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Beyond biodiversity: does "Farming with Alternative Pollinators" also boost farmers' income in wheat (*Triticum aestivum* L.) fields? a case study in Morocco

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The importance of flower visitors for ecosystem resilience and crop production underscores the need to address the current decline of flower visitors worldwide. Farming Alternative Pollinators (FAP), economic and ecological benefits of fields hosting various marketable habitat enhancement plants, developed for flower visitors protection in low- and middle-income countries, showed multiple benefits for farmers of pollinator-dependent crops, but potential benefits of FAP for production of pollinator-independent crops have not yet been assessed. Therefore, we conducted in 2021 FAP trials with wheat (*Triticum aestivum*) as the main crop in two regions of Morocco where cereals are mainly grown in monocultures in field sizes ranging from 2 to 5 ha. We tested the effects of fields adding marketable habitat enhancement plants (MHEP; coriander and canola) versus control fields on pests, natural enemies, flower visitors, and net income. We found significantly lower abundance and diversity of pests in wheat fields using MHEP, but no effect on natural enemy presence or net income. The strips of MHEP attracted a high number of flower visitors in both regions (Settat and Sidi Slimane), they supported flower visitor communities by providing plant resources and alternative habitat in monocultural landscapes extremely degraded for flower visitors.

KEYWORDS

***Coriandrum sativum*, marketable habitat enhancement plants, pest control, flower visitors, crop production, conservation biocontrol**

Introduction

Monocultures and associated increased use of pesticides and fertilizers are serious threats to beneficial insects like pollinators and natural enemies of crop pests (Aizen et al., 2019; Cole et al., 2020), which are important for yield in many crops (Christmann et al., 2021b; Raven and Wagner, 2021). Furthermore, nesting habitats and foraging resources for pollinators and other flower visiting insects have severely decreased due to agricultural intensification (Abudulai et al., 2010; Lasway et al., 2022; Raven and Wagner, 2021).

The loss of pollinators raises concerns about the future of pollination services (Deguines et al., 2014), crop production, and associated negative economic impacts (Potts et al., 2016). Eighty-seven percent of flowering plants depend on animal pollinators for sexual reproduction (Ollerton et al., 2011). Wild bees, regarded as the most effective pollinators (Potts et al., 2016), are a diverse group with more than 20,000 described species (Michener, 2007). Morocco is home to at least 1016 bee species—almost half the number of species found in Europe (2138 species) (Ghisbain et al., 2023; Lhomme et al., 2020; Reverté et al., 2023; Wood, 2023). Other important flower visiting insect such as pollinators in Morocco include 148 syrphid fly species and 45 butterfly species (Sahib et al., 2020; Verovnik et al., 2018). However, Morocco's pollinator fauna, including variuos flower visitors, is still poorly known compared to many high-income countries (Lhomme et al., 2020; Potts et al., 2016).

Several strategies have been implemented in agro-ecosystems in Europe to mitigate the decline of pollinator insects and pollination services (Defra, 2015; 2016; Ministry of Agriculture, N. and F. Q, 2018; Stout, 2020). Agri-environmental schemes (AES) have been one of the most important strategies to protect and improve biodiversity in agricultural lands (Lécuyer et al., 2022). Sowing wildflower strips (WFS) is one of the most recommended approaches to enhance wild bee and pollination services in intensively managed landscapes (Blaauw and Isaacs, 2014; 2015; Campbell et al., 2017a; b; Feltham et al., 2015; Ganser et al., 2018; Rundlöf et al., 2018; Potts et al., 2016). In low- and middle-income countries, due to the perception of wildflowers as weeds, the high priority of food security and the absence of external incentives through agroecological schemes, farmers reject seeding them (Christmann et al., 2017). For Morocco and other low- and middle-income countries, AES are not affordable (Christmann, 2020b). Furthermore, farmers in these countries often reject this method due to opportunity costs and the fear of spreading weeds (Christmann et al., 2021a). Approaches where increasing plant diversity supports both pest management (Gurr et al., 2016; 2017), pollinators and flower visiting insects might have a higher chance of being adopted than approaches highlighting pollinator protection only. Research by Wan et al. (2020) found that enhancing crop diversity (intercropping) within cereals had positive effects on natural-enemy abundance; floral resources attracted a higher diversity of predators and reduced pest densities. In another study, enhanced crop diversity supported pest predators such as spiders (Boetzl et al., 2023). Undersown (intercrop) plant mixtures have the potential to enhance both natural pest control and soil health, thereby reducing the need for fertilizers and pesticides, minimizing yield losses due to pests, and ultimately offsetting the costs of additional seeds and labor (Clough et al., 2011; Gurr et al., 2016; 2017; Wan et al., 2020).

Sustainable agricultural practices include the use of integrated pest management to reduce the need for pesticides and contribute to farm productivity. However, agricultural intensification with larger scale plantings of monocultures includes excessive use of chemical pesticides and fertilizers (Cole et al., 2020). Lack of habitat, toxicity of pesticides, and negative impacts of fertilizers, heavy machinery and tillage can negatively affect soil biodiversity, the presence of natural enemies and reduce their role in pest management (Giri and Varma, 2020). Sowing wildflowers within the main crop helps mitigate loss of habitat and negative impacts of expanded pesticide use that can harm beneficial insect populations (Griffiths-Lee et al., 2023; Gurr et al., 2017), but this approach is rarely adopted by farmers (Kleijn et al., 2019).

Diversification of agricultural systems by increasing diversity of crops has been an implemented solution to increase sustainability of agricultural production (Blaauw and Isaacs, 2015; Bommarco et al., 2013; Sardiñas and Kremen, 2015). Farming with Alternative Pollinators (FAP) (Christmann, 2019; 2020b; Christmann et al., 2017; 2021a; b; Christmann and Aw-Hassan, 2012) is a socio-economic agro-ecological farming approach focusing on better human understanding and economic sustainability and scalability of flower visitor protection in low- and middle-income countries (Christmann et al., 2021a; b). By planting so-called marketable habitat enhancement plants (MHEP) along certain parts of the fields, FAP benefits flower visitors (pollinators and natural enemies) and reduces pests instead of using insecticides (Christmann et al., 2021b). In pollinator-dependent crops it can thus ultimately increase income, providing a method-inherent and performance-related economic incentive for farmers to adopt the approach (Christmann et al., 2017; 2021a; b). FAP has been tested for pollinator-dependent crops in smallholder fields (300 m^2) (Bencharki et al., 2022; Christmann et al., 2017; 2021a; b; Sentil et al., 2021; 2022a; b) and large fields (at least 1 ha) (Bencharki et al., 2024). However, the efficiency of this practice has not been tested yet on non-entomophilous crops like wheat.

Wheat (*Triticum aestivum*) is one of the most important crops in Morocco, with a total production in 2021 of 26,335 tons (FAO, 2021). The proteins in wheat seeds are a major source of protein in the human diet (Benitez-Cardoza et al., 2007). Its nutritional and economic value add to wheat's importance in food security for the region.

Here, for the first time, we tested FAP in a pollinator-independent crop, wheat, in large fields with four objectives: 1) Assess the diversity and abundance of natural enemies and pests in FAP wheat fields (FAP fields) versus monocultural wheat fields (control fields); 2) compare FAP and control fields in terms of the diversity and abundance of pests and natural enemies in the main crop; 3) describe the diversity and abundance of flower visitors in FAP and control fields 4) compare the yield and the income of these FAP and control fields.

Materials and methods

Study sites

We developed our experiments in two Moroccan regions: Settat, situated in the semi-arid region, is characterized by cereal production, with wheat (*Triticum aestivum* L.) being the primary crop. About 90% of the arable land in Settat is used for intensive cereal cultivation, influenced by the area's climatic conditions, which include low and unpredictable rainfall, high evaporation rates, and frequent droughts. These challenges require agricultural practices that focus on maximizing yield efficiency, often leading to a heavy reliance on monoculture, synthetic fertilizers, and pesticides to maintain production under these difficult environment conditions. Sidi Slimane, located in the Rabat-Salé-Kenitra region, presents a striking contrast to Settat, primary due to its sub-humid climate, which features more consistent rainfall and milder temperatures. This advantageous climate fosters intensive horticultural production, where large-scale monocultures of fruits and vegetables dominate the agricultural landscape. The region is recognized for its high-input farming practices, including the extensive use of irrigation, fertilizers and pesticides to sustain high yields and satisfy the demands of both local and export markets. The prevalence of intensive monoculture farming has caused considerable ecological challenges, such as soil degradation, decreased habitat diversity, and declining populations of wild pollinators. These issues make both regions ideal for exploring the potential of the FAP approach. This strategy not only seeks to support biodiversity but also aims to boost agricultural productivity and farmer income, particularly in a context where environmental sustainability is increasingly threatened.

In November 2020, we established a FAP-trial in both regions with wheat (*Triticum aestivum*) as the main crop and coriander (*Coriandrum sativum*) and canola (*Brassica napus*) as marketable habitat enhancement plants (MHEP) (Figure 1). Eight fields (5 FAP fields and 3 control fields) were studied in two provinces of each region (Ouled Said and Ouled Sghir in Settat; Ouled ben Hammadi and Haouafate in Sidi Slimane (16 fields in total). All the fields, either with the main crop and MHEP or only the main crop, were managed using similar farming practices concerning tillage, fertilizer and fungicide application. The irrigation system for the fields was rainfed. Each field was 20,300 m^2, with 1 m x 100 m strips of each MHEP planted every 100 m on the edges of FAP fields (Figure 1). Two strips of coriander were planted on the two lateral edges, and one strip of canola was planted in the middle. This provided enough space for the farmers to use their equipment for planting and harvesting. Study fields were at least 1 km apart to ensure independent results. Since the field sizes in both regions ranged from 2 to 5 ha, the study fields measured 2.03 ha constituted entire fields, while others were trial areas within larger monocultures.

Marketable habitat enhancement plants

During farmer selection in the Settat region, we discovered that many farm workers had become aware of the importance of pollinators, other insects, and the benefits they provide to crops due to many FAP-trials with smallholders in 2018-2019 (Christmann et al., 2021b). We selected farmers who already knew about the importance of pollinators for many crops, non-crop plants, and wildlife. In the previous trials, participating smallholders were able to provide feedback on pollinator abundance and the variety of flower-visitors per MHEP. To select the appropriate MHEP, we involved large-scale farmers in the decision-making process, considering their knowledge about seeding, flowering times, and water demands. Farmers' inputs were particularly important in considering the market potential of specific MHEP at the targeted harvesting time. Based on criteria such as potential income, different flower types, flowering time, and seeding time, we selected two plants as MHEP: canola (*Brassica*

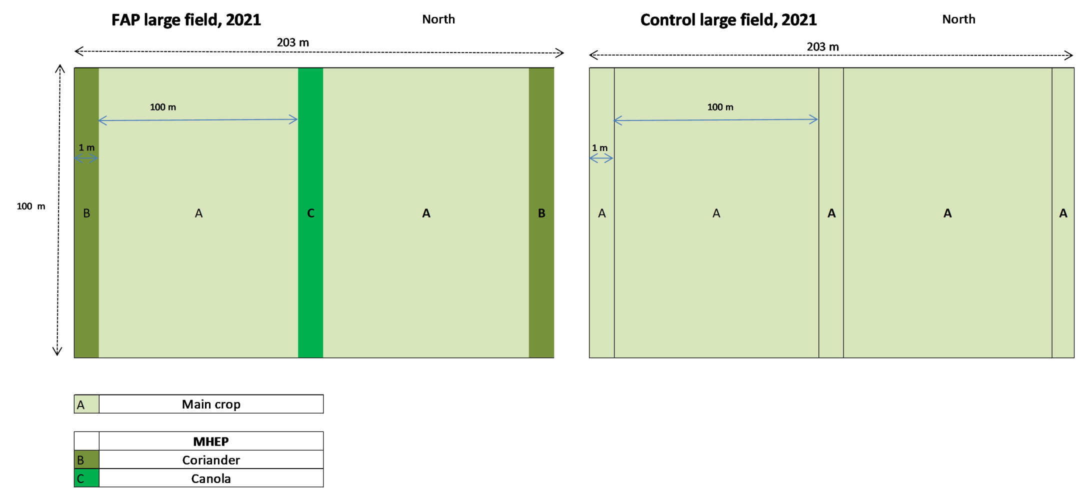

FIGURE 1
Farming with Alternative Pollinators (FAP) experimental designs of wheat (*Triticum aestivum*) for Settat (semi-arid) and Sidi Slimane (sub-humid) regions. A, main crop area with wheat; B, Marketable Habitat Enhancement Plants (MHEP) area with coriander; C, MHEP area with canola.

napus) and coriander (*Coriandrum sativum*). These plants have been shown to attract flower visitors and natural enemies in previous studies (Christmann et al., 2021b; Sentil et al., 2021; 2022). We agreed on three practices that the farmers would be responsible for: establishing the plant strips, managing the MHEP, and harvesting the crops (main crop and MHEP).

Sampling of pests and natural enemies

In March and April 2021, we conducted three samplings, with each lasting two days (four fields per day) and ten days between them. Each field was visited once for one hour to collect flower visitors, pests and natural enemies. To collect natural enemies and pests in the fields, we used funnels – 180 mm diameter and 2 ml Eppendorf tubes. For sampling of pests/natural enemies, in FAP fields we selected 10 plants randomly in each MHEP (i.e., 10 coriander plants and 10 canola plants) and 10 in the main crop to be beaten, whereas in control fields we sampled 30 plants of the main crop from different places to be beaten. In both types of fields, we conducted beating 5 times on each selected plant to collect crop natural enemies/pests. The samples were put into plastic bags and labeled with the date, field, and management. In the lab, all collected insects were sorted using dissecting microscopes and conserved in 2 ml Eppendorf tubes containing 70% ethanol. Collected specimens were identified to the lowest possible taxonomic level using microscopes and identification keys (Bonsignore and Vacante, 2012). The data collected was pooled in two different ways to compare the abundance and diversity of pests and natural enemies on (a) the whole field and for comparability in (b), we randomly selected 10 wheat plants from the 30 sampled wheat plants to compare with the 10 wheat plants from the control main crop area.

Flower-visitor sampling

To characterize the flower visitor communities in MHEP strips, we performed three samplings in March and April of 2021 in all fields. For each sampling over two consecutive days, we collected flower visitors in FAP and control fields. Although wheat is pollinator-independent, we sampled wheat and MHEP flower visitors. We used two methods to sample flower visitors: netting along transects and pan traps, because in most studies, pan traps and net transect were the most recommended methods for sampling flower visitors. In each field, we used both methods to collect the flower visitors. After collecting the data, we merged the data from each field and then summed the control and FAP fields to calculate the abundance. During MHEP bloom, we did transect sampling in the main crop for 10 minutes, randomly selecting 5 minutes in each area of 10,000 m^2 of the main crop. In FAP fields, we also sampled the MHEP strips (i.e. area of 3x100 m^2), for 10 minutes (5 minutes for each MHEP, 5 min in the canola strip and 2.5 min in each coriander strip). 1.5% area of each monoculture field was likewise sampled for 10 minutes (10 min was divided between the three strips) (Supplementary Figure 1).

To limit sampling bias between the fields, we conducted sampling during warm, calm, and sunny days between 10 am and 4 pm. Honeybees (*Apis mellifera*), carpenter bees (*Xylocopa pubescens*), and bumblebees (*Bombus terrestris*) were not collected but identified visually in the field. All other bees were collected and identified in the lab.

For pan-trap sampling, we placed bowl traps (volume of 500 ml, diameter of 145 mm, depth of 45 mm) of three different colors (yellow, white, and blue) on both sides of the wheat fields to collect flower visitors in FAP and control fields. In each (10,000 m^2) main crop area, we placed one set of three bowls towards each end of the transect line (Supplementary Figure 1). The traps were left in the fields for 30 hours, starting at 10 am on the first day, and were collected at 4 pm on the second day. Bees were identified to the genus level in the lab (following key of Michez et al., 2019) and sent to different taxonomists to determine the species level (see Acknowledgements).

Economic assessments

Economic assessments were calculated based on entire field harvests, using machines for the wheat harvest. We measured the total weight of wheat from each field and used the market price per kilogram to determine the income from the wheat crop. For the FAP and control fields, the total area of the main crop (i.e. 98.5% of the field) were weighed and calculated based on seeds market price. Regarding 1.5% area, in FAP fields, MHEP seeds were weighed and also calculated per field, and for control fields the total weight of 1.5% wheat area was considered and calculated per field. Income from MHEP was also calculated by multiplying the total weight by the market price per kilogram. Additionally, we deducted the investment costs for seeds and additional labor costs for harvesting MHEP in the 1.5% of study fields (estimated at 200 MAD, which is equivalent to 3 person-days per field). We did not consider labor costs for harvesting the 1.5% zones in control fields, as they can be quickly harvested together with the main crop.

In our economic assessments of net return, different inputs and additional labor times were recognized. Expense items were calculated based on actual producer investments and production weights, which are presented in Supplementary Material Table 1; Table 1.

Statistical analysis

To evaluate the impact of management type (FAP vs. control) and arthropod category (natural enemies vs. pests) on arthropod abundance and species richness, we conducted a series of statistical analyses. We first cleaned and organized the data to ensure completeness and generated descriptive statistics to summarize abundance and species richness across the different management types. We assessed the normality of residuals using the Shapiro-Wilk test and checked for homogeneity of variances using Levene's test. A one-way ANOVA was performed to examine the main effects and interactions between management type and arthropod categories (natural enemies and pests) regarding abundance and species richness. Significant interactions and main effects were

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TABLE 1 Most abundant bee species, wasps species, sawflies species and diptera (hoverfly and Stratiomyidae species) visiting MHEP.

Hymenoptera	Sidi Slimane		Settat	
	FAP	Control	FAP	Control
Bees species				
Apis mellifera	445	0	352	0
Andrena fulvicornis	506	0	197	0
Andrena miegiella	468	0	222	0
Eucera eucnemidea	19	0	10	0
Eucera obliterata	16	0	9	0
Seladonia gemma	15	0	5	0
Andrena flavipes	8	0	2	0
Andrena varia	0	0	10	0
Hylaeus cornutus	6	0	3	0
Sphecodes cf. ephippius	5	0	2	0
Lasioglossum malachurum	6	0	0	0
Andrena abjecta	0	0	3	0
Andrena aerinifrons	0	0	3	0
Panurgus maroccanus	0	0	3	0
Nomada bifasciata	2	0	1	0
Andrena microthorax	2	0	0	0
Andrena nitidula	2	0	0	0
Hylaeus annularis	1	0	1	0
Nomada tridentirostris	1	0	1	0
Andrena bellidis	1	0	0	0
Andrena spec	0	0	1	0
Eucera clypeata	0	0	1	0
Eucera nigrilabris	0	0	1	0
Eucera numida	0	0	1	0
Hylaeus absolutus	0	0	1	0
Hylaeus soror	1	0	0	0
Hylaeus sulphuripes	0	0	1	0
Hoplitis zaianorum	0	0	1	0
Lasioglossum pauxillum	0	0	1	0
Nomada duplex	0	0	1	0
Osmia notata	1	0	0	0
Sphecodes gibbus	0	0	1	0
Sphecodes monilicornis	1	0	0	0

(Continued)

TABLE 1 Continued

Hymenoptera	Sidi Slimane		Settat	
	FAP	Control	FAP	Control
Wasps species				
Eumeninae sp.	15	0	13	0
Dasyscolia ciliata	0	0	24	0
Ichneumon sp.	9	0	10	0
Lindenius spilostomus	7	0	2	0
Tiphia sp.	0	0	8	0
Cerceris sp.	2	0	1	0
Oxybelus sp.	2	0	1	0
Polistes dominula	3	0	0	0
Philanthus triangulum	0	0	2	0
Ectemnius hypsae	0	0	1	0
Sawfly species				
Trachelus tabidus	41	0	45	0
Athalia ancilla	16	0	16	0
Tenthredo contigua	0	0	2	0
Tenthredo corynetes	0	0	2	0
Tenthredo lucassi	0	0	1	0
Diptera	**Sidi Slimane**		**Settat**	
	FAP	**Control**	**FAP**	**Control**
Hoverfly species				
Eupeodes corollae	95	0	191	0
Sphaerophoria scripta	70	0	44	0
Episyphus balteatus	41	0	44	0
Eristalis tenax	19	0	17	0
Sphaerophoria rueppellii	12	0	8	0
Melanostoma mellinum	4	0	6	0
Syritta flaviventris	3	0	1	0
Syritta pipiens	1	0	2	0
Eristalis arbustorum	1	0	1	0
Syrphidae indet	0	0	1	0
Merodon obscuritarsis	1	0	0	0
Scaeva pyrastri	0	0	1	0
Stratiomyidae species				
Stratiomys longicornis	15	0	10	0

further investigated through *post hoc* pairwise comparisons with Bonferroni corrections. All statistical tests were conducted using R (Version 4.4.0; R Development Core Team, 2023), utilizing relevant packages for data manipulation, visualization, and analysis. The results were visualized with boxplots annotated for statistical significance, aiding in the interpretation of group differences.

We used a t-test to compare economic outcomes between FAP and control fields in terms of yield (weight) and income. It was hypothesized that yield and income in FAP fields were not significantly different from those of the control fields (considered as the null hypothesis for the t-test). To test this hypothesis, a t-test for independent samples was conducted.

Results

Diversity and abundance of pests and natural enemies in the entire field in both regions

In the Sidi Slimane region, across 8 wheat fields, we collected a total of 244 specimens of natural enemies and 689 pest specimens, highlighting the diversity and abundance of both beneficial and harmful insect populations in this area (Table 2). Similarly, in the Settat region, from 8 different wheat fields, we gathered a total of 219 specimens of natural enemies, while the number of pest specimens reached 598, providing valuable comparative data on the interactions between pests and their natural enemies across regions with differing environmental conditions (Table 2).

Impact of FAP approach on the abundance and diversity of pests and natural enemies at full field level

Natural enemy abundance was more than one time higher in FAP than in control fields but there was no statistically significant difference between FAP and control fields (Figure 2A), while pest abundance was more than two times higher in control than in FAP fields (Figure 2C). Whereas in natural enemy diversity between FAP vs. control fields while there was no difference in natural enemy diversity between FAP vs. control fields (Figure 2B), pest diversity was significantly higher in control fields (Figure 2D) Table 3.

Impact of FAP approach on the abundance and diversity of pests and natural enemies in the main crop

Natural enemy abundance was approximately the same in both managements, statistically was no difference in the abundance of natural enemies between FAP and control fields (Figure 3A), whereas pest densities were more than one time higher in control than in FAP fields (Figure 3C). Regarding the diversity of the pests and natural enemies in the main crop, there was highly significant difference between control and FAP fields only of the pests (Figure 3D), but not of the natural enemies (Figure 3B) Table 4.

Effect of MHEP strips on flower visitors

As wheat is a pollinator-independent crop, we did not collect any specimen of pollinators in the main crop. As expected, MHEP strips attracted many different flower visitors.

In Settat region we recorded 838 specimens of bees, we also collected 322 Syrphidae, 2 wasps, 13 other Vespidae and 107 Sawflies. Besides, In Sidi Slimane region we recorded 1,828 specimens of bees. We collected 253 Syrphidae, 38 wasps and 16 sawflies (Table 1).

Economic assessments

Economic assessments showed that the average net income from FAP fields was 1% higher in Settat and 2% higher in Sidi Slimane, because coriander and canola seed provide higher income per area than wheat (Tables 2; Supplementary Table 2). However, statistically the average seeds production (main crop and MHEP) of FAP fields was not significantly higher than that of control fields (t Stat = 0.06, P two-tail = 0.95) (Supplementary Table 3). Also, the average income was not significantly higher from FAP vs control fields (t Stat = 0.30, P two-tail = 0.76) (Supplementary Table 4).

Discussion

Our study confirms the value of crop diversification in pollinator-independent crops for insect conservation (Bonsignore and Vacante, 2012; Gayer et al., 2021; Griffiths-Lee et al., 2023; Middleton et al., 2021; Norris et al., 2018; Ostandie et al., 2021; Settele et al., 2019; Wan et al., 2020). MHEP reduced pests in FAP fields, and provided food resources for flower visitors. In contrast to trials with pollinator dependent crops (Bencharki et al., 2022; Christmann et al., 2017; 2021,b), FAP did not trigger higher income in wheat fields. Overall, it appears that seeding MHEP strips within wheat fields is a strategy to conserve and sustain pollinators. Sustain pollinator enhanced diversity could benefit future crops, provide resiliency in case of crop change in the course of climate change, as well as other regional wildlife (Christmann, 2020a).

FAP effects on pest control

Our study found a significant decrease in pest abundance and diversity in FAP fields probably due to habitat (food and shelter) provided by MHEP for natural enemies of pests compared to control fields (100% wheat and no MHEP). Flower strips can help reduce pest populations (Tschumi et al., 2016) by enhancing biodiversity that supports natural enemies and helps alternative prey (Aviron et al., 2009; Harrison et al., 2019). In our case, we did

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TABLE 2 Total abundance of natural enemies and pests representing in control and FAP fields in Settat and Sidi Slimane regions.

Natural enemies	Sidi Slimane		Settat	
	FAP	Control	FAP	Control
Parasitoid wasps (Hymenoptera)	112	22	60	8
Green lacewings (*Chrysoperla carnea*)	41	8	8	
Thrips (*Aeolothrips* sp. And *Haplothrips* sp.)	14	4	73	4
Lady beetles (*Hippodamia variegata*)	12	4	8	
Minute pirate bugs (*Orius* sp. and *Anthocoris* sp.)	11			
Plant bugs in the family Miridae	7			
Other Hemiptera predator	4	4		
Seven-spot ladybird beetles (*Coccinella septempunctata*)	1		33	2
True bugs (Hemiptera)			6	3
Spiders			5	
Spider mite destroyer (*Stethorus punctillum*)			2	
Ladybird beetles (*Exochomus nigromaculatus*)			1	
Lady beetles (*Scymnus* sp.)			1	
Dustywings (Conioptegiridae)			1	2
Other thrips predator			1	
Staphylinidae			1	
Pests	**Sidi Slimane**		**Settat**	
	FAP	**Control**	**FAP**	**Control**
English grain aphids (*Sitobion avenae*)	112	288	12	14
Cabbage aphids (*Brevicoryne brassicae*)	32		49	
Beetles (Coleoptera)	30	8	142	35
Blister beetles (Meloidae)	15	18	9	2
Thrips (Thripidae)	12	24	7	8
Jumping plant lice (Psylloidea)	10	8		
Carabid beetles (Carabidae)	4	2	16	10
Leaf beetles (*Cassida vittata*)	3			
Pollen beetles (*Meligethes* sp.)	3		22	
Other aphids	2	30	87	48
Bister beetles in the genus *Mylabris*	2		2	
Leaf beetles identified to the Chrysomelidae family	2	4		
Weevils (Curculionidae)	2	2		
Leafhoppers (Cicadellidae)	1	8	1	2
Chafer beetles (*Tropinota* sp.)	1			
Shield (stink) bugs (Pentatomidae)	1			
Owlet moths (Noctuidae)	1		4	7
Psyllid (Psylloidea)	10	8		
Hemiptera pests		2		

(Continued)

TABLE 2 Continued

Pests	Sidi Slimane		Settat	
	FAP	Control	FAP	Control
Cabbage aphids (*Brevicoryne brassicae*)	32		49	
Darkling beetles (Tenebrionidae)			15	26
Other leaf beetles (Chrysomelidae)	2	4	1	2
Ground beetles (Carabidae)	4	2	16	10
Cereal leaf beetle (*Oulema melanopus*)			0	2

not find any difference in natural enemies' abundance and diversity because the latter requires time to install and stabilize prey suppression over time (Jonsson et al., 2017). However, we found a significant difference in pests between FAP and control fields. This could be due to the presence of other animals or insects that were not captured by our sampling methods, such as insectivorous birds or ground-dwelling predators. Those animals or insects may play a larger role in pest control (Beaumelle et al., 2021; Nyffeler et al., 2018) or due to composition of surrounding landscape effects, for instance, habitat diversification practices such as hedgerows (Perez-Alvarez et al., 2019).

Plants like coriander (Apiaceae family) whose open flowers make nectar easily accessible to many predatory insects like parasitic wasps and hoverflies, improve ecosystem services such as pest control (Campbell et al., 2012; Wood et al., 2015). Plants such as coriander attract other beneficial invertebrates including predators (Tschumi et al., 2016). By promoting natural enemies and implementing habitat management, it is possible to potentially increase or at least maintain yield with a reduced level of pesticide inputs (Letourneau et al., 2015). Choosing appropriate MHEP may depend on the categories of natural enemies they attract, and their blooming time in relation to potential pest impacts (Wäckers et al.,

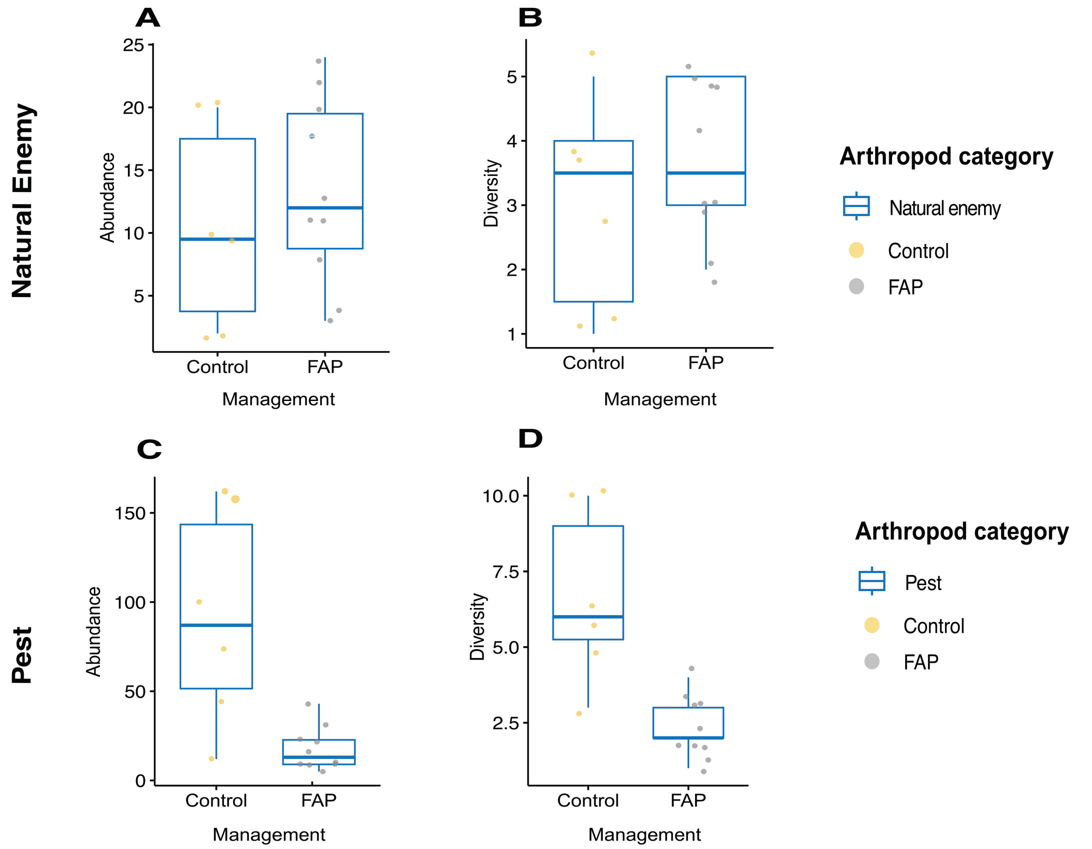

FIGURE 2
Abundance **(A, C)** and diversity **(B, D)** of natural enemies **(A, B)** and pests **(C, D)** of 10 Farming with Alternative Pollinators (FAP) (100% FAP field areas) and 6 control (100%control field areas) fields.

TABLE 3 ANOVA calculation for total abundance and diversity of natural enemies and pests at full field level.

Arthropod category	Response variable	Explanatory variable	DFn	DFd	F	N (control)	N (FAP)	p-value	Significance
Natural enemy	Abundance	Management (FAP x Control)	1	22	20.520	6	10	3.33e-1	ns
Pest		Management (FAP x Control)	1	22	14.240	6	10	p < 0.001	***
Natural enemy	Diversity	Management (FAP x Control)	1	22	0.282	6	10	0.601	ns
Pest		Management (FAP x Control)	1	22	5.30	6	10	0.0312	*

Statistical significance was determined using Bonferroni post-hoc tests, with asterisks indicating levels of significance: *p < 0.05, ***p < 0.001.

2007). Understanding the relative attractiveness of flowering plants to natural enemies against pests is important in successful adoption of these practices (Wäckers and van Rijn, 2012). Specific wheat pests in Morocco are Hessian Fly, sunn pest, Cereal leaf beetle, Wheat stem sawfly, Russian wheat aphid, Greenbug, Bird Cherry-Oat Aphid, English grain aphid and orange wheat blossom midge (Tadesse et al., 2021). In the present study, canola and coriander attracted some natural enemies reducing pests.

Natural enemy density is associated with predation rates (Boetzl et al., 2020). The greater the diversity of plants in crop areas, the greater the expected diversity and abundance of natural enemies (Wan et al., 2020). Some plants are highly attractive to particular natural enemies due to the quality of nectar (Tschumi et al., 2016). However, Albrecht et al. (2020) found no correlation between wildflower diversity and pest control service but did find a positive correlation between flower diversity and pollination service. MHEP can play those two roles by providing floral resources to natural enemies and pollinators (Christmann et al., 2021b).

Parasitoid wasps, in general known for their effectiveness in controlling pest populations especially of weevils (Lundin et al., 2012; Campbell et al., 2012; Wood et al., 2015) made up the largest percentage of predators also in FAP fields (Table 2). Green lacewings were more abundant in Sidi Slimane. They mainly prey on soft bodied insects such as aphids, thrips, mites, moths and lepidopteran eggs (Alcalá-Herrera et al., 2022; Sarwar and Salman,

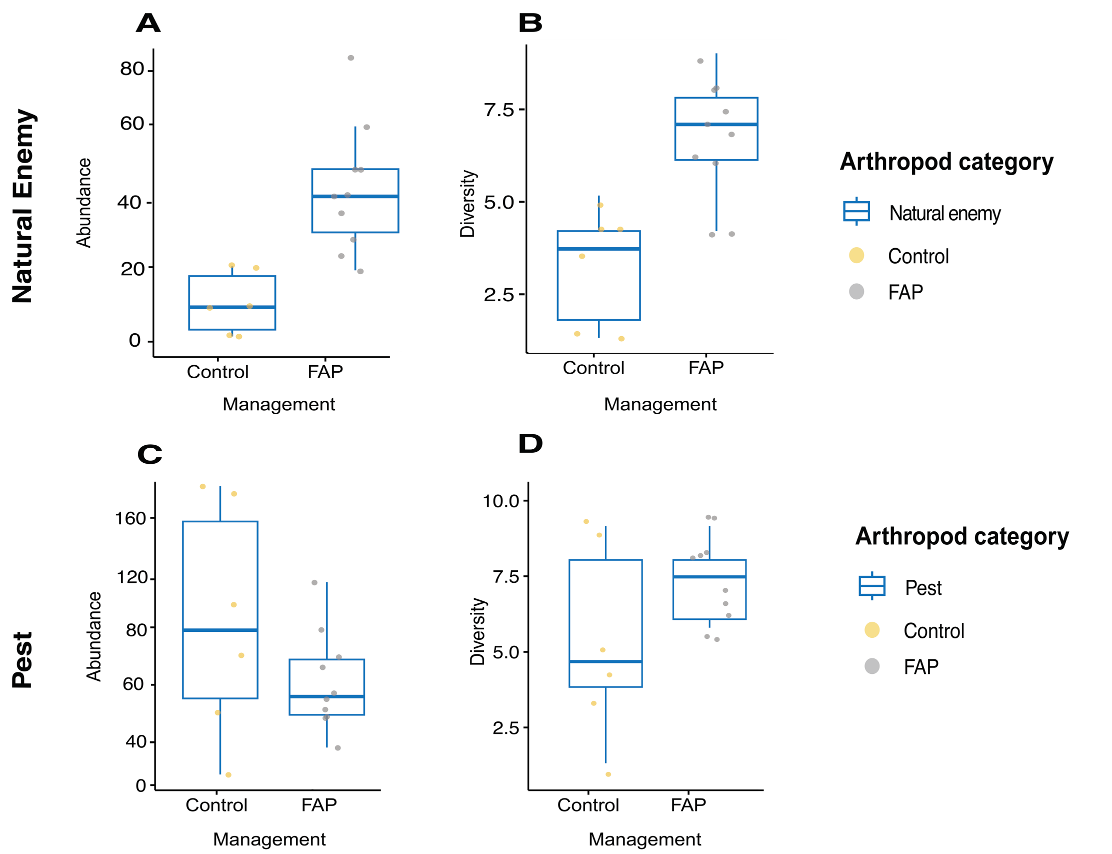

FIGURE 3
Abundance **(A, C)** and diversity **(B, D)** of natural enemies **(A, B)** and pests **(C, D)** in the main crop of 10 Farming with Alternative Pollinators (FAP) (98.5% FAP field areas) and 6 control (100% control field areas) fields.

TABLE 4 ANOVA calculation for abundance and diversity of natural enemies and pests in the main crop.

Arthropod category	Response variable	Explanatory variable	DFn	DFd	F	N (control)	N (FAP)	p-value	Significance
Natural enemy	Abundance	Management (FAP x Control)	1	28	0.043	6	10	0.837	ns
Pest		Management (FAP x Control)	1	28	28.1	6	10	p < 0.001	***
Natural enemy	Diversity	Management (FAP x Control)	1	28	0.681	6	10	0.416	ns
Pest		Management (FAP x Control)	1	28	26.5	6	10	p < 0.001	***

Statistical significance was determined using Bonferroni post-hoc tests, with asterisks indicating levels of significance: ***p < 0.001.

2016). In Settat region, the major natural enemies in our trials were seven-spot ladybird beetles. They are the main natural enemies of English grain aphids (*Sitobion avenae*) (Alhmedi et al., 2009). In FAP fields, spider densities were lower compared to those in control fields. The low densities of thrips and spiders observed in the Settat trials may be attributed to the increased abundance of Minute pirate bugs. These generalist predators are known to feed on spiders, thrips, and insect eggs found on herbaceous plants (Bonsignore and Vacante, 2012). Likely due to the presence of seven-spot ladybird beetles, the population density of aphids was lower in the trial of Settat compared to Sidi Slimane region, probably because more than 50% of Coccinellidae family prey on aphids (Bonsignore and Vacante, 2012). Overall, the low pest densities of aphids and cereal leaf beetle in both regions in FAP fields may have been camouflaged by the potential effects of FAP.

With no significant increase of natural enemies in wheat production, it is likely that natural enemies attracted by MHEP did not shift to the main crop. Similar to previous studies (Kral-O'Brien et al., 2022; Ranjitha et al., 2019), coriander and canola attracted a lot of flower visitors and natural enemies, thus we can consider them as good plants for conserving insects in pollinator-independent crops. It is possible that various MHEP complement one another by supporting a greater diversity of agriculturally beneficial insects. The addition of another MHEP such as clover (*Trifolium incarnatum*), which supports spider abundance in oats (*Avena sativa*) (Boetzl et al., 2023), could complement the habitat resources provided by canola and coriander. In the control fields, there was a higher abundance and diversity of pests than FAP fields, which could indicate that MHEP in FAP fields played a role as the trap plants, similar to beans in maize crop (Bi et al., 2023) and in wheat fields based on intercropping systems (Liu et al., 2022). The selection of plants as trap crops should be appropriate for pest reduction in field crops (Cook et al., 2007). Higher plant diversity in the main crop could reduce the abundance and diversity of pests by helping to sustain natural enemy populations (Harrison et al., 2019). This aligns with our results, as we observed a higher abundance and diversity of pests only in control fields.

Overall, our study showed that planting strips of MHEP every 100 m is a new strategy to conserve the abundance and diversity of flower visitors and natural enemies in pollinator-independent crops. Additionally, FAP reduced pests in the main crop, which could indicate that the MHEP act as trap plants. However, FAP may need to be applied consecutively across years to demonstrate a more impactful effect on pest control, and it might lead to the spillover of natural enemies from MHEP to the main crop, thereby affecting crop production as well.

FAP effects on flower visitor conservation

Even if Kral-O'Brien et al. (2022) highlighted that pollinators could benefit from pollinator-independent crops e.g., from grasses that provide abundant pollen, we did not observe any pollinator in the main crop (i.e. on wheat), but only on MEHP (i.e. coriander and canola). This behavior of collecting pollen from anemophilous plants is indeed quite rare (Michez et al., 2019). On the opposite, coriander and canola are well-known for their attractiveness to a diversity of flower visitors (Christmann et al., 2021b; El-Abdouni et al., 2022). Most flower visitors recorded were short tongued wild bees (Andrenidae family) and honey bees *Apis mellifera*. The open floral nectary of coriander (Azpiazu et al., 2020) makes nectar easily accessible (Nemeth and Szekely, 2000). Thus, seeding coriander would be positive for supporting short-tongued bees, as well as predator wasps and flies. Canola is known for its attractiveness to managed bees, because the flowers offer a high amount of crude protein to support bee nutrition (Kral-O'Brien et al., 2022). It is evident that flower visitors can be promoted by seeding strips of MHEP within wheat and without insecticides applications. Since wild bee populations have been found to be higher on organic farms (Gayer et al., 2021) due to permanent ban of chemical pesticides, the FAP approach might be providing similar benefits for more conventional agricultural systems.

Increasing floral resources diversity and rotation can have a positive impact by improving the health of managed and wild bees (O'Brien et al., 2021; Palmer et al., 2009; Sentil et al., 2022b). FAP is known for hosting a high abundance and diversity of flower visitors in small fields (Bencharki et al., 2022; Christmann et al., 2021a; b; El-Abdouni et al., 2022; Sentil et al., 2022a) and enhancing production of pollinator dependent crops (Bencharki et al., 2022; Christmann et al., 2017; 2021a; b), and confirmed concerning large fields (Bencharki et al., 2024). High flower diversity leads to an enhanced abundance of pollinators from field (Boetzl et al., 2023) to landscape scale (Kleijn et al., 2018). The effect was stronger in the semi-arid region, and adding floral resources can have implications on the landscape scale because the region is scarce of floral resources. FAP provided 65 days of floral resources in association with a crop that does not need flower visitors, this could contribute to the conservation of regional biodiversity. By connecting patches MHEP might also facilitate local or regional migration of flower visitors in regions with large cereal monocultures.

FAP effects on net income

Due to the decrease in abundance and diversity of pests in FAP fields, yield and income could be increased for farmers, but this increase was not statically significant in the present study. Östman et al. (2003) demonstrated the barley production increased by decreasing of pests' abundance. FAP trials in pollinator dependent crops found income increases due to lower pest abundance and higher diversity and abundance of flower visitors (Christmann et al., 2017; 2021a; b). However, the farmers still benefited in wheat field from the additional income of coriander and canola strips. MHEP also do not cause opportunity costs, which are caused by wildflowers strips (WFS), making MHEP more farmer-friendly (Christmann et al., 2021b). Furthermore, one year is likely not sufficient to show potential income differences, particularly since it might take time for the increased presence of natural enemies to reduce cereal aphid populations (Östman et al., 2003; Rusch et al., 2013). In addition, results may differ from year to year due to high fluctuations in both pest and predator species. Nevertheless, this study shows that FAP contributes to the conservation of flower visitors and reduced pests by seeding MHEP without subsidies in contrast to WFS. On the other hand, MHEP offer a valuable alternative for farmers (Christmann et al., 2021a; Azpiazu et al., 2020) and a habitat for pollinators and pest predators associated with pollinator-dependent crops (Christmann and Aw-Hassan, 2012). In previous studies, FAP was implemented among smallholders, where 25% of the field was planted with MHEP (Christmann et al., 2017; 2021a; b). In the present study, only 1.5% of wheat fields (in narrow 1 m wide strips) were used for habitat enhancement, this area may have been too small to provide both economic and biodiversity benefit. In contrast to the MHEP in this study, WFS are generally planted in 3-6 m width strips in large fields (often the width of a tractor to ease maintenance) (Feltham et al., 2015).

Conclusion

The FAP approach, which utilizes different MHEP, is known for harboring a higher diversity and abundance of natural enemies and flower visitors. This leads to a reduction in pests' diversity and abundance in FAP fields compared to control fields. Such a positive impact on pest control can potentially improve income. In this study we can conclude that FAP approach shows benefits also in large fields with one of the main pollinator independent crops, wheat. Incorporating MHEP in cereals production is a way to contribute to conservation of flower visitors in pollinator independent monocultures, benefiting future crop rotations and semi-natural land around. Additional future research is recommended to assess a wider range of MHEP plants in cereal production and to optimize the width and field percentage of MHEP strips in different landscape contexts. Since the study was conducted only in one year, the results may change over time. Income differences and natural enemies' effect on pest control, especially cereal aphids, may become apparent after years of using the approach. Thus, long-term studies are recommended to validate these findings across various environmental conditions, assess a broader range of MHEP species, and optimize MHEP strip designs in different landscapes.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary Material.

Ethics statement

The manuscript presents research on animals that do not require ethical approval for their study.

Author contributions

YB: Conceptualization, Data curation, Formal Analysis, Writing – original draft, Writing – review & editing. DM: Conceptualization, Data curation, Resources, Supervision, Writing – review & editing. MS: Investigation, Writing – review & editing. OI: Formal Analysis, Writing – review & editing. AA: Investigation, Writing – review & editing. AS: Investigation, Writing – review & editing. PR: Data curation, Resources, Writing – review & editing. SC: Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2025.1551190/full#supplementary-material

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