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Small floral patches are resistant reservoirs of wild floral visitor insects and the pollination service in agricultural landscapes

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ABSTRACT

Small floral patches that coexist with crops in agricultural landscapes can function as biodiversity reservoirs. However, the influence of the landscape context and agricultural management on the capacity of these small green infrastructures to support diversity is poorly understood. Here, we evaluate the effect of landscape simplification, agricultural intensification in the neighbourhood, and quality of the floral habitats on the success of these patches to support flower-visiting insect communities as well as the pollination service they provide.

To this aim, we sampled floral patches located in 18 paired olive farms with contrasting herb cover management (intensive vs. low-intensity), distributed along a wide gradient of landscape complexity at the regional scale of South Spain. We conducted surveys of flower-visiting insects in 36 multi-floral stands and 36 mono-floral stands of *Sinapis alba* Linnaeus (1753) within these floral patches. Mono-floral stands were used to evaluate variations in the pollination service through number of viable seeds and seed set.

Results revealed that the abundance and diversity of flower-visiting insects respond to the quality of the floral patch (diversity of flowers) but not to landscape context nor agricultural management around it. Moreover, the pollination service was similar and high (seed set ca. 100 %) in all floral patches regardless of their context.

Our findings highlight the importance of even small floral patches that function as reservoirs of diversity of flower-visiting insects and the pollination service. They also show the high resistance of these patches to agricultural intensification and simplification in olive grove landscapes.

1. Introduction

Semi-natural habitats constitute an essential element within agricultural landscapes that have shown a great potential as reservoirs of biodiversity and ecosystem services, such as floral visitor insects and pollination. Even small floral patches and linear green structures such as road verges, field edges or small hedgerows have demonstrated an important role for farmland arthropod diversity (Boetzl et al., 2021; Kleijn et al., 2006). The maintenance of these green structures plays a very important role for floral visitors because, in addition to providing spatially and temporally heterogeneous food and nesting resources (Holland et al., 2016; Martínez-Núñez et al., 2022), these areas buffer the continuous disturbances occurring in cultivated areas (Park et al., 2015). These attributes make semi-natural areas an important landscape component to preserve taxonomic and functional diversity of floral visitor insects. In fact, environmental legislation aiming to conserve farmland diversity by promoting set-aside areas in crops has proven successful (Albrecht et al., 2020). However, the potential of semi-natural areas to maintain diverse floral visitor communities is expected to be moderated by several factors such as landscape context, the intensity of farming management in the surrounding crop area and the quality of these areas (Bartual et al., 2019; Garratt et al., 2017; Larkin and Stanley, 2021). Studies in this regard have focused on annual row crops (e.g., Garratt et al., 2017; Li et al., 2020). The knowledge available in this respect about perennial permanent tree crops is scarce, especially for perennial non-pollinator-dependent crops such as olives, a socioeconomically key agroecosystem in Southern Europe.

Olive groves cover extensive areas in the Mediterranean being a crucial agroecosystem for the conservation of biodiversity (Martínez-Núñez et al., 2020a, 2020b; Rey et al., 2019; Tscheulin et al., 2011) and for the provision of ecosystem services (Martínez-Núñez et al., 2021a, 2021b), in the Mediterranean biodiversity hotspot. However, because olive trees are wind-pollinated, floral visitors have received very little attention in this agroecosystem even though they are still essential here

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for several reasons. First, they help the conservation of wild plant communities and the pollination of coexisting crops such as almond trees in these landscapes. Second, they indirectly ensure many in-farm key ecosystem services such as the mitigation of soil nutrient runoff, the protection against soil erosion or pest control, through supporting plant communities that constitute the natural herb cover in these permanent agroecosystem (Palese et al., 2014; Tarifa et al., 2021; Wratten et al., 2012). Potts et al. (2016) indicated that Mediterranean olive orchards with environmentally-friendly management constitute an agroecosystem with a great potential to host diverse plant-floral visitor communities. Studies have also begun to explore the effect of landscape context on wild bee communities in olive groves (e.g. Tscheulin et al., 2011) and plant-solitary bee networks (Martínez-Núñez et al., 2019). Martínez-Núñez et al. (2020a) studied the effect of the interplay between the olive grove ground herb cover management and the landscape-complexity on above-ground nesting bees. In addition, it has been shown that an important group of floral visitors, the megachilid bees, can be good bioindicators of management regime and ecosystem recovery in olive orchards (Martínez-Núñez et al., 2020b). However, to our knowledge, no study has addressed the effect of landscape complexity, farming practices and habitat quality on the role of floral patches as reservoirs for the whole flower visitor insect community, or the vulnerability of these communities and the pollination ecosystem service to local and landscape perturbations.

In this study, we evaluate how landscape simplification and management intensity affect the floral visitor community and the pollination service in small floral patches interspersed within olive grove landscapes. Our design allows us to understand the vulnerability and resilience of these small wild plant and floral visitor insect communities to local and landscape perturbations in agricultural landscapes. To this aim, we surveyed the whole floral visitor community in small multi-floral patches located on 18 paired olive farms with different herb cover and soil management (intensive vs low-intensive) along a gradient of landscape complexity. Simultaneously to these surveys, we also assessed floral visitors, number of viable seeds and seed set in mono-specific patches of *Sinapis alba* L., a ubiquitous plant species used in this study as model to assess variations in the pollination service. We hypothesize that: (a) landscape simplification and intensive herb cover management on the olive farms will decrease richness and abundance of floral visitors in floral patches; (b) landscape context and herb cover management on olive farms will affect floral visitor community composition in these floral patches; and (c) as a result of these effects, the pollination service in these floral patches will be limited by landscape simplification and management intensification. Alternatively, if these floral patches are highly independent from their surroundings and fragmentation does not affect these communities much, we should find that patch quality (abundance and richness of flowers) determines floral visitor abundance/richness, regardless of landscape and agricultural practices. This would emphasize the high resilience and important role of these floral patches as reservoirs (sensu Brosi et al., 2008) for floral visitor insects and plant communities in olive groves.

2. Materials and methods

2.1. Study site and experimental design

This study was conducted in 2018, in olive-growing areas of Andalusia, southern Spain. Andalusia is the region with the largest area dedicated to this culture in the world, with >1.5 million hectares. The sampled farms ranged from 5°4877″W to 2°6487″W and 38°4005″N to 36°9878″N. In particular, we chose 18 paired olive farms located in 9 localities (Supplementary Fig. A1). These farms are part of the study system of the LIFE project OLIVARES VIVOS, which has been largely described elsewhere (Rey et al., 2019; Martínez-Núñez et al., 2021b). Briefly, the two farms in each locality are within a circle of 2 km radius, therefore, with the same overall large-scale landscape. Mean distance between farms within localities was 1540 m (ranging 537–3389 m). Localities were chosen to encompass an ample gradient of landscape variation (range of semi-natural habitats cover: 0–37 %; range of olive grove cover 31–92 %), and on average were separated 56.3 ± 30.3 km (ranging 9.7 to 121.5 km). Each pair of olive farms is constituted by a farm with low-intensive herb cover management and a farm with intensive herb cover management. The low-intensive management consists of the maintenance of herb cover during most of the year being only removed in late spring by mechanic mowing or cattle (Supplementary Fig. A2a). Conversely, the intensive management consists of removing the herb cover permanently by using pre-emergence and/or post-emergence herbicides, sometimes in combination with ploughing the ground several times a year (Supplementary Fig. A2b). Low-intensity management typically used low levels of pesticide use if any, while intensive management applied high level of herbicides and other pesticides (e.g. insecticides); however, these intensification categories should not be truly assimilated to organic and conventional farming. These different ways to manage the herb cover in the olive orchard affects both herb species richness and cover percentage (Rey et al., 2019; Tarifa et al., 2021). In this study, the mean of herb cover in the low-intensive management was 40.5 ± 4 %, and for the intensive management was of 17.7 ± 3.97 %. All the olive farms here were of at least 7 × 8 m tree plantation frames. Ground-herb cover elimination, leaving soils uncovered, represents the most widespread and harmful intensive practices in Andalusia (Rey et al., 2019; Vilar et al., 2018).

Within each farm, we considered two multi-floral patches or stands (composed of a variety of flowering herbs) and two mono-floral stands (composed only of *Sinapis alba*) that were separated at least 150 m. Overall, size of these small floral stands were < 100 m^2. The area sampled within each floral stand was 10 m^2 (generally 2 × 5 m), big enough to get representative estimates and easily covered by one person during the survey. This area ensured a standardised sampling in all the olive farms. Mono-floral and multi-floral stands were located on different semi-natural flowering patches whenever possible and were most frequently in some unproductive areas of the farm or close to field margins. They remained unmanaged during the study.

Response of biodiversity (also of pollinating insects) to anthropogenic alteration may be dependent on the scale of examination (Dainese et al., 2015). To explore the influence of landscape complexity/quality on floral visitors and pollination service at different scales, we considered the following levels of variation: 1 km radius centred in each farm; 250 m radius around the floral stands within the farms, 100 m radius around floral stands, and the floral stands themselves. We characterized the complexity/quality of the landscape and stand at each of these levels considering several landscape and/or floral stand metrics. For 1 km radius, 250 m radius and 100 m radius scale characterization, we used recent land-use cartography (data from SIOSE 2016 available at http://www.juntadeandalucia.es/medioambiente/site/rediam/) and measured within buffers of their respective dimensions the cover (proportion) of forest and semi-natural habitat (road verges, field edges, hedgerows, meadows, grasslands and forest areas) using a GIS platform (QGIS v.2.14). Furthermore, we evaluated within the 250 m and 100 m buffers the cover of floral habitat (meaning the floral elements on road edges, farm boundaries, field margins and small semi-natural meadows) by manual digitalization using the most recent orthophotos in Google Earth. All these metrics were thought to be useful as landscape compositional variables related with suitable habitats that provide nesting and food resources to floral visitors (Tscheulin et al., 2011). Finally, at the floral stand level, we used the diversity and abundance of flowers in the stand as habitat-quality variables. We estimated visually, previously to each floral visitor census, the flower cover in the whole stand and the occurrence of each flowering species within the 10 m^2 area of each stand used for floral visitor censuses.

2.2. Floral visitor surveys in multi-species floral stands

Floral visitor surveys were conducted in multi-species floral stands to evaluate the floral visitor community structure in each olive farm. We selected thirty-six 10 m^2 multi-floral stands (2 stands per olive farm). Surveys were carried out once monthly from March to May (three rounds of sampling in total per patch, one round per month), matching with the flowering period of the wild white mustard, *S. alba*. We ensured that the weather conditions during the surveys were standard and appropriate (sunny days, wind speed below 5 km/h and temperatures above 18 °C). This period of censuses is sufficient to depict a complete picture of flower visitors in olive grove landscapes since the study area is characterized by a dry Mediterranean climate with a rainy season during winter and spring (when the flowering period begins), while the summer is extremely hot and dry. This means that flowers become normally very scarce in June (when some study localities already reach temperatures of ca. 40 °C) due to severe temperature and drought. The surveys consisted of recording the floral visitor species and their abundance in each floral patch for 15 min in the morning (until 13 h pm) and for 15 min in the afternoon (until 17 h pm) every sampling round. Insects unambiguously identifiable in the field were recorded and the others were caught with a hand net and conserved for later identification to species or morphospecies level in the laboratory. Morphospecies were mainly assigned to the genera *Andrena* and *Lasioglossum* (see characterization of morphospecies in Supplementary List A1), due to the lack of determination keys for these groups in the Iberian Peninsula. In any case, we tried to be as conservative as possible in determining the species richness by taking into account only females to define morphospecies, so the species richness was not overestimated.

2.3. Floral visitor surveys in Sinapis alba stands

Floral visitor surveys were also conducted in mono-specific floral stands of *S. alba* aiming to assess its relationships with the pollination service provided by the floral visitors in these floral patches. *S. alba* was selected as species model in our study system to assess the pollination service for several reasons: 1) it is an abundant herb species, widely distributed in the olive-growing area in this region; 2) it is a generalist plant that receives a high number of different floral visitor species (Karamaouna et al., 2019); 3) it is a self-incompatible species (Olsson, 1960); and 4) it has important functions and economic uses. For instance, *S. alba* decreases soil erosion through soil retention, it can be used for biofuel production and is known to control verticillosis, a widely-extended fugal disease killing olive trees (Saavedra et al., 2015).

We selected thirty-six 10 m^2 mono-specific stands of *S. alba* (2 stands per olive farm). Surveys were carried out in the same way as the floral visitor surveys in multi-specific floral stands with some exceptions: in each stand, five individuals of *S. alba* were selected and marked with ribbons around the stems. In each of these five individuals, we recorded the floral visitor diversity and abundance for 3 min (15 min in total per stand).

2.4. Pollinator effectiveness

In order to have a proxy of the pollination effectiveness of floral visitors, we firstly assigned an effectiveness value ranging from 1 (low pollination efficiency) to 5 (maximum pollination efficiency) to each insect species according to their behavioural (number of flower visited, the time spent per flower and the foraging behaviour on the flower) and physical features as pollinators (hairiness, presence of pollen carrying structures, etc). Specifically, the categories were coded as: 1, accidental pollinator, without specialized structures, eating flowers or standing on them by accident (e.g., spiders or some beetles); 2, opportunistic pollinators, insects with non-specialized structures and little capacity to visit different plants, but some potential to pollinate (e.g., some ants); 3, regular pollinators, flying insects with few specialized structures which contact flower reproductive structures in a limited way (e.g., some syrphids); 4, good pollinators, flying insects with specialized structures that collect pollen actively, but whose effectiveness for each specific flower is limited to some extent by their wide flower foraging niche, involving relatively short time visits to each plant species (e.g., many generalist bee species); and 5, efficient pollinators, flying insects with specialized structures that collect pollen actively and visit many flowers of specific groups of plants (most of Apidae and Megachilidae species in this study). Ascription of each species/morphospecies of flower visitor to a given effectiveness category is shown in Supplementary List A2. Then, we calculated the community-level pollinator effectiveness at the floral stand level by multiplying the abundance of each species by their coded-specific effectiveness value.

2.5. Seed set of Sinapis alba

We used the mean number of viable seeds per plant and the seed set in *S. alba* as proxies of the pollination service provided by floral visitors in olive orchards. Seed set is typically considered an appropriate proxy of pollination service on flowering plants and was preferred to fruit set because aborted fruits are rare in this species in the field. To measure the seed set in *S. alba*, a total of twenty fruits were collected along the entire length of the stem of each plant marked in each mono-specific patch of *S. alba* (3600 fruits in total). The fruits were collected in June, when they were completely dry and ripe. Subsequently, the fruits were opened in the laboratory and the seeds were counted and classified as viable (round, symmetric and dark colour) and non-viable (aborted seeds) thus obtaining the seed set per each plant, patch and farm. In total, 16,960 seeds were inspected. Unclear seeds (asymmetric, decoloured or too small; ca. 800) were germinated on Petri plates to check their viability, following the protocol in Abdollahi and Jafari (2012).

2.6. Statistical analysis

To analyse the effect of management and landscape complexity separately on diversity and abundance of floral visitors and the pollination service within floral patches we used three data sets: a) a data set with the floral visitor surveys conducted in multi-floral stands to analyse diversity, abundance and composition of the floral visitor community; b) a data set with floral visitor surveys carried out in mono-floral stands of *S. alba* to analyse the influence of the diversity and abundance of floral visitors on the pollination service (i.e., number of viable seeds and seed set); and c) a data set to test the effects of management and landscape complexity on the pollination service. Data of the floral visitor surveys were pooled over sampling rounds.

The effect of farm management and landscape complexity/quality at different scales on all these response variables were tested using linear mixed models (LMM) with ‘lme4′ (Bates et al., 2015) in R. Normal distribution was always considered, with seed set being arcsine square root transformed. Model assumptions were checked by inspection of residuals with ‘DHARMa’ package.

We grouped the landscape/floral stand explanatory variables into three groups according to the landscape scale levels considered. At the floral stand level (10 m^2 floral patch), we used floral cover and herb richness within the stand; in the case of pollination service, we included as explanatory variables for the stand level the diversity and abundance of floral visitors in the 10 m^2 patch instead of the floral stand quality variables (floral cover and herb richness), since the floral cover in mono-floral stands were composed only of *S. alba*. At 100 m radius scale, we considered the floral habitat cover surrounding each sampling stand. At 250 m radius scale, we used proportion of semi-natural habitats, natural forest areas and floral habitat cover surrounding the floral stand. Finally, at 1 km radius scale, we considered the proportion of natural forest areas in a 1 km buffer centred in the centroid of each farm. See Supplementary Table A1.

Agro-ecological theory and empirical evidence suggest that the effect of the intensification of the agricultural practices on biodiversity is frequently moderated by the landscape context (Tscharntke et al., 2005; Rey et al., 2019). Accordingly, we were particularly interested in exploring main and interaction effects of management and landscape degradation/quality at different scales (stand, 100 m radius, 250 m radius, and 1 km radius levels). Consequently, we generated at each level of landscape several models that included, both separately and in interaction (first order interaction only), herb cover management and the complexity/quality descriptors, and tested each of these models against the null model (including only the locality random factor) using AICc that penalizes overparameterization. To avoid multicollinearity, we previously explored the relation between all explanatory variables (Supplementary Table A2; see also Supplementary Fig. A3), and found a strong correlation between floral habitat cover at 100 m and 250 m buffers ($R^2 = 0.81$) and between the proportion of semi-natural habitat and the proportion of natural forest area at 250 m buffer ($R^2 = 0.75$). Therefore, we removed floral habitat cover at 100 m and semi-natural habitat at 250 m buffers from the analyses.

A model selection based on ΔAICc was carried out to choose the best model for each response variable among all models that are better than the null models. The comparison of each competing model against the null model was conducted using the *dredge* function from '*MuMIn*' package (Barton, 2015). Those models that differed in AICc ≥2 were considered equally valid, in which case we opted for the most parsimonious or the one that contained the most ecological sense. Diversity, abundance, effectiveness of pollinators, and pollination service, measured using mean number per fruit of viable seeds and seed set of *S. alba*, were used as response variables.

Lastly, using '*vegan*' package (Oksanen et al., 2020) we conducted a non-metric multidimensional scaling ordination (NMDS; Quinn and Keough, 2002) to explore the variability on species assemblages of floral patches due to the farm management and the type of sampling stand (multi-floral vs. mono-floral of *S. alba*). Similarities were calculated using Bray-Curtis coefficients.

All analyses were run with R 3.6.1 (R Core Team, 2019) using '*ggplot2*' for graphic representation (Wickham, 2016).

3. Results

A total of 167 species of floral visitors were recorded out of 4328 individuals belonging to 5 Orders (Coleoptera, Diptera, Hemiptera, Hymenoptera and Lepidoptera) (Supplementary List A2). The most abundant and diverse group was the wild bees (Anthophila) with a total of 73 species and 2302 individuals (43.71 % and 53.19 % of the total respectively), followed by the Diptera and Coleoptera groups. Diptera was represented by 30 species and 960 individuals (22.18 % and 17.96 % of the total) belonging to 10 families, highlighting bee flies (Bombyliidae) with a total of 13 species and 718 individuals (7.78 % and 16.59 % of the total). Coleoptera was represented by 29 species and 720 individuals (17.36 % and 16.64 % of the total). The least common groups were Lepidoptera and Hemiptera, comprising altogether 17 species and 196 individuals (10.17 % and 4.53 % of the total). These assemblages of floral visitors (Supplementary Table A3) visited 91 flowering species belonging to 73 genera and 23 families (Supplementary List A3). Overall, we observed a higher abundance of floral visitor insects on multi-floral than on mono-floral stands (185.4 ± 3.1 versus 58.1 ± 13.1, respectively, mean ± *SE* data pooled per farm across the study period; *P*-value ≤0.001). The same pattern was found with diversity of floral visitors (30.3 ± 1.35; in multi-floral stands and 10.0 ± 0.75, in mono-floral stands; P-value ≤0.001).

Seed set per plant of *S. alba* was close to 100 %, specifically it averaged 93.65 % ± 8.97 (mean ± *SD*; range: 40–100). This figure was virtually same as the mean seed set observed per farm (93.64 % ± 3.75, range: 82.80–97.88). The number of viable seeds per each individual fruit averaged across fruits 4.51 ± 1.37 (range: 0–10). Similar values were obtained with the mean number of viable seeds per fruit across plants (4.50 ± 0.85, range: 2.5–7) and across farms (4.51 ± 0.40, range: 3.6–5.2).

Based on the best model selected, abundance, diversity and effectiveness of pollinators were positively affected by herb richness (Fig. 1; Table 1) in the multi-floral stands. On the contrary, no variable of the landscape complexity (at the 250 m neighbourhood scale of the sampling stands or at 1 km scale) affected abundance, diversity or effectiveness of pollinators (Table 1; see Supplementary Table A4 for alternative competing models). Management type only was not incorporated to any of the best models (Table 1; see Supplementary Table A4). Some alternative competing models AP-M-3 and EP-M-3 (Supplementary Table A4), both better than the null model, incorporated herb cover management, but this effect was not statistically significant either for abundance or effectiveness of pollinators, although their means were always higher in farms with low-intensity herb cover management (Fig. 2a and b).

In *S. alba* mono-floral stands, we did not detect any significant effect of patch quality, landscape at different scales or herb management on abundance, diversity or effectiveness of floral visitor. For the abundance and effectiveness of floral visitor, the models including the interaction between the forest area at 1 km radius and the management respectively, were better than the null model (Supplementary Table A5), but such effect was not statistically significant (Table 1; see Supplementary Table A5 for alternative competing models).

The NMDS analysis did not show differences in the composition of floral visitor assemblages between intensive and low-intensity herb cover management (Supplementary Fig. A4a), but it did vary greatly between multi-floral and mono-floral stands (Supplementary Fig. A4b).

Taking *S. alba* as a species model for pollination service, our analyses revealed that within floral patches nor the seed set neither the number of seeds were affected by the management (Fig. 2c and d respectively; see also Table 1) nor by the landscape/patch quality at different scales (see alternative models in Supplementary Table A6). Unexpectedly, number of seeds and seed set of *S. alba* did not respond either to abundance and diversity of floral visitors (Supplementary Table A6), being results very similar between sampling stands.

4. Discussion

This study suggests that floral patches in olive groves can function as resistant biodiversity reservoirs against agricultural intensification, at least in terms of floral visitor conservation. Environmental legislation programmes (e.g., European Agri-Environmental Schemes) that are currently developed in order to counteract the harmful effects of agricultural intensification on biodiversity put emphasis on the preservation of landscape elements such as floral patches to increase landscape complexity (Bartual et al., 2019; Batáry et al., 2015; Krimmer et al., 2019). To this respect, it is relevant to know whether these elements still maintain the same effectiveness in very simplified landscapes and intensified croplands.

4.1. What is the role of the landscape surrounding floral patches on the floral visitor community located there?

Contrary to our expectation, landscape simplification did not have an important effect on abundance and diversity of floral visitors within floral patches in olive groves. This pattern is consistent with studies in other types of agroecosystems (e.g., Li et al., 2020) where authors found that the green flowering infrastructures can host a diverse floral visitor community even in landscapes with great land-use intensity. These studies concluded that floral visitor abundance and diversity are barely affected by the surrounding habitats (but see Cusser et al., 2019), but regulated by the quality of the habitat itself in terms of diversity and availability of resources. Martínez-Núñez et al. (2022) reported similar effects of herbaceous semi-natural habitats on diverse groups of floral visitors in mass-flowering crops, further indicating that relatively small

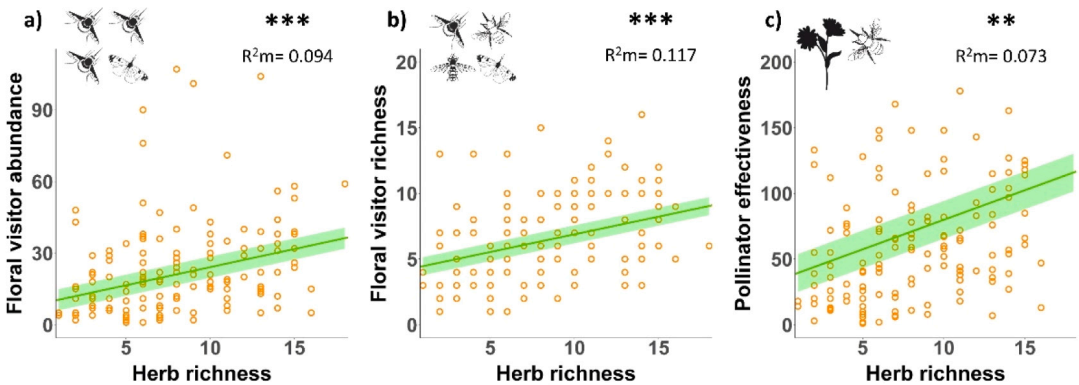

Fig. 1. Relationship between (a) floral visitor abundance, (b) floral visitor diversity, (c) pollinator effectiveness and herb richness per multi-floral sampling stands. Green line represents the response function of the linear mixed models and the green shaded area represents standard error predicted by each model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

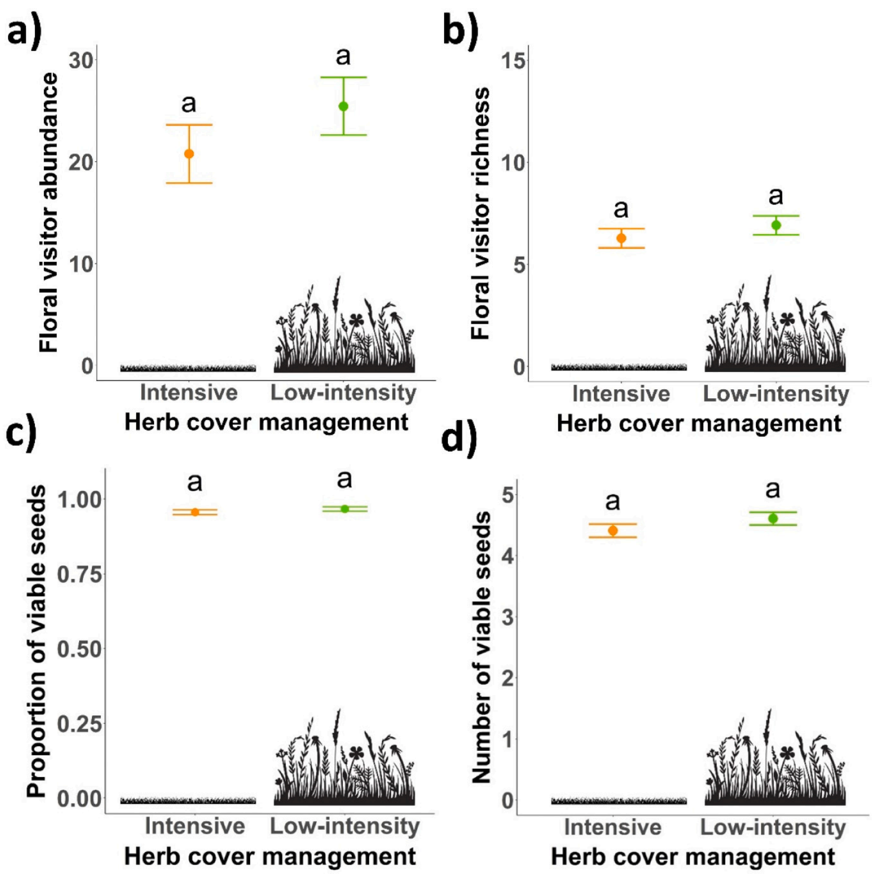

Fig. 2. Upper panels: predicted means and 95 % confidence intervals for abundance (a) and diversity (b) of floral visitor within multi-floral semi-natural stands between olive groves under different herb cover management regimes (intensive vs. low-intensity management). Only multi-floral data set considered. Lower panels: same for two proxies, seed set (c) and number of viable seeds (d), of the pollinator service for *Sinapis alba* within mono-floral stands. Letters show group assigned after post hoc Tukey's test, showing no significant difference.

proportion of semi-natural areas in the landscape provide sufficient source habitat to support a diverse community of floral visitors (see Boetzl et al., 2021, for a similar conclusion regarding AES). This shows that, in relative terms, floral habitats are even more important in simplified landscapes than in more heterogeneous ones, since their presence contributes further to the diversity of the landscape. Our results suggest that floral visitors do not really perceive the olive grove landscape as fragmented, probably because of its particular structure. This can be supported by the fact that we found no differences in floral visitor richness, abundance or community composition when comparing floral patches in fields under two contrasting agricultural regimes. Typically, even in the olive grove-dominated landscapes, where landscape heterogeneity is low, there are small green flowering areas located mainly in roadsides, field boundaries and gullies that are free from management. Therefore, these types of elements can support diverse floral visitor communities, functioning as an important source in olive landscapes.

Traditional olive groves constitute a relatively stable and structurally complex agroecosystem (Rey et al., 2019) and this may contribute to explain differences in the response of floral visitors to landscape context in olive grove landscapes compared to what happens in annual herbaceous crops. Consistent with our findings, Tscheulin et al. (2011) found that wild bees are less affected by landscape context when low-intensity ground cover management is conducted in Mediterranean olive groves.

Table 1
Estimates for the selected best model for flower visitor abundance (AP), diversity (DP) and effectiveness (EP) in multi-floral patches (i) and mono-floral patches (ii). Likewise, estimates are shown for best model of two proxies (NS = number of seeds, and SS = seed set or proportion of viable seeds) of the pollinator service for *Sinapis alba* (iii). *P*-values show significant differences from zero (in the case of the intercept) and from the intercept (in the case of the other estimates). Significant terms at $p < 0.05$ are in bold. First column identifies the code of the best model for each response variable. Forest_1km = Percentage of forest area at 1 km radius, HM = Herb cover management, HR = Floral richness of sampling stand, PR = Floral visitor richness. All models tested for each group of response variables are shown in Supplementary Tables A4, A5 and A6.

Model code	Terms	Estimate	*SE*	*z*-Value	*df*	*p*-Value
(i) Multi-floral patches data set						
AP-M-15	Intercept (intensive)	8.98	4.41	2.03	45.80	**0.047**
	Low-intensity	3.34	4.37	0.76	15.66	0.455
	HR	1.52	0.40	3.73	139.25	<**0.001**
DP-M-17	Intercept (PR)	4.37	0.61	7.06	81.44	<**0.001**
	HR	0.27	0.06	4.19	136.06	<**0.001**
EP-M-13	Intercept (intensive)	10.43	5.65	1.84	82.30	0.068
	Low-intensity	0.66	7.96	0.08	75.72	0.933
	HR	1.33	0.60	2.18	139.99	**0.030**
	Low-intensity: HR	0.32	0.81	0.40	138.75	0.687
(ii) Mono-floral patches of *S. alba* data set						
AP-S-1	Intercept (Intensive)	8.46	3.20	2.63	12.79	**0.020**
	Forest_1km	0.07	0.30	0.25	16.20	0.799
	Low-intensity	−2.92	4.56	−0.64	13.25	0.532
	Forest_1km: low intensity	0.75	0.36	2.07	17.47	0.061
DP-S-3	Intercept (intensive)	3.51	0.37	9.31	13.65	<**0.001**
	Low-intensity	0.56	0.54	1.02	14.76	0.321
EP-S-3	Intercept (Intensive)	20.97	3.36	6.22	11.82	<**0.001**
	Low-intensity	7.95	4.77	1.66	11.85	0.121
(iii) Proportion of viable seeds of *S. alba* data set						
NS-3	Intercept (intensive)	4.39	0.18	23.92	1.28	**0.011**
	HM (low-intensity)	0.22	0.12	1.79	175.42	0.070
SS-3	Intercept (intensive)	1.35	0.01	90.94	176.00	<**0.001**
	HM (low-intensity)	0.02	0.02	1.29	176.00	0.198

4.2. How do the intensity of agricultural practices and floral patch quality affect abundance and diversity of floral visitors in floral patches?

The beneficial effects of low-intensity agricultural practices on floral visitors and multiple taxa are well documented in many different croplands (e.g., Bengtsson et al., 2005; Gaspar et al., 2022; Le Féon et al., 2010; Martínez-Núñez et al., 2020a; Rosas-Ramos et al., 2020). In olive fields, less intensive farming practices favour a herbaceous cover with more rare species, as well as insect-pollinated species (Tarifa et al., 2021). Hence, it could be expected that floral patches from low-intensively managed farms harbour a more diverse floral visitor community, especially in more simple landscapes with smaller proportion of natural habitats. Nevertheless, we found no differences between floral patches placed in farms with contrasting intensity of management on the floral visitor abundance, diversity and composition. This indicates that floral patches in olive grove landscapes seem to be resistant to intensive management in their close surroundings, and that these areas may be working as pesticide-free refuges in olive groves, both for flowering plants and for pollinating insects. Moreover, this is congruent with literature showing that when the agricultural practices become more intensive, the role of these floral patches as refuges gains importance (Bengtsson et al., 2005). Another complementary explanation is the existence of a floral visitor concentration effect in these areas, especially in intensive farms, since floral visitors seem to respond to the availability of resources within the landscape (e.g., Cole et al., 2017; Jha and Kremen, 2013; Kohler et al., 2008). Consequently, in farms with low-intensive farming practices, floral visitors will be less concentrated in floral patches (Carvell et al., 2007). Therefore, a concentration effect in the few and small floral patches available in the intensively managed olive farms could be masking the expected differences for floral visitors between these patches in intensively and low-intensively managed farms. Besides, the floral visitor concentration in semi-natural flowering patches of intensive farms could be exacerbated by the foraging behaviour of most floral visitors, thereby they show more limited mobility among patches and shorter foraging distance where the resources are very localized (Redhead et al., 2016), as it occurs in intensified farms.

In olive grove landscapes, floral visitors responded positively to patch quality estimated as diversity and abundance of flowers in floral patches. Habitat quality in terms of food resources for floral visitors is crucial to their occurrence in a certain habitat, so their presence is largely determined by the presence of key nectar-rich plant species (Bartholomée et al., 2020; Gaspar et al., 2022; Holland et al., 2017). Thus, the supply of diverse floral resources by floral patches had more predictive power on floral visitor community (either abundance, diversity or composition) than the farming system in the neighbourhood environment of these patches. Though it was unexplored in this study, a possible cause to this pattern could be that the presence of key nectar-rich flowers in floral patches could be affecting the quality of the floral visitor assemblages. Thus, the composition of the assemblages would be very sensible to flower diversity in floral patches as reflected by the differences that we observed in the NMDS results for the type of sampled stand. Li et al. (2020) obtained similar results for linear green infrastructures, suggesting that diversity and abundance of floral visitor communities were determined primarily by flower diversity in these landscape elements. Consistent with this idea, flower visitors in multi-floral stands in olive groves were much more abundant and diverse than in mono-floral ones, where quality was low and homogeneous among patches. Strong positive correlation of diversity of floral resources with diversity and abundance of floral visitors has been reported very frequently (e.g., Bengtsson et al., 2005; Cole et al., 2017; Kohler et al., 2008) and highlights the importance of conducting studies at fine-grained local scale when floral visitors are involved.

Our findings support that these semi-natural floral patches are true reservoirs (sensu Brosi et al., 2008) in these agroecosystems for two reasons. First, if they were sinks, then the abundance of floral visitors should be higher within intensive farms, where the herb cover is persistently removed through the year, than within low-intensive farms, where a flowering herb cover is available for floral visitors in the entire olive field; however, this was not the case. Second, the abundance and diversity of floral visitors should be independent of the quality of the floral patches, however they increased with the quality of the patch, not only in intensive farms but also even in low-intensive farms.

The sampling design had some limitations. For instance, it did not consider floral visitor surveys in other potential types of floral patches within the olive grove landscapes, which prevents us from firmly concluding about the role of these semi-natural floral patches as reservoirs. Nevertheless, some additional arguments still point out to the potential role of these floral patches as reservoirs of floral visitor insects. These floral patches are almost the unique floral elements present in the intensively managed olive farms that are located in simplified landscapes (where olive grove is the unique land use available). In olive farms located in intermediate and complex landscapes, other semi-natural elements are more frequent and larger but they are typically woodland remnants dominated by woody anemophilous plants

(*Phillyrea*, *Pinus*, *Pistacia* or *Quercus* species) and these areas are typically grazed by livestock. Therefore, they do not generally represent important floral sources for floral visitor insects. This, in turn, may explain the lack of interaction between landscape and local management on abundance, diversity and composition of floral visitors. This might also explain that floral visitor communities varied mainly as a response to the quality of the floral patches, since more cover of semi-natural habitats in complex landscapes does not provide more abundant and diverse floral sources for floral visitors.

4.3. Is the pollination service delivered by wild floral visitors in floral patches affected by agricultural management and landscape context?

Pollination service in floral patches, measured by the total number of viable seeds in *S. alba* and the proportion of viable seeds (seed set), did not vary in olive groves in relation to intensification of management or landscape complexity. Moreover, seed set reached saturation values (seed set of *S. alba* ca. 100 %) in most floral patches. This suggests that the effectiveness of the floral visitor assemblages present in these floral patches could suffice to adequately supply the pollination function on the floral patches themselves. Since our results demonstrated that floral visitor assemblage effectiveness was strongly affected by flower diversity in floral patches, these flower-rich areas can harbour more efficient floral visitors as the floral richness and flower availability increases. Furthermore, although a close relationship has usually been reported between flower diversity and functional diversity of floral visitors (Fontaine et al., 2006), turnover among sites and patches of some dominant and efficient floral visitor species may suffice to warrant pollination function at each site or patch (Winfree et al., 2018). In this way, few efficient dominant floral visitor species could be enough to saturate the pollination service of *S. alba* in each patch.

5. Conclusions

In conclusion, we provide evidence that even small semi-natural floral patches in agricultural farms embedded in simple landscapes and under an intensive management regime can maintain essential ecosystem services such as pollination on these floral patches themselves, acting as potential reservoirs for pollinators. Promoting diverse flowery patches scattered throughout the agricultural landscape could ensure the conservation of numerous floral visitor species in the Mediterranean basin, as well as a good pollination function which ensures the sustenance of plant communities in the semi-natural remnants within olive-dominated landscapes.

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CRediT authorship contribution statement

D.C., C.M.N. and P.J.R. conceived the ideas and designed the methodology. C.M.N. and A.J.P. conducted the field work. T.S. processed the land use cartography data and produced metric of the landscape heterogeneity. D.C. and A.J.R identified the collected insects and led the data curation. D.C., C.M.N. and P.J.R. analysed the data. D.C. led the writing of the manuscript with input from C.M-N and P.J.R. All the authors contributed critically to the drafts and gave final approval for publication.

Declaration of competing interest

Domingo Cano, on behalf of all co-authors, declares that there is no conflict of interest.

Data availability

The data that has been used is confidential.

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