

Wild vegetation and 'farming with alternative pollinators' approach support pollinator diversity in farmland

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Abstract

Several management practices have been suggested to mitigate the global pollinator decline in agro-ecosystems, including wildflower strips and Farming with Alternative Pollinators (FAP). FAP proposes to dedicate 25% of the field area to seed Marketable Habitat Enhancement Plants (MHEP) around the main crop, occupying 75% of the field. However, wild pollinators may not rely fully on the resources that fields provide due to differences in flying period and host-plant preferences, and need additional resources from wild flowering plant communities. Here we aim to compare wild pollinator communities between FAP fields, monoculture of pollinator dependent crops and the nearby wild flowering plants. We developed two experimental trials with two main crops (faba bean and eggplant) in 16 fields in North-West Morocco and we compared wild pollinator richness and wild pollinator specialization between FAP fields, control fields and the nearby wild flowering plants. We recorded a significantly higher pollinator richness in FAP fields compared to wild flowering plants and monoculture. Pollinator specialization index (i.e. degree of interaction specialization at the species level) did not differ significantly between the three treatments in faba bean trial (i.e. FAP, control and wild plants), whilst in eggplant trial, wild plants harboured significantly more specialist species than FAP fields. Yet, no significant differences in pollinator specialization index were reported between the other treatments in eggplant trial (i.e. FAP vs. control and control vs. wild plants). Moreover, 28% of the pollinator species collected, were only observed on wild plants, particularly thistles. These results highlight the potential of FAP approach as a tool for pollinator conservation in farmlands. However, the FAP approach alone is not sufficient to cater the diverse pollinators present in the agro-ecosystem, and hence, the maintenance of the surrounding wild flowering plants is necessary to support pollinators in farmlands.

KEYWORDS

eggplant, faba bean, specialization, wild flowering plants

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1 | INTRODUCTION

Pollinator decline has stirred global concern (Goulson, 2019; Goulson et al., 2015; Potts, Biesmeijer, et al., 2010; Potts, Roberts, et al., 2010). Many recent studies were conducted to better characterize population trends, and to increase our understanding on the threats pollinators are encountering (agricultural intensification, pesticide usage, lack of semi-natural habitats and alternative host plants and climate change) (Biesmeijer et al., 2006; Hallmann et al., 2017; Mathiasson & Rehan, 2020; Potts, Biesmeijer, et al., 2010; Potts, Roberts, et al., 2010; Sánchez-Bayo & Wyckhuys, 2019). With the rise of concern, mitigating environmental pressures induced by human activities has become citizen and political priorities in many parts of the world (e.g. Folschweiller et al., 2019). Diverse global, regional and local mitigation strategies were suggested to support wild pollinators and boost their resilience especially in intensively managed agro-ecosystems (e.g. Farming with Alternative Pollinators and wildflower strips; Christmann & Aw-Hassan, 2012; Christmann, Aw-Hassan, et al., 2021; Christmann, Bencharki, et al., 2021; Christmann et al., 2017; Hipólito et al., 2019; MacIvor & Packer, 2015; Ouvrard et al., 2018; Sentil et al., 2021).

Some flowering crops (e.g. canola and sunflower) are a useful resource for wild pollinators (Nderitu et al., 2008; Thom et al., 2018). They compensate floral resource limitations (Todd et al., 2016) and can highly increase the abundance and species richness of wild bees in managed lands even when they are intensively managed (Holzschuh & Dormann, 2013; Iedinger et al., 2015; Rundlöf et al., 2014). However, mass-flowering crops benefit mainly generalist pollinators and not necessarily specialist flower visitors (Dieko et al., 2010; Holzschuh et al., 2011; Westphal & Tschardtke, 2009). Indeed, specialist pollinators have a limited number of host plants they can forage. If the crop does not belong to the group they can forage on and their native host plants are scarce or absent, they will be incapable to survive. Furthermore, most monocultures of pollinator dependent crops are not capable of sustaining pollinator populations due to their short flowering time period (e.g. canola and sunflower, Carvalheiro et al., 2011; Westphal & Tschardtke, 2009). Before and after this period, pollinators require additional nutritional intakes. Thus, mass-flowering crops alone cannot support all the pollinator species present in the agro-ecosystem nor cover the entire flying period of their flower visitors.

Extensive studies highlighted the importance of the maintenance of native wild flowering plants for the conservation of the local pollinator populations in farmlands (Dicks et al., 2015; Nicholls & Altieri, 2013; Wood, Holland, & Goulson, 2017). Wild flowering plant species provide various floral traits including pollen content (e.g. chemical composition; Vaudo et al., 2020), nectar (Carvell et al., 2007; Denys & Tschardtke, 2002) and phenology (Rundlöf et al., 2014). This wide range of floral traits can be associated to diverse and abundant pollinators and could prevent further losses of declining species (Grass et al., 2016; Öckinger & Smith, 2007). For instance, the research of Carvell et al. (2006, 2007) has demonstrated that sown wildflower plants increased the abundance and the

diversity of common and threatened bumble bees. For this reason, wildflower plantings have been introduced as an agri-environmental measure in several European countries to enhance pollinator biodiversity in the framework of Agri-Environmental Schemes (AES) subsidised by Common Agricultural Policies (CAP) (Haaland et al., 2011). Yet, despite their positive effects on biodiversity and ecosystem services, the high implementation costs of these schemes (Batáry et al., 2015; Christmann, 2020; Christmann et al., 2017; Kleijn et al., 2019; Uyttenbroeck et al., 2016) and their reliance on continued external funding have been broadly disputed. Adding to this, wildflower strips favour mainly generalist (i.e. able to forage on a wide diversity of plants), common pollinator species and not those that display a narrow dietary breadth (Kleijn & Sutherland, 2003; Wood, Holland, Hughes, et al., 2015). Even in areas where wildflower strips were more abundant than the nearby wild flowering plants, the abundance and the diet breadth of the solitary bee species were enhanced by the nearby wild flowering plants and not by the flower strips (Wood, Holland, & Goulson, 2017). In fact, the seed mixtures of wildflower strips were mainly tailored to provide resources for threatened bumble bee species, and thus the strips significantly affect bumble bee populations and not solitary bees (Wood, Holland, & Goulson, 2015).

Farming with Alternative Pollinators (FAP) (Christmann & Aw-Hassan, 2012; Christmann, Aw-Hassan, et al., 2021; Christmann, Bencharki, et al., 2021; Christmann et al., 2017) is an agricultural approach that focuses on farmers' priorities and motivates farmers to protect wild pollinators by demonstrating the additional net income induced by habitat enhancement for pollinators and natural enemies through Marketable Habitat Enhancement Plants (MHEP), nesting and water support. To maintain and restore pollinators in their fields, farmers are advised to dedicate 25% of their fields' areas to seed MHEP to provide diverse forage for pollinators and increase their incomes (Christmann, Aw-Hassan, et al., 2021; Christmann, Bencharki, et al., 2021; Christmann et al., 2017; Sentil et al., 2021). The MHEP may include fruits, spices, oil seeds, vegetables, medicinal plants and forage plants (e.g. melon, basil, sunflower, cucumber, rosemary and alfalfa). The selection of MHEP is based on their attractiveness to diverse pollinators (i.e. they should display various floral traits, including colour, shape, height...), their phenology (some MHEP should flower simultaneously with the main crop, some before and some after the flowering of the main crop) and farmer preferences. The FAP approach proved its effectiveness in increasing significantly pollinator communities, crop yield and income in several crop trials (e.g. faba bean, cherry and cucumber, Christmann, Bencharki, et al., 2021; Christmann et al., 2017). Since it does not require external funding, FAP approach is considered a durable, scalable and autonomous tool for pollinator conservation in agro-ecosystems and yield increase, applicable also in low- and middle-income countries, which cannot afford AES (Christmann, 2020).

Here we aim to assess the effectiveness of the FAP approach in supporting regional pollinator richness in comparison with monoculture of pollinator dependent crops (control) and the nearby native wild flowering plants. Specifically, we compare the diversity of wild

FIGURE 1 Experimental designs of FAP and control fields of faba bean trial in Settata in 2019. FAP field (faba bean planted in 75% of the field area surrounded by marketable habitat enhancement plants) in the left side. Control field (faba bean occupies the entire field area) in the right side. The two arrows in the 75% zone represent the 28 m transects and the arrow in the 25% zone corresponds to the 80 m transect (please see the experimental design of the eggplant trial in Appendix S2).

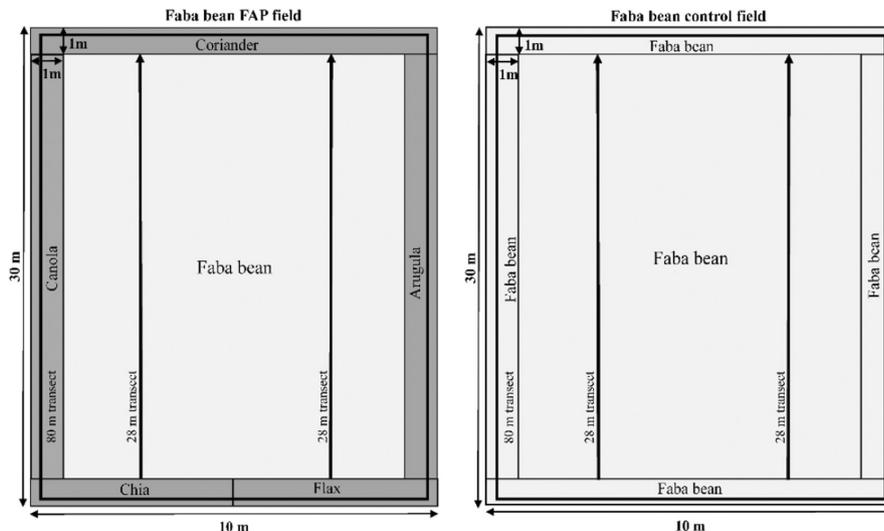


TABLE 1 Seeding and flowering time of the main crops (i.e. faba bean and eggplant) and marketable habitat enhancement plants

	Nov-18				Dec-18				Jan-19				Feb-19				Mar-19				Apr-19				May-19				Jun-19				Jul-19				Aug-19				Sep-19			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4				
Faba bean																																												
Coriander																																												
Canola																																												
Arugula																																												
Flax																																												
Chia																																												
Eggplant																																												
Coriander																																												
Sunflower																																												
Canola																																												
Zucchini																																												
Aneth																																												
Anise																																												

Note: The first row indicates the months and the years. The second row indicates the 4 weeks of each month. The dark grey represents the flowering period, the light grey the seeding time and the black bars the insect samplings.

pollinators between FAP fields (75% main crop + 25% MHEP), control fields (100% main crop) and the surrounding wild flowering plants occurring within a radius of 250m around FAP and control fields. In addition, we investigate whether the FAP approach can benefit specialist pollinators. We ask the following questions: (1) Do FAP fields host a higher pollinator richness in comparison to monoculture of pollinator dependent crops and the nearby wild flowering plants? (2) Do FAP fields support specialist pollinators? (3) What are the main wild flowering plant species that complement the floral resources provided by FAP fields and harbour specialist wild pollinator species?

We hypothesize that: (1) the FAP approach will be effective in supporting a higher pollinator richness in comparison to monoculture of pollinator dependent crops and the surrounding wild flowering plants; (2) similarly to wild plants, the FAP approach will benefit specialist flower-visitor species; (3) some nearby wild flowering plants will be vital to cater a wider array of pollinator species and for sustaining specialist pollinators.

2 | MATERIALS AND METHODS

2.1 | Study area

The study was carried out in 2019 in Morocco in two rural villages of Settata Province: Oulad Bouziri and Mzamza (latitude: 32.82175_32.9728 and longitude: -7.66524_-7.5171). The study area is semi-arid with average annual rainfall of 400 mm (Ministry of Agriculture, Fisheries, Rural Development, Water and Forests, 2018). The arable land in Settata was reported at 33.3% in 2018 (Direction Régionale de Casablanca-Settata, 2018), and most of the Moroccan farms (60%), are presented by small scale farms (i.e. <3 ha). Less than 1.3% of this cultivated land in Settata is irrigated. The landscape in Settata region is relatively homogeneous, dominated by intensively managed cereals (90) (DRCS, 2018). This region shows a low number of bee species (135 bee species) compared to other Moroccan regions (e.g. Marrakesh-Safi that hosts 494 bee species) (Lhomme et al., 2020).

2.2 | Study fields

Two main crops were used in this study; faba bean (*Vicia faba*) and eggplant (*Solanum melongena*). These crops are suitable candidates, as they attract diverse pollinator species (Marzinzig et al., 2018; Ormasari, 2018; Shebl & Farag, 2015), their flowering periods cover the foraging period of diverse pollinators in Settat (from February to July) and they are ones of the important pollinator dependent crops grown in the study region.

For each crop trial (i.e. faba bean and eggplant), we selected eight fields of 300 m² (30×10 m) (i.e. five FAP fields and three control fields), resulting in 16 fields (Appendix S1). These fields were owned by smallholders. The minimum distance between any two fields of the same crop was 400m. This distance corresponds to the maximum flying distance of the main pollinators groups (Elliott, 2009; Gathmann & Tschardtke, 2002; Wratten et al., 2003). The main crop in FAP fields was planted in 75% of the field area and marketable habitat enhancement plants (MHEP) were sown in the remaining area (25% zone), while the main crop in control fields (monoculture) occupied 100% of the field (Figure 1). The MHEP that were sown in the margins of faba bean were: flax (*Linum usitatissimum*), coriander (*Coriandrum sativum*), arugula (*Eruca sativa*), chia (*Salvia hispanica*) and canola (*Brassica napus*) (Figure 1). Eggplant in FAP fields was surrounded by canola, coriander, sunflower (*Helianthus annuus*), zucchini (*Cucurbita pepo*), anise (*Pimpinella anisum*) and dill (*Anethum graveolens*) (Appendix S2). Giving the different crop phenology and growing season (Table 1), it was not possible to have the same MHEP mixture for both crops. In order to attract a wide range of flower visiting species and provide pollinators with forage throughout their flying season, the selected MHEP had different blooming phenology (i.e. some MHEP bloomed simultaneously with the main crop, some before and some after the flowering of the main crop, Table 1), various morphological traits and high pollen and/or nectar content (Abd El-Wahab et al., 2012; Bommarco et al., 2012; El-Berry et al., 1974; Masierowska, 2003; Nderitu et al., 2008). Considering the limited number of MHEP that can be sown in the study region, the selected MHEP were the only plants meeting these two criteria. The seeding time of the main crops and the MHEP started from early November 2018 to mid-April 2019 (Table 1). Faba bean was grown using seeds, whilst eggplant was sown in seed-beds and 3 weeks later the seedlings were transplanted when they had developed three mature leaves. Fields were managed conventionally by farmers and the coordination between them was handled by the research team to ensure standardized farming practices, including the irrigation system, fertilizer and pesticide application.

2.3 | Pollinator survey

Flower visitors were recorded in FAP fields, control fields and wild flowering plants. FAP and control fields, and wild flowering plants were surveyed four times in faba bean trial and three times in eggplant trial during the flowering of the main crop and MHEP (Table 1).

All insect samplings were conducted between February and June 2019 (Table 1).

In each insect sampling, we surveyed two areas of FAP and control fields, the 75% zone (i.e. the main crop in FAP and in control fields) and the 25% zone (i.e. MHEP in FAP fields and the main crop in control fields). First, insect visits to the main crop in FAP and control fields were recorded along two 28m transects during 5 min/transect (Figure 1). In each transect, we collected the visitors landing on the flowers 2 m from each side of the transect, which cover the pollinators visiting the entire area of the main crop (i.e. 4 m width×28m length). Second, flower visitors in 25% of the field area in FAP and control fields were captured by walking at low speed for 10 min along a 1 m×80m transect (Figure 1), which cover the 25% zone in FAP and control fields. The timer was paused during the sampling in the 25% zone for the time to handle the pollinators caught in each MHEP and label the collected insects according to the MHEP they were collected from.

After each insect survey in FAP and control fields, pollinators visiting all the surrounding wild flowering plants occurring within a radius of 250m around FAP and control fields were sampled. The 250m radius covers the average flying distance of the main pollinator groups (Elliott, 2009; Gathmann & Tschardtke, 2002; Wratten et al., 2003). The sampling in wild plants nearby each field lasted 5–10 min depending on the presence and the abundance of wild flowering plants. However, given the homogeneity of the landscape in the study region (90% of the landscape area in Settat is intensively cultivated, mainly with cereals) and the low abundance of wild flowering plants, the pollinators of all the nearby wildflower plants occurring within a radius of 250m around the fields were surveyed. The timer was paused while handling insect specimens and identifying the plant species from which each flower visitor was collected. It was not feasible to determine the abundance of wild plant species surveyed due to time constraints.

With the exception of honey bees (*Apis mellifera*), bumble bees (*Bombus terrestris*) and carpenter bees (*Xylocopa pubescens*) that were identified visually, all insects that visited the flowers of crops, MHEP and wild flowering plants were sampled (when possible) using sweep net and vacuum, and subsequently killed with cyanide in a killing jar. They were later pinned, labelled and stored in insect collection boxes. The bees were identified in the laboratory to the lowest feasible taxonomic level (Michez et al., 2019), then most of them were sent to expert taxonomists for identification to species level. The remaining groups were identified to the possible taxonomic level in the laboratory using entomological publications (Borror & White, 1991). Honey bees were excluded from the database as their abundance could be biased by the presence of nearby hives (Kennedy et al., 2013).

2.4 | Statistical analyses

All statistical analyses were conducted in R software (version 3.6.3; R Development Core Team, 2020).

2.5 | Comparison of pollinator richness between FAP, control fields and wild flowering plants

We based our comparisons on pollinator richness, as it is the most reliable measurement of biodiversity (Chao et al., 2014). Since not all flower visitors were identified to the species level, we used the lowest taxonomic level available for the unidentified pollinators to compute the wild pollinator richness (i.e. genus or family for unidentified Hymenoptera and Diptera, and order for Lepidoptera specimens). Wild pollinator richness in the three treatments (i.e. FAP, control and wild flowering plants) was calculated using the visit data on wild flowering plants and the visit data on the whole FAP and control fields (i.e. addition of the three transects from the 75% zone and the 25% zone). To ensure reliable comparisons despite the uneven sampling effort between FAP fields, control fields and wild flowering plants, we applied an extrapolation method on the data. The extrapolation of species richness gives estimates of species richness based on the visitation frequency of pollinator species recorded in each single field and sampling (i.e. FAP fields, control fields and the sites where we sampled wild flowering plants) (Oksanen et al., 2019). The metric was computed for each crop trial separately. The formula to measure the metric is defined in Appendix S3. Contrary to rarefaction, extrapolation prevents the loss of additional information in the largest samples (Melo et al., 2004). We calculated the extrapolated richness for each sampling in each field using the 'estimateR' function of the 'vegan' package. Extrapolated richness values were used as a dependent variable in the following analyses.

Differences in pollinator richness between FAP, control and wild flowering plants were assessed using Generalized Linear Mixed Models (GLMM). Replicates were the three/four samplings conducted in each field, and field was included as a random effect. GLMM were fitted with a negative binomial error distributions using the function 'glmer.nb' from the lme4 package (Bates et al., 2015). The over-dispersion of the models was checked using the 'dispersion_glmer' function from the blmeo library (Korner-Nievergelt et al., 2015). Pairwise comparisons between the treatments (FAP, control and wild plants) were conducted using Tukey's post hoc multiple comparisons with the function 'glht' from the package multcomp (Hothorn et al., 2008).

2.6 | Evaluation and comparison of specialization index of pollinators between FAP, control and wild flowering plants

To account for the variation in plant phenology and seasonal changes in the activity period of pollinators, we constructed an interaction matrix for each trial (i.e. faba bean and eggplant) by pooling the pollinator records of all the transects from all the fields (i.e. the addition of the visit data of the four/three insect samplings, and all transects and fields for each trial). In each matrix, plant species (i) (MHEP, main crops and wild flowering plants) occupied rows and pollinators (j) occupied columns. The cells indicated the visitation frequency of pollinator species (a_{ij}).

To quantify the specialization of all pollinator species, we used the specialization index d' (Blüthgen et al., 2006), which is a standardized form of the Kullback-Leibler distance (d_j) (Kullback & Leibler, 1951). The specialization index d' is related to Shannon diversity. However, it does not only consider the diversity of partners, but also their respective availability (Blüthgen et al., 2006). Consequently, the specialization index compares the distribution of the interactions with each partner (p_j) to the overall partner availability (q_j). The formula for computing d' is presented in Appendix S3. High value of d' (>0.5) indicates specialist species (Blüthgen et al., 2006). Interaction networks were analysed using the Bipartite Package (Dormann et al., 2020). We employed 'Species level' function to calculate the specialization index.

The index was computed for all pollinator species in each visitation matrix. Within each trial, we compared the specialization index of pollinator species between the three treatments (control fields, FAP fields and wild plants) in faba bean and eggplant trials using one-way analysis of variance with the function 'aov' from the package car (Fox & Weisberg, 2019). When the differences were significant, we employed Tukey's post hoc test, using the 'TukeyHSD' function to determine the pairs of treatments that were significantly different. To meet the assumption of normality, the data (i.e. the specialization index) of faba bean was square root transformed and the data of eggplant was transformed with the function orderNorm within the package bestNormalize (Beasley et al., 2009).

2.7 | Pollinator species shared and unique between/to FAP, control and the wild flowering plants

Venn diagram was performed to visualize the number of pollinator species unique to wild flowering plants, FAP fields and control fields and the number of pollinator species shared between the treatments. We aggregated the visit data from faba bean and melon trials across all fields and samplings for each treatment separately (i.e. FAP, control and wild flowering plants). Due to the uneven sampling effort among FAP fields (20 min transects*5 FAP fields = 100 min), control fields (20 min transects*3 control fields = 60 min) and wild flowering plants (5–10 min transect*8 surrounding areas ≈ 60 min), we manually rarefied the visit data in FAP fields to ensure fair presentation of pollinator community in each treatment, which can be potentially biased by the sampling effort. Rarefaction was done by excluding randomly the data of two FAP fields. The Venn diagram package (Zheng et al., 2018) was applied to create the graph.

3 | RESULTS

We recorded a total of 1847 pollinator specimens, representing 101 species and morphospecies, belonging to 13 families and 35 genera, including six bee families and 25 bee genera (Sentil, 2022). 23, 333 and 1486 pollinator individuals were recorded in control fields, wild flowering plants and FAP fields, respectively (Appendix S4).

TABLE 2 List of the nearby wild flowering plant species and the number of floral visits recorded on each plant species during the two trials (i.e. faba bean and eggplant)

Wild flowering plant species	Family	Number of visits
<i>Sinapis arvensis</i>	Brassicaceae	94
<i>Silybum marianum</i>	Asteraceae	51
<i>Cynara scolymus</i>	Asteraceae	48
<i>Scolymus hispanicus</i>	Asteraceae	15
<i>Papaver rhoeas</i>	Papaveraceae	7
<i>Rapistrum rugosum</i>	Brassicaceae	6
<i>Cichorium intybus</i>	Asteraceae	4
<i>Carduus pycnocephalus</i>	Asteraceae	3
<i>Centaurea calcitrapa</i>	Asteraceae	2
<i>Eruca vesicaria</i>	Brassicaceae	2
<i>Rosmarinus officinalis</i>	Lamiaceae	1

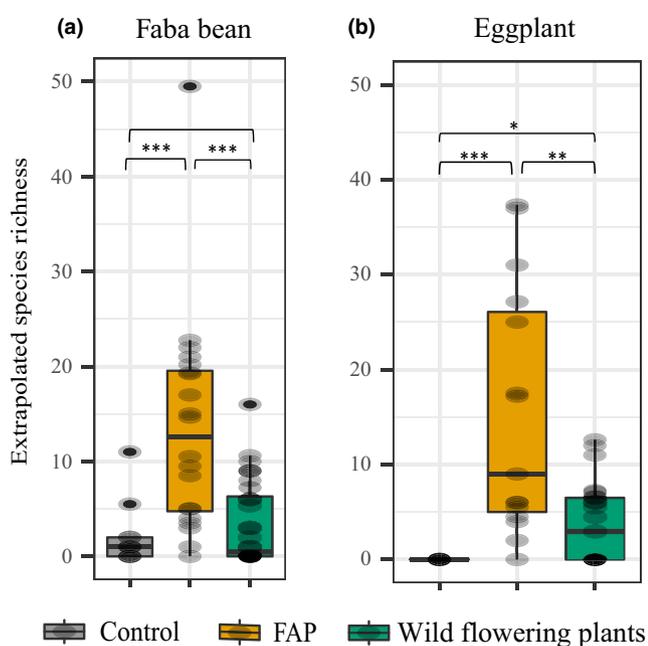


FIGURE 2 Wild pollinator extrapolated species richness in FAP (i.e. 75% main crop +25% marketable habitat enhancement plants), control (i.e. 100% monoculture of the main crop) and the nearby wild flowering plants in the two trials: (a) faba bean and (b) eggplant. Box plots show the median and 25–75% percentiles. Whiskers show all data excluding outliers. Outliers (circles) are values being more than 1.5 times box length from upper and lower edge of respective box. Asterisks indicate significant differences (post hoc Tukey test; * $p < 0.05$; ** $p < 0.01$, *** $p < 0.001$). [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

Halictidae, Andrenidae and Apidae represented 74% of the specimens recorded, the remaining individuals encompassed the following groups: other bees: 7% of the specimens recorded, Syrphidae: 5%, wasps: 13% (Sphecidae, Scoliidae, Vespidae, Pompilidae and Chrysididae) and Lepidoptera: 0.22% (Appendix S5). At the genus level, *Andrena* (Andrenidae), *Lasioglossum* (Halictidae) and *Eucera*

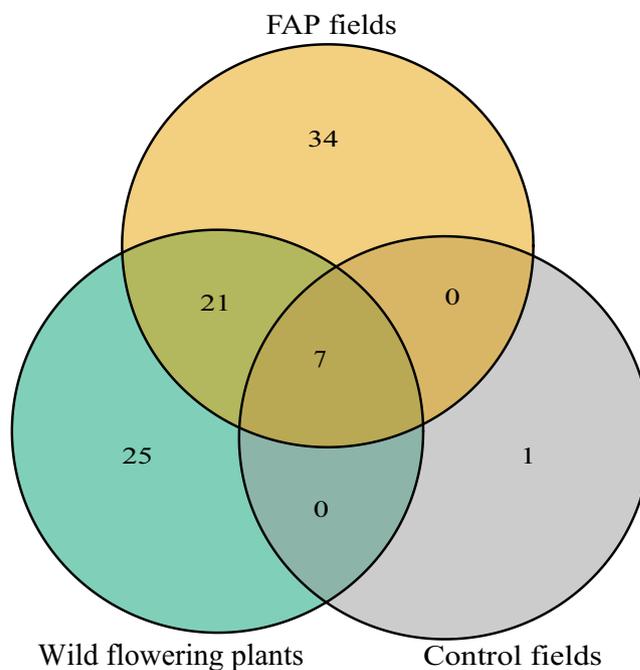


FIGURE 3 Venn diagram showing the wild pollinator species unique to FAP (i.e. 75% main crop +25% marketable habitat enhancement plants), control (i.e. 100% monoculture of the main crop) and wild flowering plants, and the pollinators shared between the three treatments. The flower-visitor species recorded in faba bean and eggplant trials (after rarefaction) were used in this graph. Wild pollinator species sampled in FAP fields are represented with the yellow circle, wild pollinators species collected in wild flowering plants are indicated with the green circle and wild pollinators collected in control fields are marked with the grey circle. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

(Apidae) represented 65% of the individuals collected (Appendix S6). The number of wild flowering plant species assessed during the two trials accounted for 11 species belonging to four families and 11 genera (Table 2).

3.1 | Pollinator richness and specialization index

Pollinators in faba bean and eggplant trials were significantly richer in FAP fields compared to control fields (Post hoc Tukey test in faba bean; $p = 4.3 \times 10^{-4}$; Figure 2a, in eggplant; $p = 1 \times 10^{-4}$; Figure 2b) and to wild flowering plants (Post hoc Tukey test in faba bean; $p = 4.45 \times 10^{-5}$; Figure 2a, in eggplant; $p = 7.67 \times 10^{-3}$; Figure 2b). When comparing control fields and wild flowering plants, wild pollinator richness was significantly supported by wild plants in eggplant trial (Post hoc Tukey test; $p = 0.031$; Figure 2b). Nevertheless, there was no significant difference in the richness between control fields and wild flowering plants in faba bean trial (Post hoc Tukey test; $p = 0.55$; Figure 2a).

The specialization index of pollinator species (d') did not vary significantly between FAP, control and wild flowering plants in faba bean trial (ANOVA test; $p = 0.507$). These results indicate that all treatments in faba bean trial attracted flower visitors with similar

specialization indices. In contrast to faba bean, the difference in the specialization index of pollinator species (d') between the three treatments in eggplant trial was significant (ANOVA test; $p = 0.54 \times 10^{-05}$). Indeed, wild flowering plants in eggplant trial hosted significantly more specialist flower-visitor species than FAP fields (Post hoc Tukey test; $p = 1.54 \times 10^{-05}$).

3.2 | Unique and shared pollinators between/to FAP, control and wild flowering plants

Among the 88 wild pollinator species recorded in the two trials (after rarefaction), only seven species were shared between FAP fields, control fields and wild flowering plants. The Venn diagram showed that each treatment had unique species: 38% of the total species number were only sampled in FAP fields, 28% were unique species on wild flowering plants and only one species was unique to control fields (Figure 3). A total of 32% of the pollinator species were shared between FAP fields and wild flowering plants, whilst control fields shared 7% and 7% of the total number of species with FAP fields and wild flowering plants, respectively (Figure 3).

3.3 | Key wild flowering plant species complementing the floral resources provided by FAP fields

Among the 11 studied wild flowering plant species, eight plant species were visited by pollinators that were not recorded in FAP fields and monoculture of pollinator dependent crops. Of these, *Silybum marianum* (Asteraceae), *Sinapis arvensis* (Brassicaceae), *Cynara scolymus* (Asteraceae) and *Scolymus hispanicus* (Asteraceae) were visited by 39%, 26%, 13% and 10% of the unique flower-visitor species recorded on these wild plants, respectively (Appendix S7).

From the 11 studied wild flowering plant species, four of them (all Asteraceae) hosted specialist flower visitors, (i.e. visitors with a d' higher than 0.5). These visitors are: *Scolymus hispanicus*, *Cichorium intybus*, *Cynara scolymus* and *Scolymus marianum* (Figure 4a,b).

4 | DISCUSSION

4.1 | Pollinator richness and specialization index in FAP fields, control fields and on wild flowering plants

In this study, we compared wild pollinator richness between monoculture of pollinator dependent crops (control), fields managed with the FAP approach (i.e. with 25% of the field with additional marketable plants) and the surrounding wild flowering plants. We demonstrated that there is a higher pollinator richness visiting FAP fields and wild flowering plants compared to monoculture.

These findings are in line with studies that have found that diverse floral resources offer improved floral rewards to wild

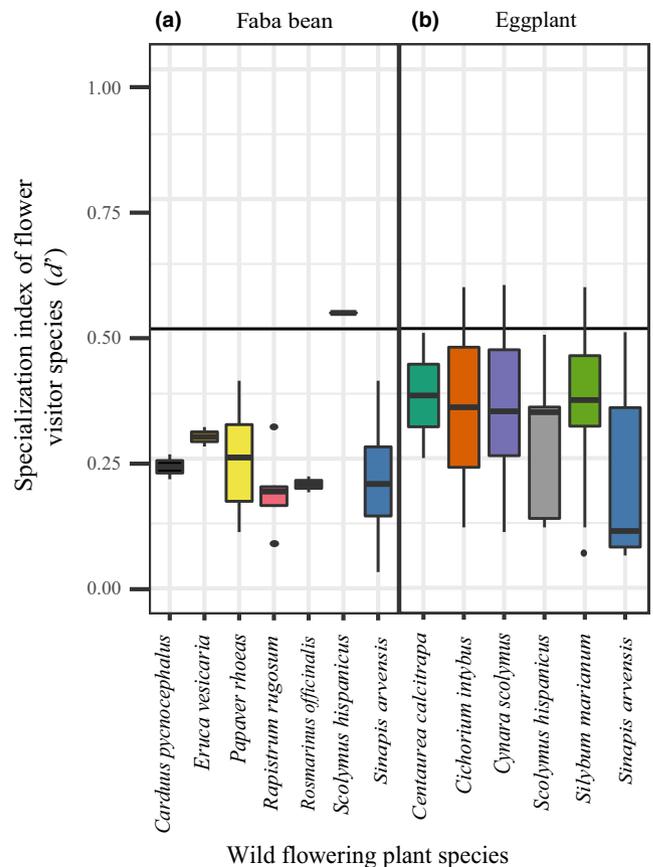


FIGURE 4 Specialization index (d') in each wild flowering plant species per trial. (a) d' in the seven wild flowering plant species sampled during faba bean trial. (b) d' in the six wild flowering plant species assessed during eggplant trial. Whiskers show all data excluding outliers. Outliers (circles) are values being more than 1.5 times box length from upper and lower edge of respective box. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1111/jen.13600)]

pollinators, which result in an increase in their richness (Albrecht et al., 2020; Christmann, Aw-Hassan, et al., 2021; Christmann, Bencharki, et al., 2021; Christmann et al., 2017; Fründ et al., 2010; Isbell et al., 2011; da Silva et al., 2012; Havens & Vitt, 2016; Sentil et al., 2021). This was also demonstrated in agro-ecosystems, where additional floral resources are established (e.g. MHEP, wildflower strips) (Christmann, Aw-Hassan, et al., 2021; Christmann, Bencharki, et al., 2021; M'Gonigle et al., 2015; Morandin & Kremen, 2013; Sentil et al., 2021; Sutter et al., 2017; Zamorano et al., 2020) or naturally occur (i.e. native wild plants; Blaauw & Isaacs, 2014; Haaland et al., 2011; Morandin & Kremen, 2013). Although monoculture fields may provide a large amount of floral rewards, a single plant is incapable to meet the nutritional requirements of a large group of pollinators, and it cannot cover provision for pollinators outside the blooming period (Vaudo et al., 2015). Therefore, it was expected that FAP fields and wild flowering plants host higher pollinator richness as they bloom longer (Table 1) and they show higher plant diversity. Moreover, FAP fields offer a high density of flowering plants, which maximizes the foraging efficiency of flower visitors and renders the approach more advantageous than wild flowering plants that

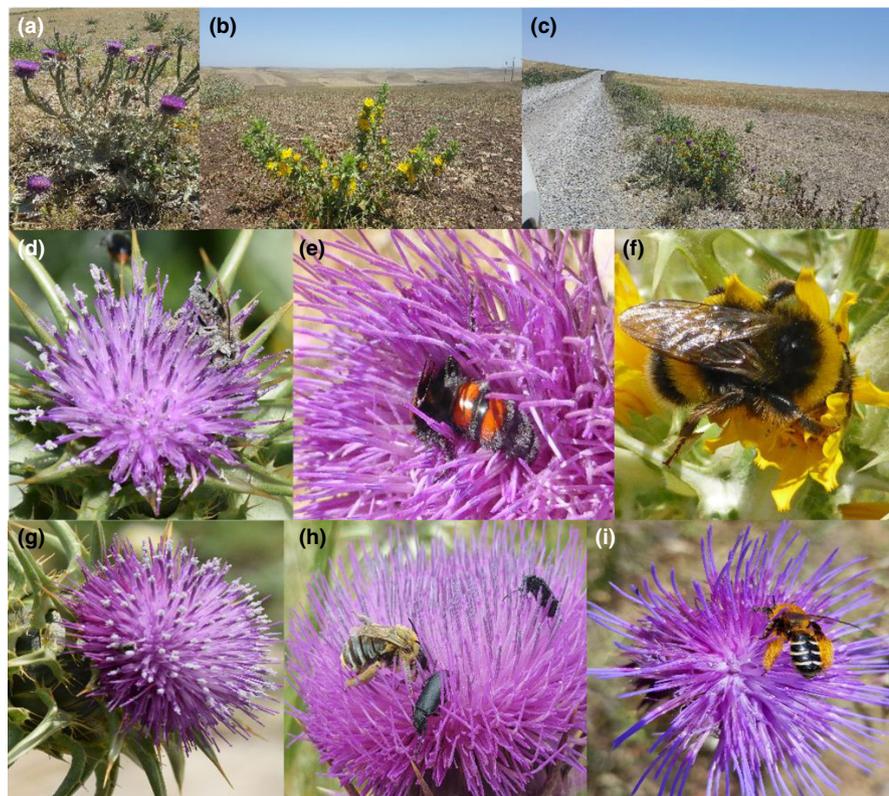


FIGURE 5 Photos of some wild flowering plants and insect visiting species observed during insect surveys. (a) *Cynara scolymus* (Asteraceae), (b) *Scolymus maculatus* (Asteraceae), (c) thistle plants occurring in field borders, (d) bee species foraging on a thistle plant, (e) *Megascolia bidens* foraging on *Cynara scolymus* (photo Rasmont Pierre), (f) *Bombus terrestris* foraging on *Scolymus* sp. (photo Rasmont Pierre), (g) thistle flower showing a great amount of pollen and (h) wild bee of the genus *Eucera* sp. and two beetles foraging on a thistle flower, (i) *Dasygaster maura* foraging on a thistle flower (photo Michez Denis). [Colour figure can be viewed at wileyonlinelibrary.com]

were represented by one or few individuals occurring in fragmented patches in, for example eggplant trial (Figure 5a–c). In fact, it is assumed that bees search and target the flowering patches that maximize the intake of calories per time to fly and forage (Waddington & Holden, 1979). Thus, flower visitors such as bees can discern and select the flower patch (e.g. FAP fields) that minimizes the flying distance and the time spent to find a new source of forage (Akter et al., 2017; Hendriksma & Shafir, 2016).

The absence of significant difference in wild pollinator richness between control and wild flowering plants in faba bean trial could be possibly explained by the dilution hypothesis (Tscharntke et al., 2012). More specifically, the flowering season of faba bean coincides with the occurrence of a widespread cover of wild flowering plants (e.g. *Sinapis arvensis*) in the surrounding landscape. Thus, local pollinator abundances in and around the fields of faba bean might not increase with increased cover of wild plants due to dilution of pollinator individuals in the landscape (Reverté et al., 2019), whilst in eggplant trial there were sparsely distributed patches of wild plants where flower visitors were concentrated and diverse, resulting in a significant difference in pollinator richness in favour of wild plants, compared to control fields, where no pollinators were recorded.

Differences in specialization index (d') were not significant between the three treatments in faba bean trial, indicating that similarly to native wild plants, FAP and control fields were effective at provisioning specialist pollinators as well. These results are in contrast to previous works on the impact of wildflower strips. Wood, Holland, Hughes, et al. (2015) demonstrated that this scheme benefits mainly generalist common pollinators and

do not cater the wider pollinator community (Wood, Holland, & Goulson, 2015, 2017). Nevertheless, the studies of Wood, Holland, and Goulson (2015), Wood, Holland, Hughes, et al. (2015) and Wood, Holland, and Goulson (2017) were conducted in temperate areas, whilst our study was carried out in Mediterranean area. The Mediterranean basin constitutes the extreme of a positive diversity gradient extending from the north to the south-Palaeartic (Patiny et al., 2009; Waser et al., 1996). One of the features that have been proposed to explain the polarity of the bee diversity gradient (i.e. the higher pollinator diversity in the Mediterranean basin compared to temperature area) is the increase in specialization from the north to the south-Palaeartic (Minckley et al., 2000; Patiny et al., 2009), which results in difference in pollinator communities (i.e. polylectism or oligolectism) between mesic (e.g. Europe) and xeric areas (i.e. Morocco). The absence of significant difference in the specialization index between FAP, control and wild plants in faba bean trial could be tied to the morphology of faba bean flower. Indeed, faba bean flower is characterized by a deep and curved nectar tube that enable only longue-tongued pollinators (e.g. *Anthophora* and *Bombus*) to reach the floral rewards (Goulson & Darvill, 2004). Longue-tongued pollinators, particularly bees, are considered to be more specialized in their pollen host-plant selection than short-tongued species (Michez et al., 2019), which could explain the absence of difference in d' between the treatments.

Contrary to faba bean trial, the specialization index differed significantly between the treatments in eggplant trial. This result could be associated to the high number of wild flowering plant species nearby eggplant trial that were hosting specialist species (Figure 4b)

compared to wild plants adjacent to faba bean trial (Figure 4a). Previous research demonstrated the vital role of wild plants in hosting specialist species that have a limited host-plant preferences (e.g. *Dasygaster visnaga*, *Colletes ligatus*, *Hoplitis adunca*, *Andrena vaga*; Bischoff, 2003; Burger et al., 2010; Müller & Kuhlmann, 2008; El Abdouni et al., 2021).

We acknowledge that pollinators were surveyed over a short time-frame. As sampling duration affects directly the number of species and the interactions that form the network (Fründ et al., 2016), we assume that some pollinators would be regarded as more generalist if surveys were conducted over larger special scale and longer periods.

The pollination service was not assessed in our study. However, pollinator visits are a reliable predictor of pollination service (Garibaldi et al., 2013). As our study demonstrated a higher pollinator richness in FAP fields in comparison to control fields in both crop trials, we assume that the pollination service was positively affected by the FAP approach, especially that the research of Christmann, Bencharki, et al. (2021) showed a significant income increase in faba bean and eggplant in response to the FAP approach in Morocco.

4.2 | Unique and shared pollinators between/to FAP fields, control fields and wild flowering plants

Wild plant species shared 28 flower-visitor species with FAP fields. 34 and 25 species were unique to FAP fields and wild flowering plants, respectively, whilst only one species was unique to control fields. These findings shed light on the success of FAP approach that utilizes MHEP in hosting a high number of unique pollinator species and outline the role played by the surrounding wild flowering plants in catering the remaining flower-visitor species. The FAP approach may offer good resources for flower visitors, yet additional resources are necessary for two reasons. First, pollinators shared between the two systems still need to complement their diet with alternative forage resources (i.e. wild flowering plants). Indeed, crops and MHEP (canola, coriander, arugula, sunflower and faba bean) were not the only source of forage for the generalist bee *Bombus terrestris* along the course of the study, but also wild flowering plants (*Cynara scolymus*, *Scolymus hispanicus* and *Silybum marianum*). This result is consistent with a case study by Requier et al. (2015) who showed that even when the generalist honey bee *Apis mellifera* was using highly rewarding crops like canola and sunflower, wild plants played a major role in supplementing its diet. Furthermore, based on pollen load analyses of faba bean flower visitors (Sentil et al., 2022) we found that the surrounding wild flowering plants (e.g. *Centaurea* sp., *Sinapis* sp., *Papaver* sp.) were clearly offering supplementary pollen resources to these visitors. Second, oligolectic species require specific plant species to meet their entire nutritional needs (Cariveau et al., 2021). For instance, *Andrena obsoleta* that was classified as oligolectic species on Brassicaceae (Wood & Roberts, 2017), was only recorded on *Sinapis arvensis* (Brassicaceae) during eggplant trial. Thus, even if MHEP support a high pollinator richness due to their

high attractiveness, they cannot benefit all pollinator species present in the agro-ecosystem.

4.3 | Key wild flowering plant species complementing the floral resources provided by FAP fields

Our results showed that eight wild flowering plant species, particularly three thistle species (*Silybum marianum*, *Cynara scolymus* and *Scolymus hispanicus*) and one Brassicaceae (*Sinapis arvensis*), catered a great proportion of species that were not recorded either in FAP or control fields. Almost the same thistles (*Silybum marianum* and *Scolymus hispanicus*) in addition to *Cichorium intybus* and *Cynara scolymus*, were hosting specialist pollinators.

A large number of studies highlighted the role played by thistle plants in providing copious floral resources to many important pollinator taxa, such as bumble bees (Vray et al., 2017), other bees (Michez et al., 2004; Müller & Kuhlmann, 2008; Wood & Roberts, 2018), beetles (Lyle & Schultz, 1960), butterflies (Haaland et al., 2011), flies and wasps (Proctor & Yeo, 1973). Their attractiveness could be attributed to the high sugar concentration of the nectar (Tartaglia & Handel, 2014) and the particular chemical composition of the pollen leading to host-plant specialization (Vanderplanck et al., 2018). Furthermore, the strong resistance to drought, the ability to grow in very poor soils, the hard spines that prevent the grazing animals to feed upon them, make these plants a major foraging sources for pollinators when other wild flowering plants are absent (Long, 1941). The patches of these species, occurring frequently on relatively degraded sites nearby crop fields (Figures 4c and 5a,b), help sustaining pollinators and allow sufficient numbers to survive (Haaland & Gyllin, 2010; Kapkoti et al., 2016). Moreover, regarding *S. arvensis* (wild mustard), we recorded a wide variety of insect species visiting it. A similar result was found in other studies (Hochkirch et al., 2012; Mulligan & Bailey, 1975; Warwick et al., 2000). This diversity could be explained by the high number of flowers of wild mustard, the high reflectance of the petals in the yellow and the strong smell secreted by the flowers (Hochkirch et al., 2012). Besides that, wild mustard was the first wild plant to emerge (February) and was occurring everywhere in the study region.

Regarding specialization of pollinators visiting wild plants, mainly thistle plants were visited by species with a high d' , which supports the findings of other authors (El Abdouni et al., 2021; Hopwood et al., 2015) that thistles such as *Scolymus hispanicus* and *Scolymus marianum* harbour specialist pollinator species. This result can be associated with the pollen properties of Asteraceae that shape plant selection by bees (Praz et al., 2008; Sedivy et al., 2011; Vanderplanck et al., 2018). Specifically, flower shape of Asteraceae enables diverse flower-visitor species to easily access both pollen and nectar without the need for specialized morphological structures (Müller & Kuhlmann, 2008). However, to protect floral rewards from excessive pollen harvesting by generalist bees, plant species from Asteraceae display special chemical and mechanical defences (e.g. nutrient

deficit or toxic compounds) that render the pollen unfavourable for polylectic species (Genissel et al., 2002; Müller & Kuhlmann, 2008; Praz et al., 2008; Sedivy et al., 2011; Vanderplanck et al., 2018; Vanderplanck et al., 2020).

Our study demonstrated that the FAP approach was significantly effective in supporting pollinator richness compared to monoculture field and the surrounding wild flowering plants. Nevertheless, some wild plant species (e.g. thistles and wild mustard) supported a wide range of pollinator species catered in the agro-ecosystem. These results, underline the importance of considering and maintaining the described wild flowering plants (i.e. species that provision unique and specialist pollinator species) to complement the floral resources delivered by FAP fields, and hence benefiting the widest range possible of flower-visitor species. MHEP are acceptable for farmers, while they greatly dislike wildflowers even with payment from AES (Kleijn et al., 2019) or simply reject them (Christmann et al., 2017). Farmers, who once learned the value of wild pollinators through FAP, assessing also the significant and substantial net income increase in comparison to control fields (Christmann, Aw-Hassan, et al., 2021; Christmann, Bencharki, et al., 2021; Christmann et al., 2017), might be more easily convinced not to eradicate these wild plants than farmers not aware of the economic value of wild pollinators.

AUTHOR CONTRIBUTIONS

AS, DM and PL conceived the structure of the manuscript. Statistical analyses have been performed by AS and SR. Field work has been made by AS and YB. Data management has been made by PR. SC developed FAP, designed and coordinated the project. All authors have read the manuscript, participated in the revisions and approved the final version.

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CONFLICT OF INTEREST

The authors have no competing interests to declare that are relevant to the content of this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in Figshare at <https://doi.org/10.6084/m9.figshare.19333487.v1>

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SUPPORTING INFORMATION

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