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'Farming with alternative pollinators' approach supports diverse and abundant pollinator community in melon fields in a semi-arid landscape

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Abstract

The presence of pollinating insects in crop fields is an essential factor for agricultural production and pollinator conservation. Agricultural intensification has been identified as a driver of pollinator decline over the last decades and challenges the efficiency of pollination. Several approaches are used to support pollinators and their ecosystem services, notably reward-based wildflower strips. 'Farming with Alternative Pollinators' (FAP) aims to attract and sustain pollinators using marketable habitat enhancement plants (MHEP) in the field borders instead of wildflowers. These MHEP are selected in conjunction with farmers. We tested here whether the FAP approach increases diversity and abundance of flower visitors in melon fields in a semi-arid landscape in Morocco. Moreover, we examined whether MHEP increase flower-visitor abundance in melon flowers. We recorded a total of 1330 insect specimens including 573 specimens of wild bees. *Lasioglossum malachurum* was the major flower visitor in melon and several MHEP. As flower-visitor abundance and diversity in FAP fields were higher than in control fields, we conclude that FAP can be a valuable approach for pollinator protection in agro-ecosystems; 16.5% of wild bees and wasps showed spillover from the field borders to the melon fields.

Introduction

Many wild and domesticated plants depend on the pollination services provided by pollinators for their sexual reproduction (Biesmeijer *et al.*, 2006; Ollerton *et al.*, 2011; Garibaldi *et al.*, 2014). Eighty-seven percent of flowering plant species, including many important crops, rely on animal pollinators (Klein *et al.*, 2007; Ollerton *et al.*, 2011). Wild and managed bees are considered to be the most important pollinators among the biotic vectors (Garibaldi *et al.*, 2014; Zattara and Aizen, 2021).

Although wild bees often provide superior or complementary services compared to managed honeybees (Garibaldi *et al.*, 2014), they are often neglected by farmers and suffer from competition for nectar and pollen against dense populations of honeybees (*Apis mellifera*) (Hudewenz and Klein, 2013; Ropars *et al.*, 2020).

Unfortunately, wild bees are declining worldwide (Zattara and Aizen, 2020). This could have severe impacts on the regeneration of wild plant diversity, ecosystem stability, crop production, food security and human welfare (Potts *et al.*, 2010, 2016; Christmann, 2019). Agricultural intensification is described as a major driver of wild bee decline. However, some mitigation strategies have been recently implemented in agro-ecosystems in Western countries (Defra, 2015, 2016; Goulson and Hughes, 2015; Ministry of Agriculture, 2018).

Sown wildflower strips (WFS) have been the most common measure in agri-environmental schemes in several European countries to enhance pollinator diversity and abundance (Ganser *et al.*, 2021). WFS are used to provide a diversity of floral resources across the entire flowering season to mitigate some of the negative consequences of monocultures on pollinators (Ganser *et al.*, 2018). However, they do not address the lack of nesting resources (Christmann, 2022) and they also do not oblige farmers to use less pesticides. Hence, several important factors causing pollinator decline, such as lack of nesting and (over-)use of chemicals (Goulson and Hughes, 2015), are not addressed. Farmers receive payment for a seeding service, but the incentive does not change their knowledge, behavior or field management (Christmann *et al.*, 2021), although behavior change is what is most needed (Christmann *et al.*, 2021; Marselle *et al.*, 2021). While WFS host a high diversity of wild bees and can also promote pollination services in nearby crops, pollinator diversity is often restricted to the crop edges near the WFS (Zamorano *et al.*, 2020; Ganser *et al.*, 2021). They contribute to pollinator conservation, but whether they also increase agricultural production is unclear, as they cause opportunity costs (a part of the agricultural land cannot be used for agricultural production; Christmann *et al.*, 2021). The impacts of WFS are limited in various aspects (Kleijn *et al.*, 2019). Even with financial incentives, farmers dislike them (Kleijn *et al.*, 2019) and reject them in countries without incentives (Christmann *et al.*, 2017). As low- and middle-income countries cannot afford these kinds of agricultural subsidies, farmers in these countries are reluctant to seed WFS to protect pollinators (Christmann *et al.*, 2017, 2021).

Farming with Alternative Pollinators (FAP) is an alternative pollinator-protection approach developed to protect pollinators also in low- and middle-income countries. Instead of receiving external compensation for a seeding service, FAP uses farmer-friendly marketable habitat enhancement plants (MHEP), nesting and water support (Christmann and Aw-Hassan, 2012; Christmann *et al.*, 2017, 2021). MHEP contribute to farmers' incomes and better production in quantity and for some crops, also in quality (e.g., cucumber and eggplant) by attracting higher diversity and abundance of flower visitors and natural enemies (Christmann and Aw-Hassan, 2012; Christmann *et al.*, 2017; Christmann, 2020; Christmann *et al.*, 2021). One main difference between the WFS and the FAP approach is that WFS focuses on plants and plant-pollinator-networks and (usually) AES pay for a simple seeding service, whereas FAP addresses the reality of the Anthropocene and focuses on changing human behavior through a method-inherent and performance-related incentive: higher income induced by beneficial insects attracted through habitat enhancement (Christmann *et al.*, 2021). Therefore, compared to WFS, FAP research measures the impact of habitat enhancement on diversity and abundance of flower visitors, natural enemies and pests of crops as well as net income per service (considering yield quantity and quality) and communicates the results to farmers (Christmann *et al.*, 2017, 2021). However, in contrast to WFS, FAP requires capacity building for farmers concerning, e.g., insect diversity, habitat requirement and the value of pollinators (Christmann *et al.*, 2021).

In comparison to wild plants, MHEP also have multiple advantages in sustaining natural pest enemies, particularly in irrigated systems in drylands, e.g., crops provide more resources for insects than natural habitats do, and the insect density is usually higher (Tscharntke *et al.*, 2016). Within FAP, MHEP are specifically selected based on their attractiveness to pollinators, flowering times and farmers' preferences (Christmann *et al.*, 2017). In general, the FAP approach uses four to eight different MHEP (e.g., spices, crops, oil seeds, vegetables and medicinal plants) as a multi-species plant assemblage characterized by diverse flower traits (flower colors, shapes, corolla depth, …) and different flowering phenology. The blooming times of MHEP should overlap. Some MHEP flower before, during and after the blooming of the main crop and provide more floral nectar and pollen rewards over a prolonged period than a monocultural field (Christmann *et al.*, 2021). In small fields, MHEP are planted at the border of FAP fields (25% of the field surface) to host diversity and abundance of flower visitors and natural enemies (Christmann *et al.*, 2017, 2021; Sentil *et al.*, 2021, 2022a, 2022b; Abdouni *et al.*, 2022).

In Morocco, pollinator-dependent agricultural production has increased for decades (Potts *et al.*, 2016) and has a high economic value estimated at 1 850 000 000 € in 2019 (≃ 1.74% of Moroccan PIB, 2019); (Anougmar, 2021). For field trials, i.e. testing the efficiency of FAP in hosting diverse and abundant pollinators, we selected melon as a main crop for the following reasons. In the melon crop, its pollinator dependence is described as 'essential' (up to 90% loss of productivity without pollinators; Klein *et al.*, 2007; Rodrigo Gómez *et al.*, 2016). In Morocco, melon is a very important crop providing a high-income to farmers, with a planted area of 13.594 ha. In 2019, Morocco produced 39,0571 tonnes (FAO, 2019) and exported 50,505 tonnes (Selina, 2022). At the peak of the growing season, melon, in contrast to, e.g., apricot or cherry (20 MAD = 1.87 USD even at the peak of the season), is affordable (7 MAD or 0.65 USD per kg) even for the low-income strata in Morocco.

Wild bees are known to be the most important pollinators of cucurbits (Klein *et al.*, 2007; Rodrigo Gómez *et al.*, 2016). Therefore, our research concerning the melon trials focuses on wild bees. Melon presents hermaphrodite flowers with a large diameter corolla and wide nectar chambers, and male flowers, with a greater height and nectar volume. These characteristics could explain the higher visitation to melon flowers (Kiill *et al.*, 2016). Therefore, melon requires pollinators for successful reproduction, and the pollination services are considered essential (dependence > 90%) for its production (Klein *et al.*, 2007).

This work has three specific objectives: (1) identify the key flower visitors of melon in semi-arid landscapes in Morocco; (2) assess and compare the species richness and abundance of floral visitors in FAP melon fields and monocultural control melon fields; (3) investigate whether flower-visitors attracted by MHEP also visit the main crop. Our hypothesis is that availability of floral resources surrounding melon should enhance abundance and diversity of flower-visiting insects in FAP fields in comparison to monocultural control fields.

Materials and methods

Study sites, experimental design and crop characteristics

This experiment was carried out in Settat region, Ouled Sghir province (Morocco) (Fig. 1). Settat region is located in the north of the country (33°00′ N – 7°36′ W) within an area of 7000 km^2 and a maximum elevation of 600 m (Fig. 1). Settat has a Mediterranean climate with cold winters, hot summers and low rainfall (300–400 mm per year (Lachgar *et al.*, 2021). This area has large monocultures of cereal fields (90% of the arable land), and melon fields account for a very small percentage of the territory. Floral resources in field edges are scarce. Compared to other Moroccan regions, Settat region shows a relatively low species diversity of wild bees (i.e., 135 species) (Lhomme *et al.*, 2020).

In 2018 and 2019, we conducted on-farm trials with smallholders including five FAP fields and three control fields. There were no honeybee hives for 2 km around the fields. Most wild pollinators forage in a small area of approximately 50–2000 m radius from the nest (Kohler *et al.*, 2008; Garibaldi *et al.*, 2014). FAP melon fields were almost 1 km apart from each other, while control fields were usually closer to each other, mostly surrounded by crops not depending on pollinators, such as maize, wheat or potato.

All farmers used the same amount of fertilizer and drip irrigation. All fields encompassed 30 m × 10 m. In FAP fields, the main crop (melon) occupied a 75% zone of the field area and the MHEP were planted on the margins of the main crop (i.e., the

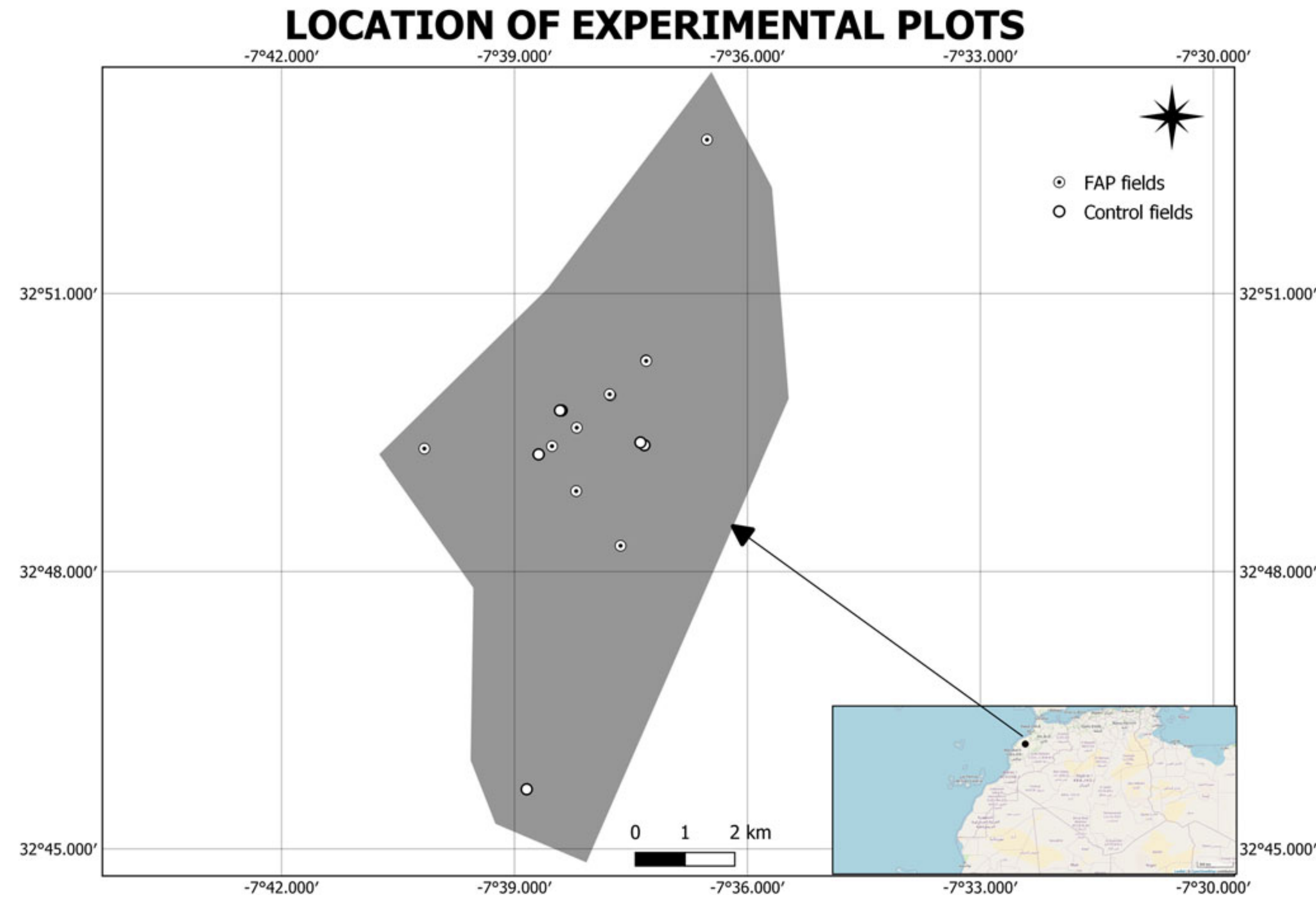

Fig. 1. Location of experimental plots close to Settat, farms with FAP fields are marked in topo pop capital and farms with control fields in dot white, some farms were partly used in both years, other farms just once.

25% marginal zone); in control fields this 25% marginal zone was also planted with the main crop (Fig. 1 Supplementary Material). The 75% zone consisted of the same randomized plot of 16 parcels in the middle in FAP and control fields (Fig. 1 and Supplementary Material). In 2018, four hybrid cultivars of melon were seeded in the 75% zones of each field (Hoda, Miami, Bijour, Starplus). In 2019, as some cultivars where no longer available, the hybrid cultivars Chorouk, Miami, Wifak and Starplus were employed. In 2018, the 25% marginal zone of control was planted with the cultivar Jamil, in 2019 with the cultivar Lexus. The selection of MHEP was based on their attractiveness to pollinators, farmers' suggestions and the flowering periods, which should partly overlap with the blooming period of melon, starting either earlier or lasting longer to sustain pollinators over a longer period (Christmann *et al.*, 2017). As MHEP, we used separately coriander (*Coriandrum sativum*), sunflower (*Helianthus annuus*), anise (*Pimpinella anisum*), eggplant (*Solanum melongena*), dill (*Anethum graveolens*), zucchini (*Cucurbita pepo*), cumin (*Cuminum cyminum*) and basil (*Ocimum basilicum*).

Flower biology

Melon (*Cucumis melo)* is grown as a main crop; it is an andromonoecious plant, bears male and hermaphrodite perfect flowers on the same plant. The flowers are yellow. Melon depends on biotic pollination and bees play an important role in successful reproduction (Roubik, 1995; Kiatoko *et al.*, 2021). In Morocco, flowering starts in June and lasts up to September and the harvesting starts in mid-June to mid-August. Zucchini (*C. pepo*) belongs to the Cucurbitaceae family and like melon, the plants are monoecious and produce male flowers three to four days before producing female flowers. Therefore, *C. pepo* requires insects to transfer pollen (Abu-Hammour, 2008). The flowers are yellow and bloom during summer (May to end of July), producing fruits from mid-June until the beginning of July. Sunflower (*H. annuus*) is a cross-pollinating plant, the head is composed of hundreds of brown florets that can set seeds when they are pollinated. The outer ray female florets are yellow, orange and are infertile (Zea and Subsp, 1998). This plant stays in bloom for 45 days, from mid-May to July and the seeds are harvested in mid-July. Coriander (*C. sativum*), anise (*P. anisum*), dill (*A. graveolens*) *and* cumin (*C. cyminum*) belong to the Apiaceae family. Their inflorescence consists of compound umbels that are characteristic of the family and the flowers are small and either white, pink or of greenish color. The flowering features promote a high degree of outcrossing and for each species, proterandry is characteristic (Nemeth and Szekely, 2000). The blooming of all these species of Apiaceae lasts 90 days (from May to July) and seeds are harvested in August. Basil (*O. basilicum*) is an aromatic plant of decorative leaves and flowers. Like the majority of Lamiaceae species, the flowers are bisexual, typically zygomorphic and bilabiate. They are of different colors, white to pink-violet and seem to be a good source of nectar (Nurzyńska-Wierdak, 2012; Latif *et al.*, 2017). Basil flowering starts in May and lasts up to mid-June and

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Table 1. Blooming times of the main crop (melon) and of marketable habitat enhancement plants during trials in 2018 and 2019

the seeds are ready to be harvested in mid-July. Eggplant (*S. melongena*) is a self-pollinated plant from the Solanaceae family. The flowers are solitary, star-shaped and usually violet in color. The cone-like formation of eggplant anthers favors self-pollination. However, as the stigma is projected beyond the anthers, there is a considerable chance for cross-pollination and it indicates adaptation to the buzz-pollination mechanism (Kowalska, 2008; Sękara and Bieniasz, 2012). Eggplant flowers from mid-May to August; the fruits are harvested from mid-June to August.

Flower-visitor sampling

In 2018, the melon main crop flowered from 1 June to 30 August and in 2019, from 24 May to 15 August. In 2018, we sampled insects in the time periods 20–21 June, 10–11 July and 7–8 August and in 2019, we sampled insects in the time periods 13–14 May, 24–25 May and 13–19 July. In 2019, this was done also before and after flowering of the main crop (Table 1). We used sweep nets and pan traps. Each sampling lasted two days (four fields per day) in total and sampling order was randomized. Sampling was performed between 10:00 and 16:00 under suitable weather conditions for bee foraging (minimum temperature of 19°C, clear sky and light or no wind).

We used net sweeping along transects and pan traps for sampling. Sampling in melon consisted of two transects of 28 m long × 2 m wide (we divided the 75% zone of the field area into two parts (T1 and T2), we did transect in T1 and transect in T2, 5 min transect^{-1}, 10 min plot^{-1} in total). The insects from sweep nets were captured by an insect vacuum. All insects were collected except for honeybees (*A. mellifera*), the buff-tailed bumble bee (*Bombus terrestris*) and the carpenter bee *Xylocopa pubescens*, which were counted and identified visually on site. The collected insects were first immobilized with ethyl acetate, then put inside killing jars filled with cyanide, and pinned and labeled in the laboratory. Concerning MHEP, we assessed the diversity of flower visitors by transects of 76 m long × 1 m wide (1 or 2 min transect^{-1}, 8 min plot^{-1} in total in 2018 as well as 9 min plot^{-1} in total in 2019). The sampling duration in the 25% zone varied depending on the size of the seeding area of each MHEP, 2 min in 14 m^2 of sunflower, 1 min in 5 m^2 of anise, 1 min in 5 m^2 of eggplant, 2 min in 14 m^2 of coriander, 1 min in 5 m^2 of dill, 1 min in 5 m^2 of zucchini, 1 min in 5 m^2 of cumin and 1 min in 4 m^2 of basil. In the control fields the visitors of the 25% zones were collected alongside a transect of 76 m long × 1 m wide for 10 min (Fig. 1 Supplementary Material).

We sampled insects also with pan traps to get more insight on flower visitors and insects available in the region. In pan traps, we collected, e.g., 671 insects. Pan trapping was performed during each sampling. Three sets of three pan traps (volume of 500 ml, diameter of 145 mm, depth of 45 mm) colored in yellow, white and blue UV-reflecting paint (Rocol Top, Belgium) were used following standard protocols proposed by (Westphal *et al.*, 2008). Two sets were placed inside the melon fields. The pan traps were collected after 24 h at the end of each sampling session. However, we did not take the species sampled in pan traps into consideration for our analysis, as we cannot clarify whether they foraged on the main crop, MHEP or just in the region. Detailed analyses and results on insects sampled in pan traps are presented in Figure 2 Supplementary Material.

Bee specimens were identified to family, tribe or genus level by the research team using the key of Michez *et al.* (2019). Afterwards, all specimens were sent to specialists for identification to species level:

Sphecodes and *Nomada* were sent to Jakub Straka (University of Prague, Czechia), *Osmiini* to Andreas Müller (Institute of Agricultural Sciences, Zürich, Switzerland), *Eucera* to Achik Dorchin (University of Mons, Belgium), *Hylaeus* to Holger Dathe (Humboldt Universität, Berlin, Germany), *Andrena* to Thomas Wood (University of Mons, Belgium), *Anthophora* to Pierre Rasmont (University of Mons, Belgium), Halictini (*Halictus*, *Lasioglossum*) and *Nomioides* to Alain Pauly (Royal Belgian Institute of Natural Sciences, Brussels, Belgium). The remaining insect visitors were identified to family or genus level.

Statistical analysis

All analyses and graphs were performed with the metafor package (Viechtbauer, 2010) through R version 3.4.4.

Flower visitors of the main crop (Melon)

To illustrate the relative abundance of melon visitors, we used rank abundance curves package BiodiversityR; (Kindt, 2013). Therefore, to represent the average abundance of the three major groups of melon visitors collected from transects, (honeybees, wasps and wild bees) from the main crop (melon) of all the fields (75% zone of FAP fields and 100% zone of control fields), we used the packages dplyr (Wickham *et al.*, 2018) and ggplots2 (Wickham *et al.*, 2018). In order to characterize and compare the abundance of the three functional groups (honeybees, wasps and wild bees) of melon visitors, we assessed the variable abundance (the total number of each group of melon visitors). The abundance of the three functional groups was compared using one way ANOVA when test assumptions of normality and homogeneity of variance were met. The analysis was performed using the BiodiversityR package. When the variables were not normally distributed or there were unequal variances on the scores across groups, a non-parametric Kruskal–Wallis test was used. The equality of variances for abundance and species richness was assessed using Levene's test, Car package (Fox and Weisberg, 2019) and the normality was tested numerically using Shapiro test, Mvnormtest package (Jarek, 2012).

We used Kruskal–Wallis test because the variances were not homogeneous (Levene's Test: F value = 4.540, P-value = 0.018, Df = 2 & 33), and the data were not normally distributed (Shapiro–Wilk's normality test: W = 0.4901, P-value < 0.0001). Post hoc Mann–Whitney U tests were performed to measure significant differences between groups of visitors.

Impact of FAP approach on flower visitor community at field level

ANOVA test was performed on the abundance data collected in the entire melon area of each field (FAP and control). In order to characterize and compare the flower visitor community between FAP and control fields, we assessed two variables, species richness (the number of species and number of taxa determined at the lowest taxonomic level, this metric being described later as species diversity) and abundance (the total number of visitors). The two variables were compared between FAP and control fields using one way ANOVA when test assumptions of normality and homogeneity of variance were met. For this analysis we used the BiodiversityR package. When the variables were not normally distributed or there were unequal variances, a non-parametric Kruskal–Wallis test was used. The equality of variances for abundance and species richness was assessed using Levene's test, Car package; (Fox and Weisberg, 2019) and the normality was tested numerically using a Shapiro test, Mvnormtest package (Jarek, 2012).

Kruskal–Wallis test was also performed on the honeybee abundance data because although the variances were homogeneous (Levene's Test: F value = 2.744, P-value = 0.126, Df = 1 & 11), the data departed far from normality (Shapiro–Wilk's normality test: W = 0.645, P-value = 0.001).

Kruskal–Wallis test was performed on the wasp abundance data because the variances were not homogeneous (Levene's Test: F value = 7.474, P-value = 0.019, Df = 1 & 11) and the data departed from normality (Shapiro–Wilk's normality test: W = 0.818, P-value = 0.011).

Kruskal–Wallis test was performed on the wild bee abundance data because the variances were not homogeneous (Levene's Test: F value = 7.731, P-value = 0.018, Df = 1 & 11) and the data departed from normality (Shapiro–Wilk's normality test: W = 0.844, P-value = 0.020).

Kruskal–Wallis test was performed on the total abundance data because both variances were not homogeneous (Levene's test: F-value = 7.590, P-value = 0.010, Df = 1 & 11) and data seemed to violate the normality expectations (Shapiro–Wilk's normality test: W = 0.790, P-value = 0.006).

ANOVA test was performed on the total species data because the variances were homogeneous (Levene's test: F-value = 2.790, P-value = 0.120, Df = 1 & 6) and the data had a normal distribution (Shapiro–Wilk's normality test: W = 0.890, P-value = 0.100).

Impact of FAP approach on the abundance of flower visitors in the main crop

To characterize and compare the melon visitor community between FAP and control fields, we assessed two variables, namely species richness (the number of melon-visiting species) and abundance (the total number of melon visitors). The two variables were compared between the 75% area of FAP (melon area) and control fields using one way ANOVA when test assumptions of normality and homogeneity of variance were met. For this analysis, we used the BiodiversityR package. When the variables were not normally distributed or there were unequal variances, a non-parametric Kruskal–Wallis test was used. The equality of variances for abundance and species richness was assessed using Levene's test, Car package (Fox and Weisberg, 2019) and the normality was tested numerically using a Shapiro test, Mvnormtest package (Jarek, 2012).

Kruskal–Wallis test was performed on the wild bee abundance data because although the variances were homogeneous (Levene's Test: F value = 0.917, P-value = 0.360, Df = 1 & 10), the data departed far from normality (Shapiro–Wilk's normality test: W = 0.590, P-value = 8.929×10^{-05}).

Kruskal–Wallis test was performed on the honeybee abundance data because although the variances were homogeneous (Levene's Test: F value = 3.006, P-value = 0.123, Df = 1 & 10), the data departed far from normality (Shapiro–Wilk's normality test: W = 0.674, P-value = 0.001).

Kruskal–Wallis test was performed on the wasp abundance data because although the variances were homogeneous (Levene's Test: F value = 0.484, P-value = 0.503, Df = 1 & 10), the data departed far from normality (Shapiro–Wilk's normality test: W = 0.835, P-value = 0.024).

To compare the impact of FAP approaches on melon visitors' abundance and species richness (75% zone of the fields), we analyzed the data using the Kruskal–Wallis test, a test performed on abundance data where the variances were homogeneous (Levene's test: F-value = 0.594, P-value = 0.450, Df = 1 & 10) and the data departed far from normality (Shapiro–Wilk's normality test: W = 0.660, P-value = 0.001). ANOVA test was performed on the species data because the variances were homogeneous (Levene's test: F-value = 0.016, P-value = 0.890, Df = 1 & 10) with a normal distribution (Shapiro–Wilk's normality test: W = 0.954, P-value = 0.680). In this analysis, we only used the data collected in the 75% zone of FAP and control fields.

Flower visitors in common between melon and MHEP in FAP fields

We pooled the visitation data of each crop (melon in FAP fields and MHEP) collected in the different fields within a weighted matrix, in which the flower visitors are listed in columns and melon and the seven MHEP are listed in rows. To assess the similarity of the flower-visitor communities between melon in FAP fields and each MHEP, we proceeded in two different ways: First, we identified the common pollinators between melon and MHEP with a table using the bipartite package (Dormann *et al.*, 2008), then we exploited the rank abundance curve using the package BiodiversityR (Kindt, 2013) in order to show the dominant species in each MHEP.

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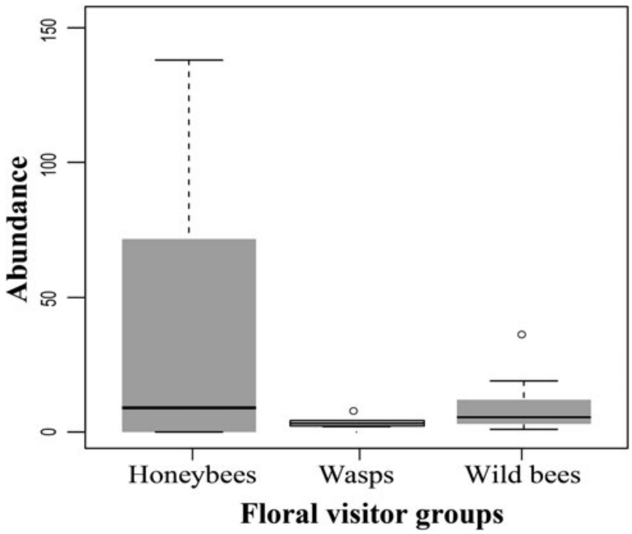

Fig. 2. Boxplot showing the abundance of major groups of melon floral visitors (honeybees, wasps and wild bees) from all fields (75% zone of FAP fields & 100% zone of control fields). Significant differences are shown by the statistical test (Kruskal–Wallis).

Results

During our two-years trials, we collected a total of 1330 flower-visitor specimens including 573 specimens of wild bees (43.1%) from 19 bee genera (*Amegilla, Andrena, Camptopoeum, Ceratina, Colletes, Eucera, Halictus, Hylaeus, Lasioglossum, Megachile, Nomada, Nomiapis, Osmia, Schmiedeknechtia, Seladonia, Sphecodes, Vestitohalictus, Bombus* and *Xylocopa*), 560 specimens of honeybees (42.1%) belonging to one species *A. mellifera*, 197 specimens of wasps (14.8%) from ten groups [Chrysididae, Crabronidae, *Cerceris* (Crabronidae), *Eumenes* (Vespidae), *Euodynerus* (Eumenidae), *Oxybelus* (Crabronidae), *Polistes* (Vespidae), Pompilidae, *Scolia* (Scoliidae) and *Tiphia* (Tiphiidae)].

Wild bees were the dominant group (43.1%) and were mostly attracted by the following plants: coriander (32.7%), anise (22.8%), melon (22.2%), sunflower (8.6%), zucchini (7.9%), dill (4.9%), basil (1%) and cumin (0.1%) (Table 1 Supplementary Material).

Flower visitors of the main crop (melon)

The main visitors of melon belong to various insect groups (Fig. 2). Mean abundance of the three different groups of melon visitors were significantly different (Kruskal–Wallis χ^2 = 7.560, df = 2, *P*-value = 0.023). Honeybees were the most abundant, followed by wild bees and wasps (Mann–Whitney *U* test: *P*-value (wild bees and wasps) = 0.003, *P*-value (wild bees & honeybees) = 1.00, *P*-value (wasps & honeybees) = 0.668 (Fig. 3). In the wild bee group, the four most abundant species, by order of importance, were *L. malachurum, L. subbirum, L. interruptum* and *Vestitohalicus pollinosus* (Fig. 3).

Impact of FAP approach on richness and abundance of flower visitors

Wild bees were more abundant in FAP fields than in control fields (Kruskal–Wallis χ^2 = 8.571, df = 1, *P*-value = 0.003**). Wasps were also more abundance in FAP compared to control fields (Kruskal–Wallis χ^2 = 7.865, df = 1, *P*-value = 0.005**). No significant difference in honeybee abundance (Kruskal–Wallis χ^2 = 1.279, df = 1, *P*-value = 0.258) was found between FAP and control fields (Fig. 4).

We noticed significantly higher abundance of wildflower visitors in FAP compared to control fields (Kruskal–Wallis χ^2 = 8.590, df = 1, *P*-value = 0.003**) and with a higher species richness (ANOVA test: *F*-value = 13.290, df = 1&11, *P*-value = 0.003**) (Fig. 5).

Impact of FAP approach on the abundance and species richness of flower visitors in the main crop (75% field zone):

When comparing FAP and control melon areas in the central 75% areas, there was no difference between FAP and control fields concerning the abundance of wildflower visitors (Kruskal–Wallis χ^2 = 3.549, df = 1, *P*-value = 0.059), honeybee abundance (Kruskal–Wallis χ^2 = 31.198, df = 1, *P*-value = 0.273) or wasp abundance (Kruskal–Wallis χ^2 = 0, df = 1, *P*-value = 1) (Fig. 3 and Supplementary Material).

Moreover, there was no significant difference between FAP and control fields in melon flower visitor abundance (Kruskal–Wallis χ^2 = 1.920, df = 1, *P*-value = 0.166) and species richness of melon visitors (ANOVA test: *F*-value = 1.101, df = 1&10, *P*-value = 0.310) (Fig. 4 and Supplementary Material).

Common flower visitors between MHEP and main crop

We sampled 24 flower visitor species on seven plant species. *Apis mellifera* was the most common visitor species of melon (540 specimens) followed by species of the diverse genus *Lasioglossum* (Halictidae family) and particularly the species *L. machalarum* (39 specimens). *L. machalarum* visited all plants species, except dill. The most visited plant species was anise with 11 flower visitor species, followed by coriander and melon [Fig. 6 and Table 2 Supplementary Material (different color)].

L. malachurum is the most abundant flower visitor species in FAP fields with 31 specimens in zucchini, 17 specimens in sunflower and four specimens in basil. Coriander was mainly visited by *Lasioglossum algericolellum* (49 specimens), whereas anise was mostly visited by *Camptopoeum sp.* (38 specimens). *Nomioides facilis* was the main visitor of dill with 18 specimens collected [Table 2 Supplementary Material (different color)]. Sunflower, zucchini and basil were hosting the main melon-visiting species (Fig. 5 Supplementary Material), namely *L. machalarum*.

Discussion

Pollinator studies are often conducted in high-income countries and to a much lesser extent in low- and middle-income countries (IPBES, 2016). Studies on the effect of field margin floral enhancements on pollinators have primarily focused on assessing diversity and abundance of pollinators only within the field margins, and fewer efforts have been invested to understand how these management tools affect diversity and abundance of flower visitors and natural enemies in fields and even less on impacts on crop pollination (Kleijn *et al.*, 2019; Albrecht *et al.*, 2020; Christmann *et al.*, 2021). Research on farmers, the decision makers on land management, has been rarely part of such research (Uyttenbroeck *et al.*, 2016; Christmann *et al.*, 2017, 2021; Kleijn *et al.*, 2019). The knowledge of farmers about pollinators has been assessed in some countries (Kasina *et al.*, 2009; Munyuli 2011; Frimpong-Anin *et al.*, 2013; Hanes *et al.*, 2013;

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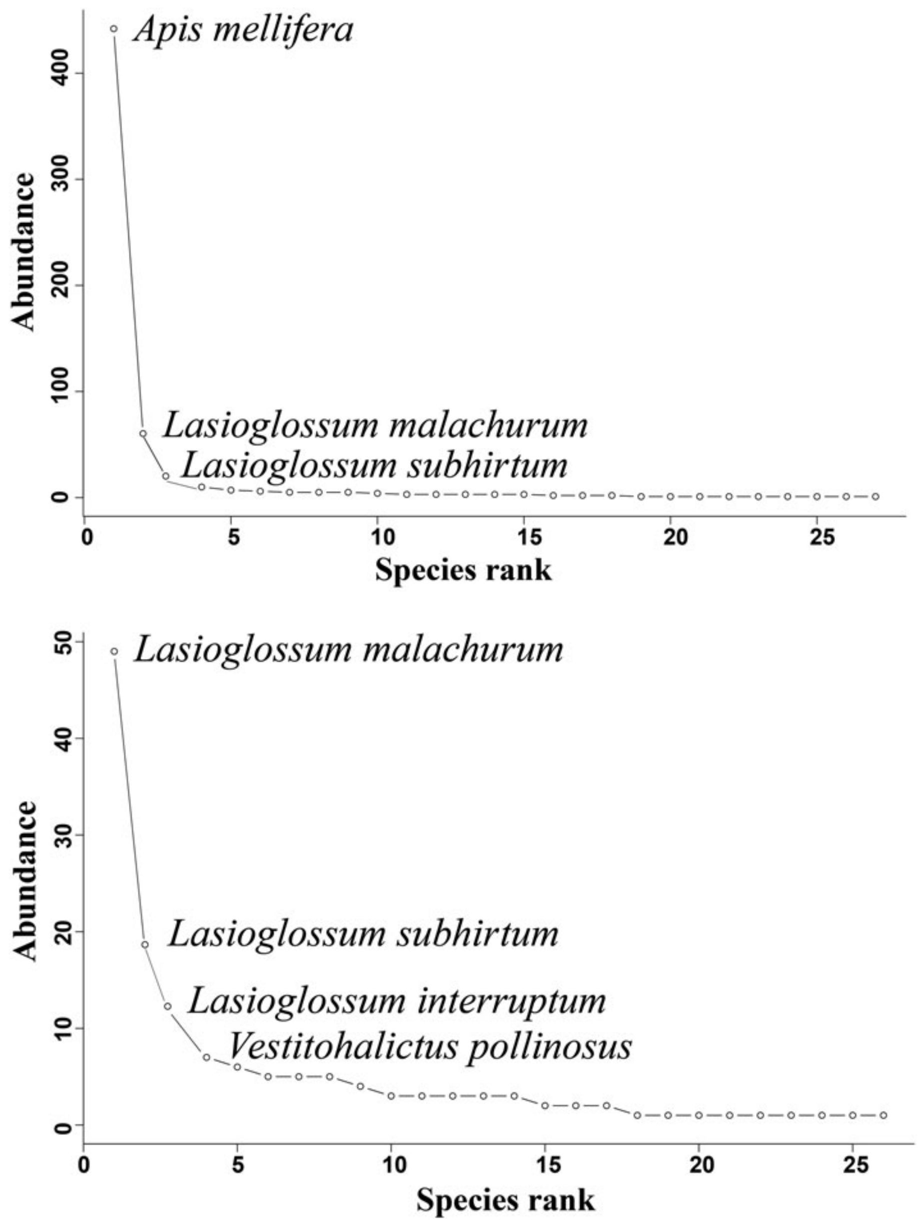

Fig. 3. Rank abundance curve representing the wild bee species visiting melon from all fields (75% zone of FAP fields & 100% zone of control fields). (Left, Fig. 3a: with honeybees; right, Fig. 3b: without honeybees).

Elisante *et al.*, 2019; Hevia *et al.*, 2020; Christmann *et al.*, 2021), but there seems to be very limited communication between entomologists working on WFS and such social researchers.

Flower visitors of melon

Our results confirm that the dominant floral visitors in melon are honeybees, considered the prevailing managed species worldwide for crop pollination (Valido *et al.*, 2019). Honeybees have already been shown to be the most abundant visitors of melon flowers (Da Silva *et al.*, 2021), although *L. malachurum* has been heralded as the key wild floral visitor and highly effective pollinator of melon in Spain (Rodrigo Gómez *et al.*, 2021). Floral displays of melon have been hypothesized to facilitate pollination by small bees with short tongues like *Lasioglossum* sp. from the bee family Halictidae (Ghazoul, 2006). Our study confirmed that *Lasioglossum sp.* is an abundant floral visitor of melon (in Morocco). It was shown by Campbell *et al.* (2019) that although honeybees were the most common visitors in commercial *Cucurbita* fields in north-central Florida, sweat bees (Halictidae) were the most effective pollinators, because they transferred more pollen than honeybees. Thus, we can also expect that *Lasioglossum* are efficient pollinators in Morocco.

Cucurbit yield can increase when the fields are surrounded by diverse floral resources, which could increase species richness and abundance of wild pollinators and probably improve pollination services (Hoehn *et al.*, 2008). Wild bees efficiently pollinate once they exist in adjacent crop areas (Garibaldi *et al.*, 2014). With increasing diversity of pollinator communities, interspecific interactions may modify insect visiting behavior and increase pollination service (Kremen, 2008). In our study, the abundance and species richness of wild pollinators in the total area of the fields (100%) was significantly higher in FAP fields compared to control fields. Besides, melon has a low number of open flowers each day and not all flowers are accessible for the whole day. However, flower visitors are always looking for more resources in terms of

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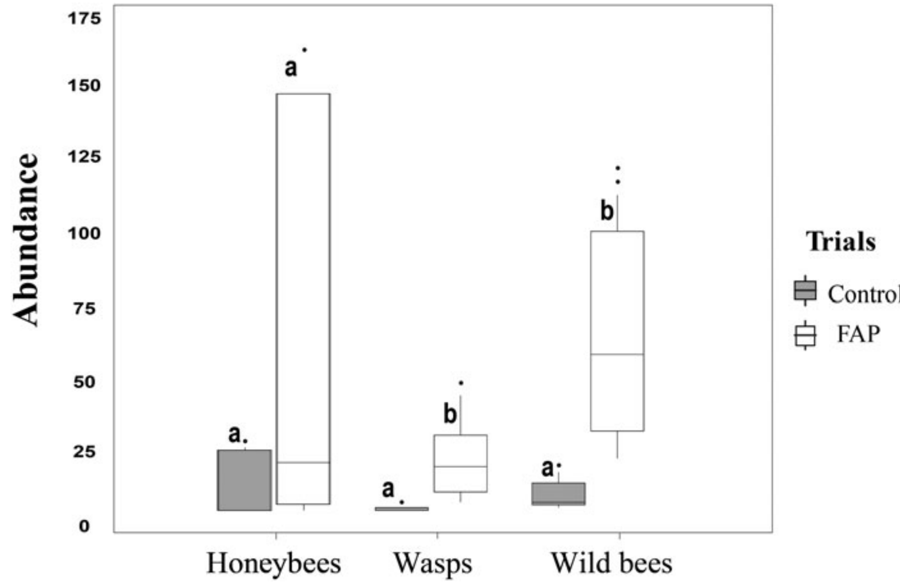

Fig. 4. Boxplots encompass the difference of mean abundance of four floral visitor groups between two type of sites FAP fields (75% zone main crop & 25% zone MHEP) and control fields (100% zone main crop). Significant differences are shown by the statistical test (Kruskal–Wallis).

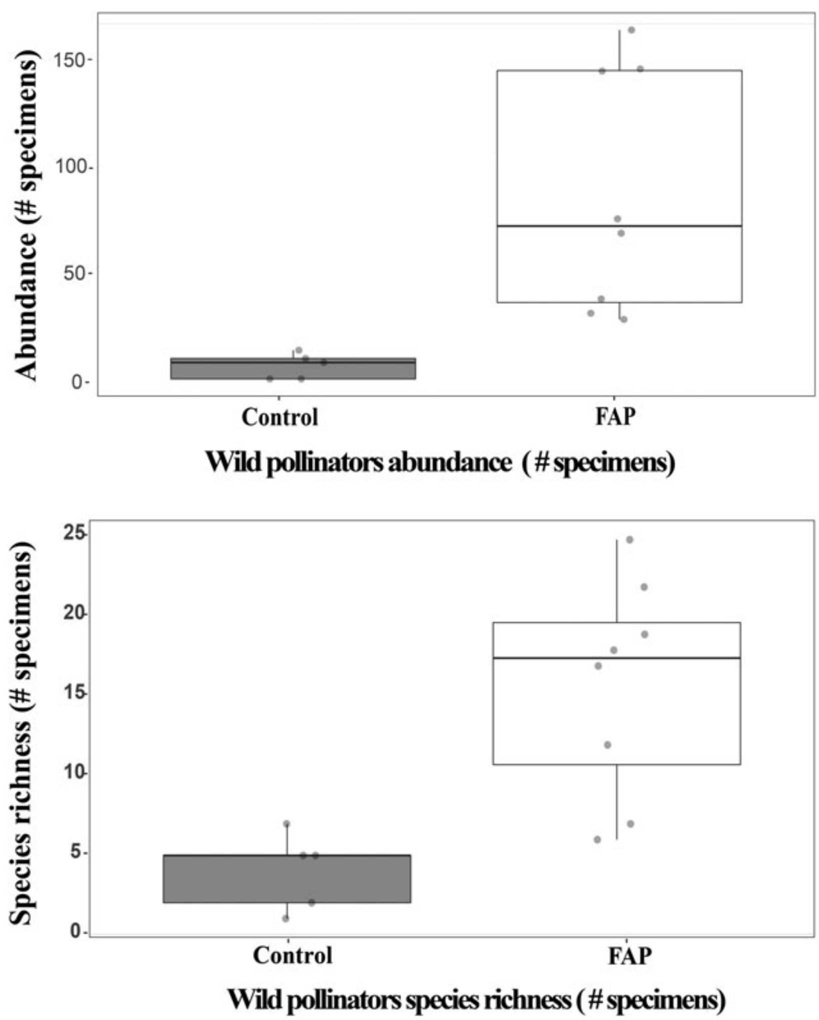

Fig. 5. Boxplots showing the total mean abundance of wild pollinators (left, Fig. 5a) and species richness (right, Fig. 5b) in FAP (75% zone main crop & 25% zone MHEP) and control (100% zone main crop) fields. Significant differences are shown by the statistical test. (Kruskal–Wallis and ANOVA Test).

quantity and quality of nectar and pollen (Hicks *et al.*, 2016). Hence, the FAP approach meets this demand of flower visitors to use as much time as possible each day for foraging in a small region by offering floral resources other than melon. Sentil *et al.* (2022a) demonstrated in FAP trials using faba bean and eggplant as main crops, that FAP fields host even higher

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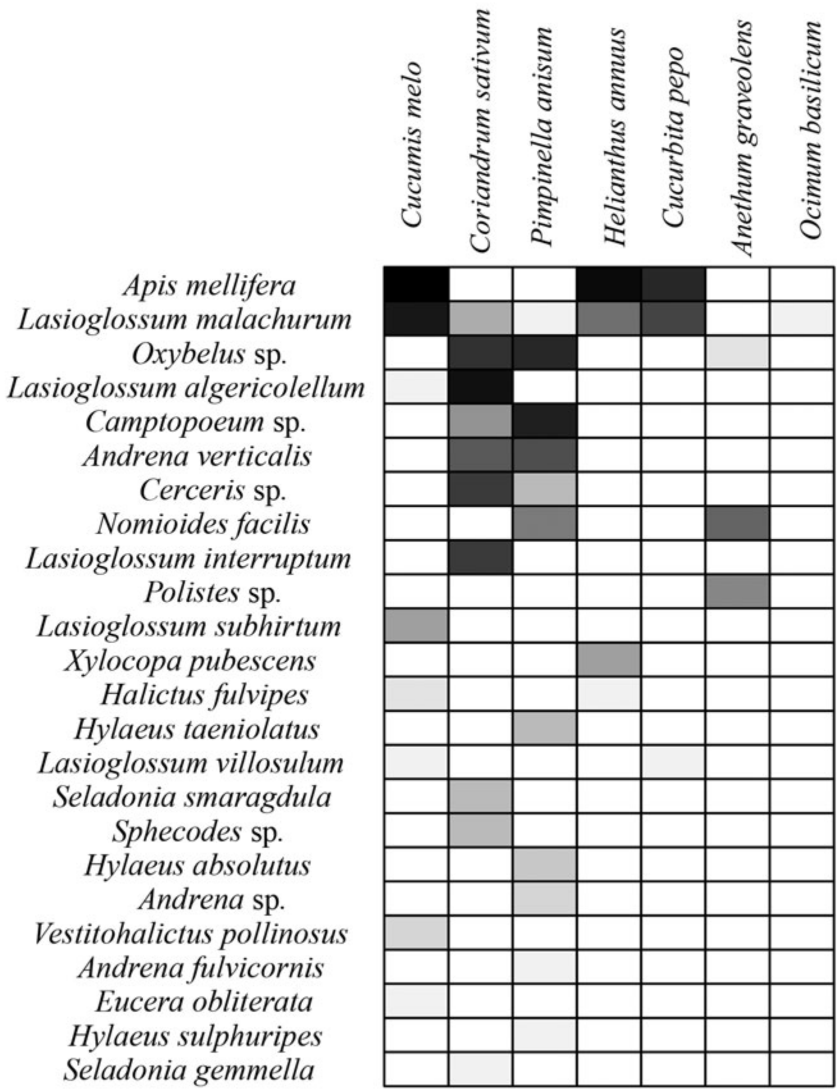

Fig. 6. Plant visitor matrix illustrating species interactions between only species common to MHEP and main crop. Darker black represents high abundance.

diversity of flower visitors than nearby wild plants. Higher diversity of pollen can be beneficial for the health of flower visitors (Sentil *et al.*, 2022b). Therefore, in particular for melon, additional flowering plants are recommended (Azpiazu *et al.*, 2020).

Our study demonstrated that there is no significant difference concerning diversity and abundance of flower visitors between the 75% zone in FAP and control. Most of the flower visitors attracted by MHEP did not spill over to the main crop. The higher productivity of the 75% zones in both years (2018: 76.6%; 2019: 46.9%) might be related to either more activities of flower visitors in FAP fields or more healthy and productive main crops, as pest control was enhanced in FAP fields. A publication analyzing 31 FAP trials identified average reduction of pest abundance in the main crop of 65% (Christmann *et al.*, 2021). However, the productivity (number of fruits) as an indicator for good pollination of melon in FAP fields was higher in both years: 54.3%, the same as the total average net income increase in 2018/2019 (61%; Christmann *et al.*, 2021).

The comparison of 100% of the fields showed a significant difference between FAP and control fields in terms of diversity and abundance of flower visitors, clearly demonstrating the positive impact of FAP for pollinator protection. In FAP fields, a higher diversity of flowers nourished flower visitors during the whole day and for a prolonged period, 120 days in comparison to 90 days in control. Also, pest control was thus prolonged (Christmann *et al.*, 2021).

FAP approach and conservation of flower visitors

In our study, abundance and species richness of wildflower visitors in the total area of the fields (100%) was significantly higher in FAP fields compared to control fields. Sentil *et al.* (2022a) had similar results in FAP trials using faba bean and eggplant as main crops. Enhancing floral richness in the field has been heralded as one of the most effective measures to increase pollinator diversity at the field edge (Zamorano *et al.*, 2020), but it can also enhance bee diversity in fields (Holzschuh *et al.*, 2013; Christmann *et al.*, 2017, 2021; Sentil *et al.*, 2021, 2022a, 2022b). Albrecht *et al.* (2020) highlighted the need to better understand the drivers that lead to success or failure of flower strips to promote pollination service. Our case study confirms Azpiazu *et al.* (2020) that some edge flowering plants can have common pollinators with the main crop. The MHEP which hosted the same key flower visitors of melon are sunflower and zucchini, and, to a lesser

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extent, basil, but basil occupied a smaller area than the other MHEP (Fig. 4 Supplementary Material). Zucchini and melon are both Cucurbitaceae; they have the same flower morphology, which explains their attractiveness for common flower visitors (Balachandran *et al.*, 2017). Coriander hosts in general a high diversity and abundance of pollinators and other insects which was confirmed also by Ranjitha *et al.* (2019). In our trial, we seeded this plant in 30 m^2. This MHEP attracted a range of flower visitors, among them *Lasioglosum agericolellum,* which it is not a main flower visitor of melon, but belongs to the same family and genus of melon key flower visitors (i.e. Halictidae, *Lasioglosum*). The melon trial identified coriander as MHEP with high potential for conservation of flower visitors.

Anise hosted *Camptopoeum sp*. and dill attracted *N. facilis*, hence these MHEP contributed exclusively to the FAP target of conservation of high diversity of pollinators in agricultural land (Christmann and Aw-Hassan, 2012; Christmann *et al.*, 2021), whereas coriander might additionally support the agricultural FAP target of better pollination and better pest control, both promoting a higher net income as incentive for farmers to enhance habitats (Christmann *et al.*, 2017, 2021). In our melon trials, many flower visitors in FAP fields stayed in the 25% zones. Of the flower visitor species, 37.6% visited the main crop, with the most abundant species *A. mellifera*. The spillover of flower visitors from MHEP to the main crop accounted for 16.5%. This might explain to some extent why the net income increase in melon trials (61%) was much lower than on average that of seven different main crops (121%; Christmann *et al.*, 2021) though the pollinator dependency is 'essential' (Klein *et al.*, 2007). However, 61% higher income can still be an incentive for farmers to seed MHEP around melon and thus contribute to pollinator protection, notably in countries unable to afford agroecological schemes for WFS (Christmann, 2020).

However, for WFS research, we agree with Kleijn *et al.* (2019) that this research should widen its approach and also focus more on farmers as decision makers.

Conclusion and perspectives

We conclude that FAP fields are more valuable compared to the monocultural control fields in terms of diversity and abundance of flower visitors. MHEP offer phenological and functional diversity of plants for flower visitors and provide a prolonged blooming period in field areas. Farmers had agreed to seed MHEP, whereas they rejected wild flowering plants, which they call weeds. As farms are business entities (Christmann *et al.*, 2017), the criteria of the decision makers should guide the recommendations of researchers when recommending habitat enhancement for pollinator protection.

During trials, we noticed one more interesting aspect. As the Settat area in Morocco grows mainly cereals, pollinator diversity is low (Lhomme, *et al.*, 2020). However, participating farmers realized the high return of some MHEP from invested irrigation water. The trials and the experience with MHEP triggered discussions, as to whether they should further diversify their production towards high value pollinator-dependent crops. As climate change already increases drought in Morocco, farmers might be forced to adapt to climate change by crop change and may use smaller areas for crop production than currently and more areas as rangelands for small ruminants. Besides the value for pollinator protection, through FAP, farmers might gain initial experience with more crops to manage such development in the near future. This will greatly support pollinator conservation.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S1742170522000394

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