also meaningful to assess the level of nitrogen fertilizer and how this may modulate the pollination services provided by pollinators. This kind of information could provide scientific guidance in recommendations for nitrogen inputs for orchards.

6.7 Concluding remarks

In my thesis, I showed the overriding importance of managed honeybees to KFP pollination KFP is a pollinator-dependent fruit crop which is less attractive to wild pollinators that are prevalent in the area in which KFP is grown. In the light of the global shortage of honeybee colonies (Mashilingi et al., 2022), my results on honeybees suggest that combining managed honeybee colonies with native flowering plants and honeybee attractants can increase the pollination efficiency of honeybees. Regarding the global insect and pollinator decline (Wagner et al., 2021), my results on wild bees confirmed previous studies that the total abundance of wild bees has a positive response to semi-natural habitats in the surrounding landscape, but my results further stress that these responses are species-specific. Also, flowering apricot trees and flowering wild plants in field edges can support wild bee communities during and after KFP blooming. Overall, our results point out pathways toward strengthening pollination services in KFP in intensive fruit production systems in Xinjiang. Such management strategies on honeybees and conservation efforts for wild bee communities may facilitate sustained pollination services and crop production, but this will also require understanding of the farmer’s perspectives on these management strategies.

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Summary

Pollination is essential for the production of many crops, including fruit and vegetables, and therefore plays a key role in supporting global food production and security. Honeybees and wild bees are important crop pollinators, but there is concern about the decline of wild pollinators in many parts of the world. This decline may be particularly relevant for China as it is a major fruit production country. However, there is a lack of scientific evidence on how much honeybees and wild pollinators contribute to fruit production in China, and how pollination services can be augmented using habitat and pollinator management. This lack of information hinders the implementation of management to conserve wild bee communities and strengthen crop pollination services. This thesis focuses on the pollination of Korla fragrant pear (hereafter "KFP"), *Pyrus sinkiangensis*, in Xinjiang, China.

In **Chapter 2**, I conducted a four-year field experiment in 52 KFP orchards to assess the pollination deficit in KFP by comparing the fruit set between the open-pollinated flowers and hand-pollinated flowers. To assess the contribution of managed honeybees to fruit yield and quality of KFP, I also measured the flower visitation rate, fruit set, and fruit quality in orchards with and without managed beehives in 2020 and 2021. The insect pollinator diversity was monitored using colored pan traps and visual observation. Fruit set in KFP orchards was much lower with open pollination (8%) than with hand pollination (74%), and this result was consistent across four years. While 72% of the pollinators in the pan traps were wild bees, almost no wild bees were observed on pear flowers. In contrast, 66% of the flower visits were made by honeybees. Fruit set was 38% higher in orchards that contained beehives, but there was no significant effect of the presence beehives on fruit quality (fruit weight, seed set, and sugar content). These findings indicate that the pollination deficit in KFP can be mitigated by introducing managed honeybee hives. In addition, although wild bees were frequently observed in pan traps, they hardly contributed to KFP pollination.

In **Chapter 3**, I assessed how wild bee abundance and diversity in KFP orchards

were influenced by the land use surrounding these orchards. The wild bee specimens that were collected in pan traps in the 52 KFP orchards of **Chapter 2** were identified at the species level and contained a total of 3594 individuals of 28 wild bee species. *Andrena yamagishi* (57%), *Lasioglossum pseudannulipes* (17%), and *Lasioglossum niveocinctum* (16%) made up 90% of trap catches in KFP orchards. These three most abundant species showed different responses to land use types. The abundance of *A. yamagishi* and *L. pseudannulipes* was positively associated with semi-natural habitat and annual crops, respectively. *L. niveocinctum* only showed a weak response to landscape context. Neither wild bee richness nor diversity was associated with landscape context. These findings highlight that wild bees show species-specific responses to landscape context, even when the species are from the same genus.

In **Chapter 4**, I assessed how early-flowering apricot trees influenced the abundance of bees and pollination success of KFP at the field and landscape level, and how this influence is moderated by apricot flowering time. Scattered apricot trees in KFP orchards increased the abundance of wild bees and honeybees on nearby KFP trees. Apricot tree rows only increased the abundance of wild bees and honeybees on the adjacent KFP trees (5 m), but not on KFP trees at further distances (15, 30, 50, and 100 m). Apricot trees in the surrounding landscape did not significantly influence the bee abundance in KFP orchards. The positive effect of apricot trees on bee abundance was only observed during apricot blooming and did not lead to an increased fruit set of KFP. These findings indicate that flowering apricot trees in KFP orchards can increase bee abundance, but only at a relatively small spatial scale and during the short apricot flowering time.

In **Chapter 5**, I assessed the influence of synthetic Nasonov gland pheromone (hereafter “NGP”) on the abundance and flower visitation rate of honeybees in KFP orchards with or without honeybee hives. In pear orchards with beehives, honeybee abundance and flower visitation were 2.5-fold higher and 5.7-fold higher on trees with NGP than on trees without NGP, respectively. This effect was less pronounced in pear orchards without beehives. NGP also increased honeybee abundance in mixed apricot-pear orchards. These findings indicate that NGP lures attract honeybees to flowering KFP trees and that this effect is greatest in orchards with beehives.

In **Chapter 6,** I summarized and synthesized the main findings from Chapters 2-5, put my findings into a broader context, and identified limitations of my research. I highlighted the important contribution of managed honeybees to the pollination of KFP and the importance of wild bees to biodiversity conservation in the intensive fruit production systems in Xinjiang. Overall, this thesis provides information on how to better capitalize on crop pollination through habitat management (e.g., semi-natural habitats and early flowering resources) and pollinator management (e.g., use of honeybees and synthetic honeybee attractants). For future studies, it is important to explore and understand farmer's perspectives on pollination and pollinator conservation, which can help to implement pollinator-friendly management in agricultural production system.

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About the author

Qian Li was born on June 2, 1992, in Xinjiang, China. She was raised in Xinjiang and completed her bachelor's degree at Shihezi University with a major in Plant Protection. Driven by curiosity about the broader world outside of Xinjiang, she did her MSc program at Huazhong Agricultural University in Wuhan, studying agricultural insect and pest control. During the second year of her MSc program, she was involved in a collaborative project between Huazhong Agricultural University and the Institute of Plant Protection, Chinese Academy of Agricultural Sciences (IPP-CAAS). The experience in IPP-CAAS confirmed her passion and motivated her to seek further opportunities as a PhD candidate abroad.

In March 2017, a joint Ph.D. opportunity at Wageningen University & Research (WUR) and CAAS attracted her attention, and she applied for this position. Luckily, the application was successful and she started her PhD program in September 2017 with financial support from the China Scholarship Council and CAAS. Under the supervision of Dr. Wopke van der Werf, Dr. Felix Bianchi at WUR, and Dr. Yanhui Lu at IPP-CAAS, she worked on the project "Strengthening pollination service in Korla fragrant pear in China". The results of this project are presented in this book.

List of Publications

Li, Q., Sun, M.X., Liu, Y.T., Liu, B., van der Werf, W., Bianchi, F.J.J.A., Lu, Y.H. 2023. Synthetic Nasonov gland pheromone enhances abundance and visitation of honeybee, *Apis mellifera*, in Korla fragrant pear*, Pyrus sinkiangensis*. Agricultural and Forest Entomology, 25, 365-374.

Li, Q., Sun, M.X., Liu, Y.T., Liu, B., Bianchi, F.J.J.A., van der Werf, W., Lu, Y.H. 2022. High pollination deficit and strong dependence on honeybees in pollination of Korla fragrant pear, *Pyrus sinkiangensis*. Plants, 11,1734.

Li, Q., Liu, B., Bianchi, F.J.J.A., van der Werf, W., Lu, Y.H. Apricot trees affect the distribution of bees in Korla fragrant pear (*Pyrus sinkiangensis*) at the orchard level, but not at the landscape level. Submitted

Li, Q., Liu, B., Bianchi, F.J.J.A., van der Werf, W., Lu, Y.H. Species-specific responses of wild bees in *Pyrus sinkiangensis* pear orchards to landscape context. Submitted.

Li, H.Q*., **Li, Q*.,** Liu, B., Yang, L., Wang, D.M., Zhang, J.P., Liu, J., Lu, Y.H., 2021. No influence on population dynamics of spider mites in cotton fields of intercropping with walnut, a poor-quality host. Crop Protection*,* 148, 105733. (*shared first authorship)

Li, H.Q*, **Li, Q*.,** Wang, D.M., Liu J., Zhang, J.P., Lu, Y.H., 2020. Effect of a cotton intercrop on spider mite populations in jujube trees. Journal of Asia-Pacific Entomology, 23, 167-171. (* shared first authorship)

Liu, J.P., Liu, Y., **Li, Q.,** Lu, Y.H. 2023. Heat shock protein 70 and Cathepsin B genes are involved in the thermal tolerance of *Aphis gossypii*. Pest Management Science, 79, 2075-2086.

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Yang, L., Xu, L., Liu, B., Zhang, Q., Pan, Y.F., **Li, Q.,** Li, H.Q., Lu, Y.H., 2019. Non-crop habitats promote the abundance of predatory ladybeetles in maize fields in the agricultural landscape of northern China. Agriculture, Ecosystems & Environment, 277, 44-52.

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review/project proposal (10.5 ECTS)

- Potential of habitat diversification for strengthening biocontrol and pollination services in orchard fruit production in China
- Diversification for strengthening ecosystem services in orchards in Xinjiang, China

Post-graduate courses (8.5 ECTS)

- What's bugging you how bugs support sustainable crop production and biodiversity; PE&RC (2023)
- Protein transition; PE&RC (2023)
- Design of experiments; WIAS/PE&RC (2023)
- Mixed linear models; PE&RC (2023)
- Meta-analysis; PE&RC (2023)

Invited review of journal manuscripts (2 ECTS)

- Basic and Applied Ecology: A global assessment of the species composition and effectiveness of watermelon pollinators (2023)
- Journal of Applied Entomology: Wild vegetation and farming with alternative pollinators approach support pollinator diversity in farmland (2023)

Deficiency, refresh, brush-up courses (12 ECTS)

- Advanced statistics; PE&RC (2018)
- Ecological modelling and data analysis in R; PE&RC (2019)

Competence, skills and career-oriented activities (3.4)

- Effective academic development including academic writing and presenting in English; PE&RC (2017)
- Reviewing a scientific paper; WUR (2018)
- Project and time management; WUR (2019)
- Ethics in plant and environmental sciences; WUR (2019)

Scientific integrity/ethics in science activities (0.6 ECTS)

- Scientific integrity; PE&RC (2019)
-

PE&RC Annual meetings, seminars and PE&RC weekend/retreat (1.5 ECTS)

- PE&RC First year weekend (2019)
- PE&RC Last year weekend (2023)

Discussion groups/local seminars or scientific meetings (6.4 ECTS)

- 1st International congress on biological control; IPP-CAAS/CABI, Beijing, China (2018)
- Reading club for book from experimental network to meta- analysis; Wageningen, the Netherlands (2020)
- AAB Meeting, crop production with reduced pesticide and fertilizer inputs without compromising yield and quality; online (2021)
- Local scientific meeting with Chinese scientists; online (2021-2022)
- Pollination discussion group; Wageningen, the Netherlands (2023)
- Insects and society; Wageningen, the Netherlands (2023)

International symposia, workshops and conferences (8.5 ECTS)

- Netherlands ecology meeting; poster presentation; the Netherlands (2019)
- 2nd International congress of biological control; oral presentation; Davos, Switzerland (2021)
- AAB meeting, shaping the future for pollinators innovations in farmed landscapes; poster presentation; Slough, UK (2022)
- XII European congress of entomology; oral presentation; Crete, Greece (2023)

BSc/MSc thesis supervision (3 ECTS)

- Pollination services in relation to the surrounding landscape and insect communities in jujube in Aksu, Xinjiang

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