Journal of Environmental Management 394 (2025) 127496

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

The potential role of "soft" management in sustaining wild bee populations in riparian marginal areas of Mediterranean regions

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ARTICLE INFO

Keywords:
Solitary bees
Entomophilous plants
Policies
Pollinator conservation
Insect biodiversity

ABSTRACT

Increasing trophic resources by sowing flower strips, in arable lands or inter-row of permanent tree crops, is among the "landscapes and biodiversity" measures supported by the European CAPs to favour pollinating insects. To be effective and offer the proper trophic support to the diversity of pollinating insects, this action requires an accurate choice of the plant mixtures to be sown, in terms of flower shape and colour, and flowering times. Similarly, sowing entomophilous plants in marginal disturbed areas can enrich the pollinator community in urban and periurban contexts. In this study, we have sown different plots of recently reconfigured flood detention basins with three types of mixtures (two commercial and one non-commercial) of entomophilous plants in two lowland periurban zones in Tuscany (Italy). Sowing took place in 2022, and monitoring of vegetation and wild bees was carried out every two weeks from 2022 to 2024. We observed that the total abundance of bees increased significantly thanks to the presence of both sown and spontaneous flowering plants, the latter favoured by tillage. Our analyses showed that the bee species are expected to increase by 16.1 % for each additional flowering species. Therefore, we demonstrated that by combining suitable plant mixtures with one annual mowing, marginal areas along rivers in periurban contexts are indeed very appropriate to sustain an abundant and diverse bee community (about 17 % of Italian wild bee fauna), including species of conservation concern.

1. Introduction

Animal pollination is fundamental to the proper functioning of most terrestrial ecosystems, as up to 78 % and 94 % of eudicot species from temperate and tropical environments, respectively, depend on animals for their reproductive success (Ollerton et al., 2011). The resilience of these ecosystems decreases as plant-pollinator interactions deteriorate (Ollerton et al., 2011; Wratten et al., 2012). In recent years, many studies and reports have documented the loss of pollinator species at a global level (IPBES, 2016; Klein et al., 2007; Nieto et al., 2014; Potts et al., 2016; Vujić et al., 2022), in addition to the lack of information on the conservation status of most wild bees (Nieto et al., 2014). Many threat factors including land use, habitat fragmentation and degradation, pesticide use and climate change, have contributed synergistically to the loss of pollinator diversity (IPBES, 2016) and consequently, to a decrease in pollination services with important consequences on crops and many terrestrial ecosystems (Kremen et al., 2002; Larsen et al., 2005; Potts et al., 2016). To counteract the loss of pollinator biodiversity, some conservation actions have focused on the so-called "ecological intensification", which means encouraging pollinator-friendly practices (Bommarco et al., 2013). In this sense, the European Union has introduced into the Common Agriculture Politics (CAPs) support measures (called eco-schemes in the current CAP and agri-environmental schemes, AES, in the previous CASPs), in favour of management practices focused on pollinator conservation and restrictions on the use of pesticides (Duque-Trujillo et al., 2023; Moldoveanu et al., 2024). Urbanisation is also an important factor in habitat degradation and deterioration; therefore, interventions to reverse the trend of pollinator decline can be implemented in many environments, including peri-urban and urban ones (Süle et al., 2023; Zeng et al., 2023). The

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https://doi.org/10.1016/j.jenvman.2025.127496
Received 1 April 2025; Received in revised form 24 September 2025; Accepted 28 September 2025
Available online 1 October 2025

"Nature Restoration Law" recently approved by the EU Council also includes measures to support pollinators as one of the main steps towards restoring many degraded ecosystems (Moldoveanu et al., 2024).

The main actions to support pollinating insects focus on increasing trophic resources through seeding flower strips (Bommarco et al., 2021; Duque-Trujillo et al., 2023). Pollinating insects, such as wild bees, display diets from generalists to oligolectic and monolectic species (Bogusch et al., 2020; Michener, 2007). Therefore, the sown mixtures of nectariferous and polleniferous plants must include species suitable for the different types of diets (Williams and Lonsdorf, 2018). Moreover, they should contain species blooming over a long period to provide trophic resources to insects with different flight times (Zeng et al., 2023). In addition to plant species diversity, flower trait diversity within flowering strips is also important (Balzan et al., 2014a), and a good diversity of morphologies and corolla colours is required to meet the needs of all functional groups of pollinators and restore plant-pollinator interactions (Cardinale et al., 2006). In addition to trophic resources, some pollinating insects are also highly dependent on the availability of nesting sites (Duque-Trujillo et al., 2023). Among man-made environments, marginal lands and non-productive areas can be managed with practices aimed at the conservation of pollinators (Heneberg et al., 2013; Twerd and Banaszak-Cibicka, 2019). Conversely, a rich and diverse pollinator community can support a diverse plant community by restoring the functionality of degraded ecosystems (Exeler et al., 2009; Twerd and Banaszak-Cibicka, 2019). In many European countries, portions of lowland marginal areas are often exploited for irrigation or hydraulic defence of the territory, and their restoration may favour the conservation of many pollinator species (Groning et al., 2007). Most studies about the potentiality of marginal lands in supporting pollinating insects have been conducted in Central and Eastern Europe (Exeler et al., 2009; Moldoveanu et al., 2024; Süle et al., 2023). Twerd and Banaszak-Cibicka (2019) found that the so-called "wastelands" are favourable environments for the conservation of pollinator communities using wild bees as indicators for the proper management of such areas (Twerd and Banaszak-Cibicka, 2019). Süle et al. (2023) compared different management practices in marginal and unfavourable areas of some eastern European cities to promote pollinator-friendly practices and increase the awareness of citizens and policymakers towards the preservation of these species (Süle et al., 2023). Different management included gradual to intensive mowing and entomophilous plant seeding. Less recently, the work of Exeler et al. (2009) considered the succession of wild bee species in riverine areas subjected to major restoration, including the removal of dykes and the seeding of an oligotrophic plant community using the hay-bed technique. This type of intervention has promoted the rapid establishment of a diverse and rich bee community, suggesting that these measures may be very effective for restoring the river and peri-fluvial ecosystems and conserving pollinators (Exeler et al., 2009). The Mediterranean region is considered a diversity hotspot for wild bees, and Italy is one of the European countries with the highest number of species (Ghisbain et al., 2023). In Italy, authorities in charge of hydraulic safety (Consorzi di Bonifica) manage over 59 % of the national territory (https://www.anbi.it/). Riparian zones may include uncultivated and marginal areas mainly managed for the hydrogeological safety of the territory, where environmental restoration or amelioration could favour many animal species, including pollinators. In agricultural environments, flower strips for pollinators have been investigated by some studies (Barbir et al., 2015; Blaauw and Isaacs, 2014; Campbell et al., 2017; Krimmer et al., 2019), but only a few works have assessed the downstream effectiveness of such interventions in non-agricultural landscapes (Süle et al., 2023). Williams and Lonsdorf (2018) built a model aimed at predicting the bee community supported by a certain plant mixture. This model also introduced seed cost and can be implemented based on further data or objectives; it is therefore necessary to acquire more and more information on the trophic preferences of wild bee communities of an area to sustain their populations. Our work considered three main questions: *i)* is the sowing of entomophilous plant mixtures actually effective in supporting wild bees in marginal riparian areas? *ii)* how does the number of flowering species affect the diversity of the bee community? *iii)* which plant species are most likely to support the bee community in these areas?

2. Materials and methods

2.1. Study sites

Study areas are found in floodplains of two major tributaries of the Arno River in Tuscany, Italy (Fig. 1). Both are managed by the Consorzio di Bonifica 3 Medio Valdarno (CBMV 3), the local body in charge of managing the territory through the construction of hydraulic works such as dams, embankments, and lamination reservoirs, the management of vegetation in watercourses and proximal areas, and the management of irrigated areas near rivers (https://www.anbi.it/).

The first area is named "Castelletti", and it is enclosed by an elbow of the Ombrone River in the municipality of Carmignano (PO); the second area, "Bramasole", is found in the council of Montelupo Fiorentino (FI) along the Pesa River. Both areas are recently (2021 and 2022 respectively) realised detention basins; the first has a surface of about 6.5 ha, the second of about 5 ha, and they are less than 9 km apart in a beeline. Both are embedded in peri-urban and agricultural landscapes and may experience occasional flooding during wet seasons but are also exposed to drought during summer. On average, the Ombrone River is expected to be flooded every 30 years, and a partial flood occurred once in November 2023. The Pesa River, on the other hand, is less prone to overflowing, and the reservoir containing our experimental areas was never flooded during our study. Both areas were poor in trophic resources since the ground was almost completely covered by grasses, colonising the area after the massive earthworks. Guidelines for the construction of detention reservoirs recommend sowing grass mixtures necessary to prevent soil runoff on the embankments (Tuscany Region Approval No. 1315 of 2019, Annex A). Still, for the deeper surface, there are no recommendations. These areas are considered non-productive and marginal and often referred to as "unfavourable areas".

2.2. Experimental design

The experimental design was carried out in collaboration with the Consorzio di Bonifica 3 Medio Valdarno (Fig. 2). The seeds were purchased from "Padana Sementi Elette" S.r.l., based in Tombolo (PD); the company markets seed mixtures of nectariferous and polliniferous plants developed under the "Operation Pollinator©" project in collaboration with Syngenta (Miscugli Operation Pollinator | Padana Sementi). Mixtures were selected considering the company's advice, the goals of this work, i.e. increasing wild bee presence, and the management and maintenance obligations of the CBMV 3. The two mixtures named "Fasce Tampone Fiorite" (F) and "Operation Pollinator Rustico Dicotiledoni" (R) were selected. F is a mixture suitable for ecological infrastructures on crop margins (grasses, vegetables, orchards), with the main purpose of hosting pollinators and other beneficial insects favouring crop productivity in organic and traditional agriculture. The mix consists of 31 herbaceous species and has the greatest species diversity among those available in the catalogue (species in Supplementary Materials "Plant of mixtures"). The recommended dosage was 40–45 kg of seeds/ha for this mix. The R mixture, characterised by lower specific diversity, contains more robust essences. It consists of a medium-to-high size turfgrass with an anti-runoff effect and very low maintenance needs, suitable for grassing buffer strips and field edges of both herbaceous and tree crops (species in Supplementary Materials "Plant of mixtures"). The recommended dosage is 30–35 kg/ha.

The third mixture, not commercial, is based on the R mixture and named "Rustico Dicotiledoni modified" (Rn). Compared to R, Rn did not include the naturalised species *Phacelia tanacetifolia*, but two Boraginaceae, one Asteraceae and one Fabaceae species (species in

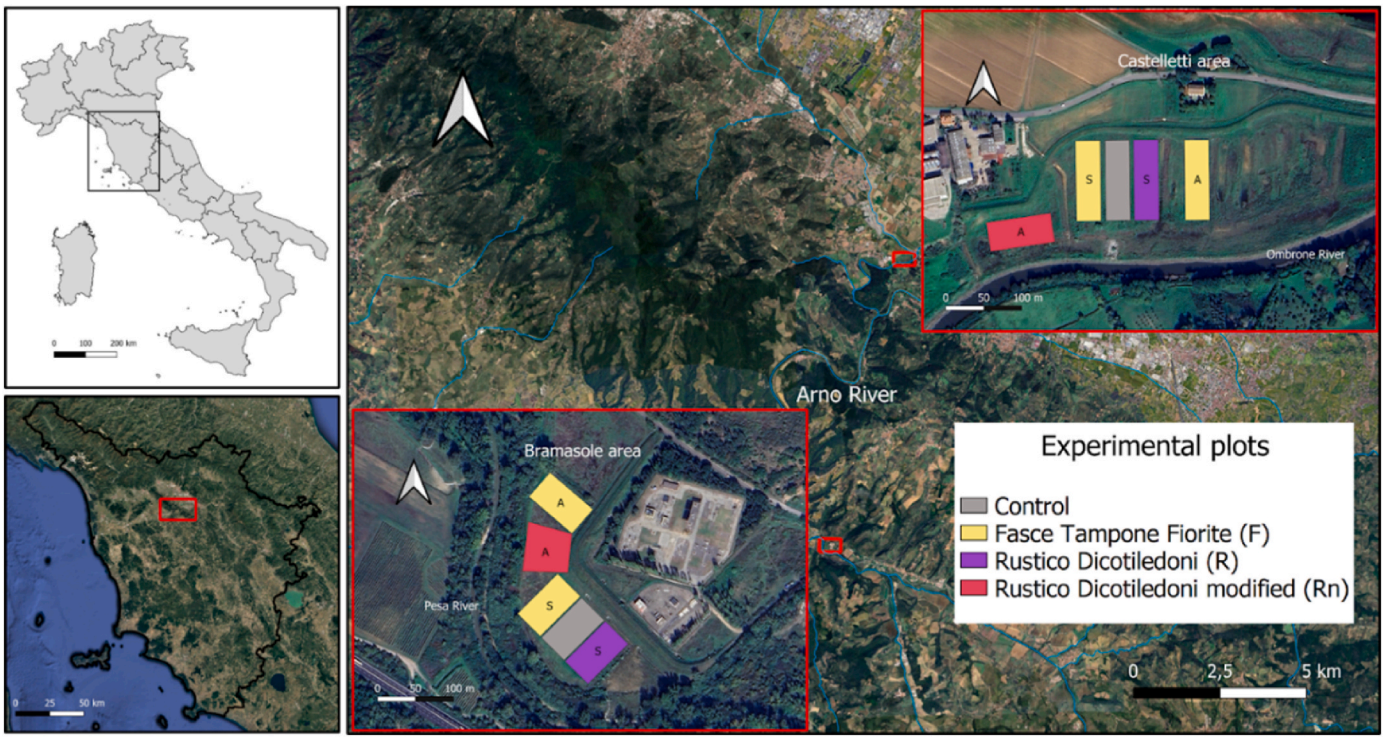

Fig. 1. The map displays, at different scales, the geographical context of the two experimental areas located along two major tributaries of the Arno River: "Castelletti", along the Ombrone River and "Bramasole", along the Pesa River. Within each area, experimental plots are coded by treatment: yellow for "Fasce Tampone Fiorite (F), purple for "Rustico Dicotiledoni" (R), red for "Rustico Dicotiledoni modified" (Rn) and grey for Control. The letters above the plots indicate the sowing period: spring 2022 (S) and autumn 2022 (A). Data are from Google Satellite and the map was created using QGIS 3.34.15-Prizren.

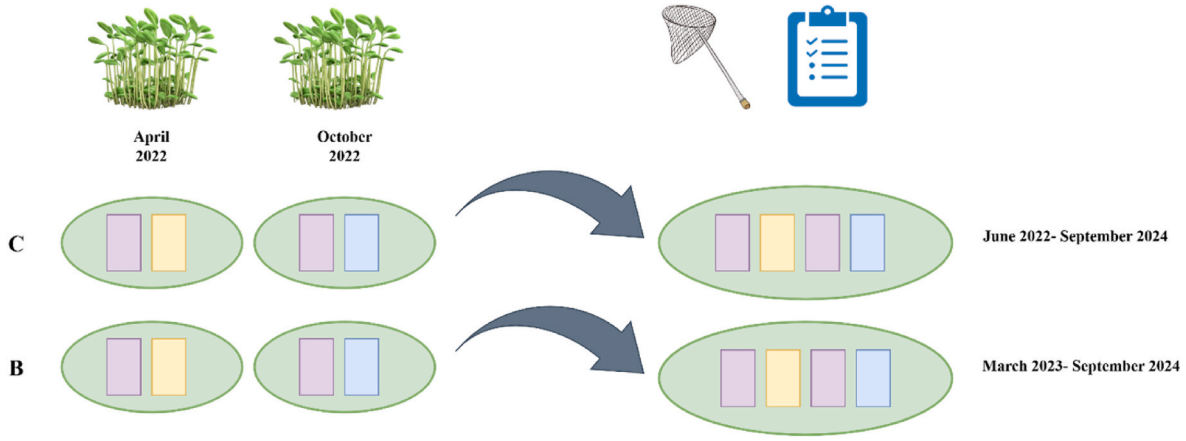

Fig. 2. Diagram of the experimental set-up where C stands for "Castelletti" and B stands for "Bramasole" areas.

Supplementary Materials "Plant of mixtures"). There was no recommended dosage for this mixture as it was prepared for this study, but the same as for the R mixture was sown. Most of the mixtures' species are listed in Annex IX of the Italian Agriculture Ministry Decree (December 23, 2022 No. 660087, referring to Regulation, 2021/2115 of the European Parliament), reporting the plants suitable for the eco-scheme specific for pollinators (eco-scheme 5 in the Italian CAP). The experimental plots within the "Castelletti" and "Bramasole" areas were identified, as shown in Fig. 1. Each plot is approximately 0.33 ha in size. The sowing operations were conducted in early spring 2022 (one F plot, and one R plot separated by a control, untreated plot for each area) and in autumn 2022 (a further F and Rn plot, separated by a control untreated plot in each area). Vegetation mowing operations were conducted once a year for each sown plot, usually between the end of July and August.

2.3. Vegetation surveys

The seeded mixtures were monitored for their development through the vegetation period twice per month, from spring 2022 to late summer 2024 in the "Castelletti" area and from spring 2023 to late summer 2024 in the "Bramasole" area. Each sown plot was quite uniform in terms of species present and vegetation coverage. The survey was based on a 2m × 2m "grid-crossing scheme". The sampling methodology consisted of counting and recognising all individuals intersecting our crossing grid. For each plant survey, we registered the following information: the average vegetation coverage, the percentage of flowering coverage, the number of individuals for each species, the average height for each species, and the phenological stage of the specimens (no flowering, flowering, fruiting/seeding). Two grids per mixture were surveyed in

each session. This information was used to monitor the species of the mixtures that germinated, grew, flowered and seeded, and thus assess the germinability and adaptability of the mixtures to the study areas. For the dominant sown species, nectar extraction was also performed, and the sugar concentration was quantified. This allowed community analysis to be carried out to understand which characteristics of these plants were a major driver for the bee community in these areas (See Supplementary Materials "Nectar").

2.4. Wild bee monitoring and species identification

Sampling was carried out from the early spring to the late summer except for 2022 when, following the spring sowing, we started monitoring in June. Wild bee monitoring was carried out from 2022 to 2024 in the "Castelletti" area and from 2023 to 2024 in the "Bramasole" area. Insect monitoring was performed only if climatic conditions were suitable for pollinators: i.e. with a minimum of 15 °C, little to moderate wind, no rain and dry vegetation (Westphal et al., 2008). Three sampling methodologies were used: permanent standardised transects (STs), pan traps (PTs) and artificial bee nests. In 2022 in "Bramasole", only bee nests were used as a sampling method since vegetation had a very reduced development and flowering. STs were conducted bi-weekly, and a permanent transect uniformly covering the plot was established. During transects, bees that could not be recognised in situ were captured using an entomological net. When species could not be promptly recognised, recognition and specimen collection in the field were based on morphospecies, to avoid impact on the local bee populations. For each field-identified or captured specimen, the plant species on which it was observed was noted. For each ST we also noticed: initial and final temperature; a cloudiness index ranging from 0 to 5; a wind intensity index from 0 to 5, based on the Beaufort scale; and vegetation and flowering percentage coverage of the whole plot. In all plots, two triplets of PTs were placed once a month for 24 h. Trap nests were also used in 2022 and 2023. The nests were placed in the field at the end of winter and brought back to the laboratory in December 2022 and 2023.

Collected specimens were identified at the taxonomic species level using dichotomous keys for the bee fauna of different European countries since keys for the Italian bee species are not available (see Supplementary Materials "Identification Keys") and most underwent DNA barcoding. By combining morphological and DNA barcoding identification we drew a checklist of the wild bee species present in the studied areas (see Supplementary Materials "Species"). For each identified species we considered its conservation status as reported in the IUCN Red List of European Bees (Nieto et al., 2014).

2.5. Data analysis

All analyses were conducted with R software (R version 4.2.2). We decided to keep the analyses separate for the two study areas to ensure the homogeneity of the data. In the first instance, we investigated the development of the seed mixtures by calculating their germination, the plot vegetation and flowering coverage, and the response of the surrounding vegetation in terms of spontaneous intrusive species developing among the sown plants and the percentage of these that contributed to flowering. For each of the two areas, we produced violin plots showing the wild bee abundance (always excluding the honeybee from the analyses) for each mixture and the control over the years. For the violin plots, the ggplot2 package in R was used (Wickham, 2016). A proportional Euler diagram was also displayed for each area to understand the distribution of unique species between seed types and control (eulerr package, Larsson, 2024). To understand whether the sown plots attracted higher abundances of bees than the control, we computed a GLM(M) with a binomial negative function chosen according to the parsimony principle based on AIC, including as random factors site and year. The binomial neg function was selected as data showed overdispersion. We used the emmeans function (package emmeans, Length, 2024) which provides estimated marginal averages (emmeans) for different treatments and pairwise comparisons (contrasts) between treatments. In this way, emmeans provides the estimated log-abundance for each treatment, together with the standard error (SE) and confidence intervals (lower and upper asymptotic confidence limits) allowing us to understand the differences between treatments (mixture and control) and quantify them. To evaluate whether an increase in the species that flowered corresponded to an increase in bee species in the plot, we calculated a second GLM(M). Again, the negative binomial function was chosen due to the overdispersion of the data and the comparison of AIC values, and the following were used as random factors: site, year, sown mixture, temperature, cloud and wind values. The GLM(M) were constructed using the package lme4 while the graphs were performed with the package ggplot2 (Bates et al., 2015; Wickham, 2016). Finally, we decided to perform community analyses for each study area to understand which plant species among the sown and wild ones were most relevant to most bee species and how these latter exploited the availability of trophic resources. Two CCAs were then performed, one for each study area, using the bee community of each area as the response variable and the flowering plant community as the environmental variable. For this analysis, we used the number of specimens of each plant and bee species in each sampling session. For these analyses, we only considered bee species with more than five individuals and plant species with at least ten individuals. This allowed us to simplify the CCAs that would otherwise have been too complex to visualise. We performed ANOVA, bootstrap, and prcrust tests on all CCAs. These analyses were performed using the vegan package (Oksanen et al., 2017).

3. Results

In "Castelletti", the mixtures bloomed from the very first months after sowing, while in "Bramasole", it was necessary to wait until the following year for the mixtures to bloom. Table 1 shows, for each mixture, the sprouting, the average cover and the contribution to the plot flowering for each sown species, and the spontaneous flowering species that intruded into the mixtures. In both areas, the R mixture had the highest average sprouting percentage and F the lowest. Also, the F mixture had the lowest average blooming coverage compared to the other mixtures but the highest percentage of spontaneous and intrusive flowering species. In both areas, flowering species in the sown plots gave a much higher flower coverage than in control plots (Fig. 3).

During the three years of monitoring at "Castelletti", we recorded 142 bee species, while 102 were recorded in the 2 years at "Bramasole"

Table 1
Features (as average values) of the seeded mixtures and the spontaneous plants for each study area in the three years of experimentation.

	Bramasole			Castelletti		
	F	R	Rn	F	R	Rn
Percentage of sprouting mixture's species	40.00 %	54.60 %	53.30 %	56.00 %	72.70 %	66.60 %
Number of sprouting mixture's species	10\25	6\11	8\15	14\25	8\11	10\15
Number of flowering mixture's species	9\25	6\11	8\15	12\25	8\11	9\15
Number of flowering intrusive species	18	3	8	31	20	19
Percentage of vegetation coverage in the plot	89.00 %	97.20 %	85.17 %	84.30 %	92.40 %	88.40 %
Average height during flowering season (cm)	46.70	43.00	52.90	45.90	41.60	55.00

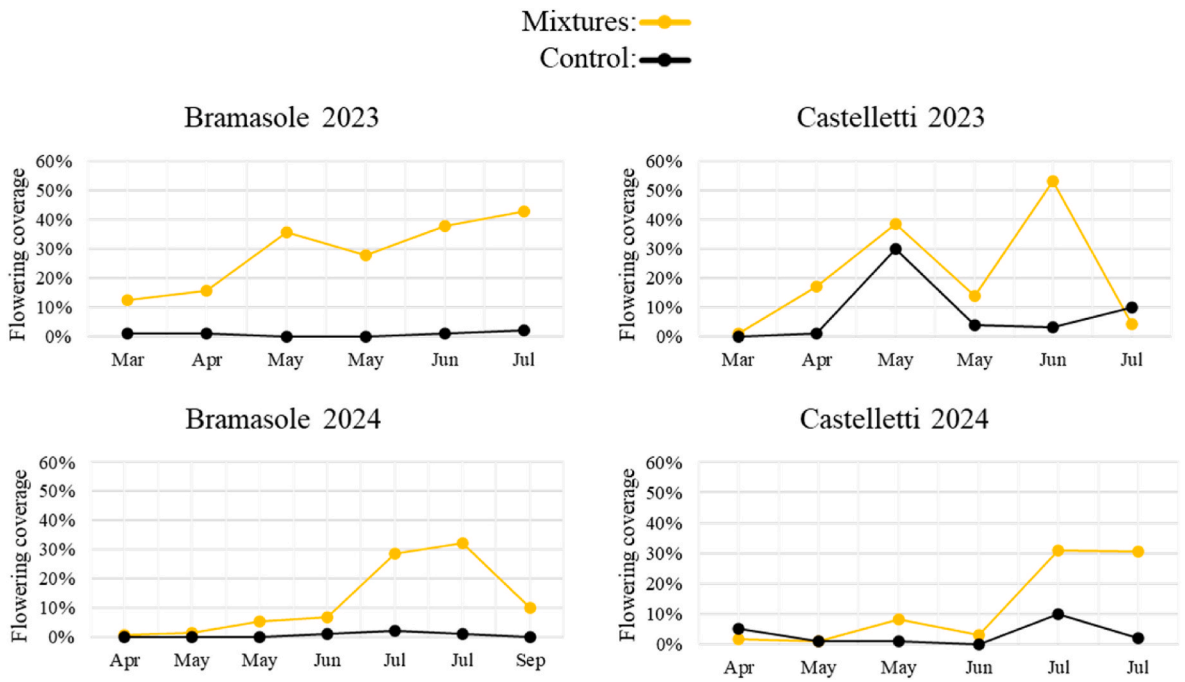

Fig. 3. Flower coverage during the months of the year when there is the main activity of adult bees, for each study area in 2023 and 2024. The black and yellow lines represent respectively the control and the sown plots.

(see Supplementary Materials for the list of species in "Species"). Overall, we identified 44 species classified as DD, 7 NT and 1 EN by the IUCN (See Supplementary Materials in "Species"; Nieto et al., 2014).

In both study areas, the control generally attracted fewer bees than each of the three types of sown plots (Fig. 4a and 5a). A much higher variability (Std. Dev) was found between years than between study areas (Table 2). Bee abundances depended significantly on the seed mixture with the Rn and F having the greatest effect on bee abundance compared to the R mixture and the control (Table 2). A higher variability was found between years (Std. Dev. 0.565) than between study areas (Table 2). Significant differences were found between the Control and F mixture, and the Control and the Rn mixture. Both F and Rn treatments attracted more bees than the control, but no significant differences were found between any of the sown plots and between R and the control (Table 3). In both areas, the highest number of species was observed in the F experimental plots where they accounted for 65.98 % and 57.57 % of the total number of species (Fig. 4b and 5b). In "Castelletti", bee species of Rn was a subset of those shared by the other sown plots and the F and R mixtures attracted a higher number of unique species (Fig. 4b). In the "Bramasole" area, the R mixture was a subset of the other seeded plots, and the F and Rn mixes attracted a higher number of unique species (Fig. 5b). However, in the "Castelletti" area, the control contributed also to sampling a high number of unique species.

The number of flowering species strongly affected the wild bee species' richness independently of treatment (sown mixtures) and site (study areas) (Table 4). Both fixed effects are highly significant ($p < 0.001$), meaning that both variables contributed significantly to explaining the variation in the bee species community. According to the model, for each additional flowering species, the count of bee species is expected to increase by 16.1 % (Fig. 6).

The CCA model for the "Castelletti" area (Fig. 7) explained about 80 % of the total variance in wild bee species community based on the abundance of flowering plant species. This indicates that plant species play a significant role in shaping bee communities. The first three canonical axes explained 24.94 % of the total variance, with CCA1 having an eigenvalue of 55.68 %. The low variance explained by the axes CCA1

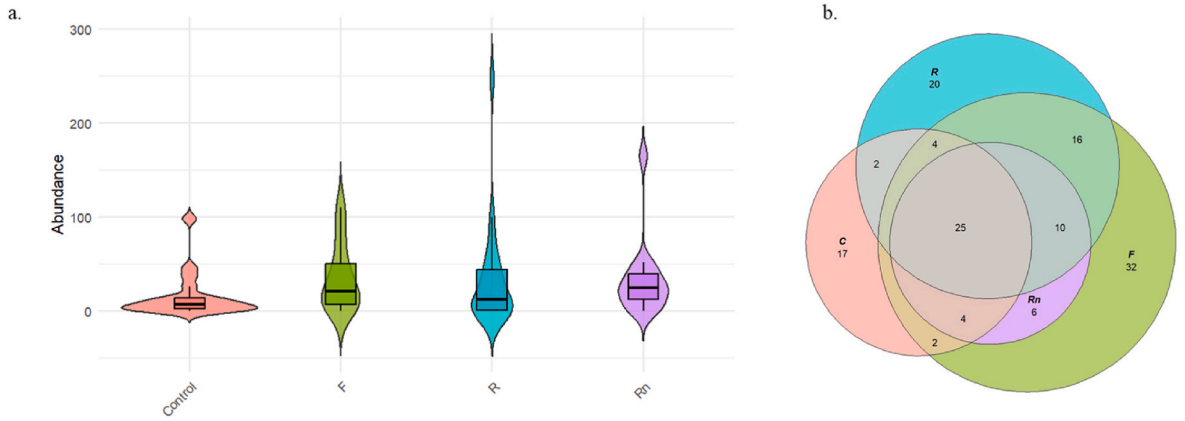

Fig. 4. (a) Violin plot of the abundance of wild bees sampled in the "Castelletti" area from 2022 to 2024 for each type of seed mixture (F, R, Rn) and the control plot. (b) Proportional Euler diagram of the wild bee species sampled in the same area during the same period in the seeded and control (C) plot. Both diagrams are based only on specimens and species sampled during walking transects.

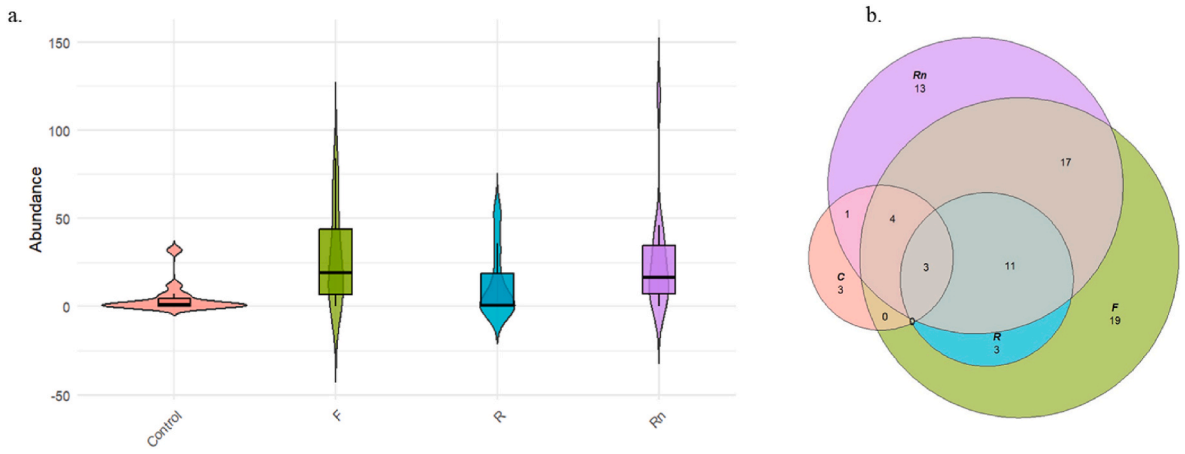

Fig. 5. (a) Violin plot of the abundance of wild bees sampled in the "Bramasole" area in 2023 and 2024 for each type of seed mixture (F, R, Rn) and the control plot. (b) Proportional Euler diagram of the wild bee species sampled in the same area during the same period in the seeded and control (C) plot. Both diagrams are based only on specimens and species sampled during walking transects.

Table 2
Negative Binomial Model (nbinom2) based on lower AIC on the effect of sown mixtures compared to control plots on the abundances of wild bees; Year (2022, 2023, 2024) and Areas ("Castelletti", "Bramasole") were considered as random effects.

Fixed effects	Estimate	Std. Error	z-value	p-value
Intercept (Abundance of wild bees)	2.372	0.446	5.317	<0.001 (***)
Treatment (F)	1.332	0.361	3.685	<0.001 (***)
Treatment (R)	0.718	0.359	2.002	<0.01 (*)
Treatment (Rn)	1.362	0.379	3.586	<0.001 (***)
Random effects	**Variance**	**Std. Dev**		
Area	0.0316	0.0177		
Year	0.319	0.565		

Table 3
Estimated marginal means (function emmeans) and pairwise comparison among each treatment (seed mix types) and the control based on the abundances of wild bees and the output of the Negative Binomial Model (in Table 2).

Estimated Marginal means				
Treatment	**Estimated Mean (emmean)**	**SE**	**95 % CI Lower**	**95 % CI Upper**
Control	2.37	0.446	1.50	3.25
F	3.7	0.443	2.84	4.57
R	3.09	0.431	2.25	3.93
Rn	3.73	0.469	2.81	4.65
Pairwise Contrasts				
Contrast	**Estimate**	**SE**	**z-ratio**	**p-value**
Control-F	−1.332	0.361	−3.685	<0.001 (***)
Control-R	−0.718	0.359	−2.002	>0.05
Control-Rn	−1.362	0.380	−3.586	<0.001 (***)
F-R	0.614	0.362	1.696	>0.05
F-Rn	−0.031	0.370	−0.082	>0.05
R-Rn	−0.645	0.388	−1.661	>0.05

and CCA2 could be due to the excessive database of the number of bee species, although these are not unusual values for ecological data. The intrusive plant species *Trifolium campestre* Schreb. and *Lathyrus hirsutus* L. had the strongest positive correlations with CCA1(|0.982| and |0.979| respectively), suggesting they are important for the distribution of bee species. *Lathyrus satyvus* L. 1753, *Lotus corniculatus* L., *Trifolium incarnatum* L. 1753, *Polygonum aviculare* L. and *Borago officinalis* L., were the other plant species with higher absolute contributions to CCA. The Bootstrap and Procrustes results suggested that the CCA model is robust ($p < 0.05$) and captures meaningful patterns in the data, indicating that the relationship between plant species and bee species is unlikely to be due to random variation. Moreover, we found no multicollinearity, ensuring that the plant species are not highly correlated with one another. However, the data may be overfitted due to the high number of species and therefore, the ANOVA was not significant ($p > 0.05$). The CCA model for the "Bramasole" area (Fig. 8) explained over 75.00 % of the variance in wild bee species community based on the flowering plants. This indicates that plant species play a significant role in shaping bee communities. The first three canonical axes explained 35.37 % of the total variance, with CCA1 having an eigenvalue of 66.24 %. The plant species *Borago officinalis* and *Trifolium incarnatum* had the strongest positive correlations with CCA1(|0.678| and |0.668| respectively), suggesting they are important for the distribution of bee species. *Papaver roheas* L., 1753, *Scabiosa* sp. and *Anthemis arvensis* L. were the other plant species with higher absolute contributions to CCA. The Bootstrap and Procrustes results suggest that the CCA model is robust ($p < 0.001$) and captures meaningful patterns in the data. Moreover, we found no

Table 4
Negative Binomial Model (nbinom2, function glmer) based on lower AIC, considering the effect of the flowering species number on the wild bee species richness, with climatic conditions, year (2022, 2023, 2024) and site ("Castelletti", "Bramasole") as random effects.

Fixed effects	Estimate	Std. Error	z-value	p-value
Intercept (Number of wild bee species)	1.0744	0.199	5.411	<0.001 (***)
Number of flowering species	0.149	0.018	8.439	<0.001 (***)
Random effects	**Variance**	**Std. Dev**		
Temperature	1.47E-01	3.84E-01		
Cloudiness	1.06E-11	3.24E-06		
Wind	5.34E-03	7.32E-02		
Treatment (seed mix)	4.95E-11	7.03E-06		
Year	3.23E-02	1.79E-01		
Site	9.87E-12	3.14E-06		

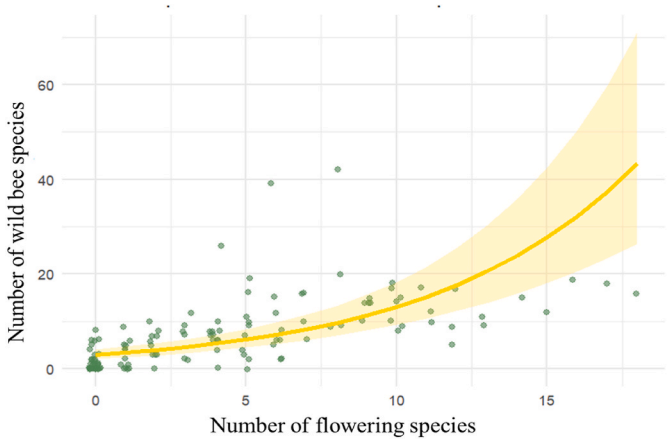

Fig. 6. Relationship between flower species richness and bee species richness. Raw data points (green) reveal variability across observations, while the yellow line depicts predicted values derived from the model and the confidence intervals (Table 4). The trend suggests a positive relationship, with higher flower species richness associated with greater bee species richness.

multicollinearity, ensuring that the plant species are not highly correlated with one another. However, the data may be overfitted due to the high number of species as for the "Castelletti" area, and therefore, the ANOVA was not significant ($p > 0.05$).

4. Discussion and conclusions

The new European policies and directives propose actions aimed at the conservation of pollinating insects (Giovanetti and Bortolotti, 2023; Moldoveanu et al., 2024). Since the decline of this group of organisms due to the synergistic effect of multiple factors is documented, the outstanding goal is to reverse the current trend and increase their abundance and biodiversity (Potts et al., 2024). Increasing the trophic resources for pollinators is among the main and immediately effective actions achievable both in agricultural and urban environments (Balzan et al., 2014a). Although other actions are also necessary, such as favouring nesting resources for the preimaginal development of the different taxa of pollinators, increasing trophic sources would reduce intra- and interspecific competition, favouring, therefore, the entire pollinator community (Balzan et al., 2014b; Uyttenbroeck et al., 2017). Since man-made non-productive perifluvial areas are common in urban and periurban environments, we consider them of interest for pollinator conservation in these contexts. Only a few works have studied the conservation potential of these areas for wild bees, including species of special concern (Heneberg et al., 2013; Twerd and Banaszak-Cibicka, 2019).

During our monitoring, we found *Trachusa interrupta* (Fabricius, 1781), an EN species according to the IUCN Red List of European Bees (Nieto et al., 2014). This species is a resin bee in the tribe Anthidiini with a mainly Mediterranean and south-eastern European distribution (Kasparek, 2020). It flies from June to August and prefers Dipsacaceae species having been found foraging mainly on *Cephalaria* Schrad. (1818) and *Scabiosa* L., 1753 (Amiet et al., 2004; Bees, Wasps & Ants Recording Society, 2013). In our case, it was found foraging on *Dipsacus* sp. L., 1753, a spontaneous flowering species of the Caprifoliaceae family. Among the NT species, we found *Andrena ovatula* (Kirby, 1802). This is a bivoltine species, distributed throughout the European continent. Although solitary, it has been reported as breeding in large aggregations in eastern Europe. This species prefers nesting in sloping sandy soils, such as dunes, coastlines and embankments (Scheuchl and Willner, 2016; BeesWasps & Ants Recording Society, 2013a) where it can form large aggregations. Although it is not reported to have any particular trophic preferences and the plants on which it forages vary between the first and second generation, the subgenus *Taeniandrena* is reported to have a preference for Fabaceae (Wood, 2023; BeesWasps & Ants Recording Society, 2013a) . The specimens we surveyed were observed mostly on *T. incarnatum* and *T. pratense*. *Lasioglossum angusticeps* (Perkins, 1895) is another NT species that we have found in our areas. The species is particularly known to nest in small aggregations in dune or coastal habitats with steep slopes and clay soils (Scheuchl and Willner,

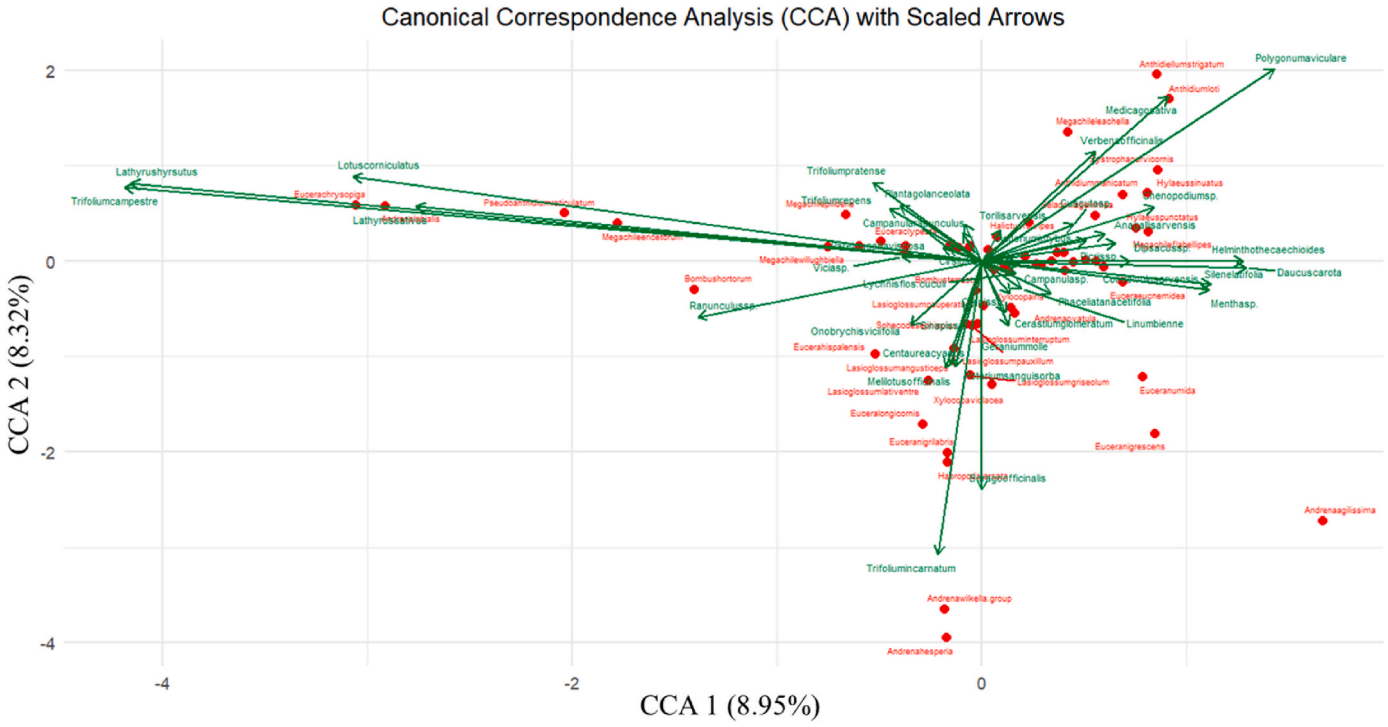

Fig. 7. Canonical Correspondence Analysis (CCA) for the wild bee and flowering plant communities in the "Castelletti" area; red dots represent bee species, green arrows plant species.

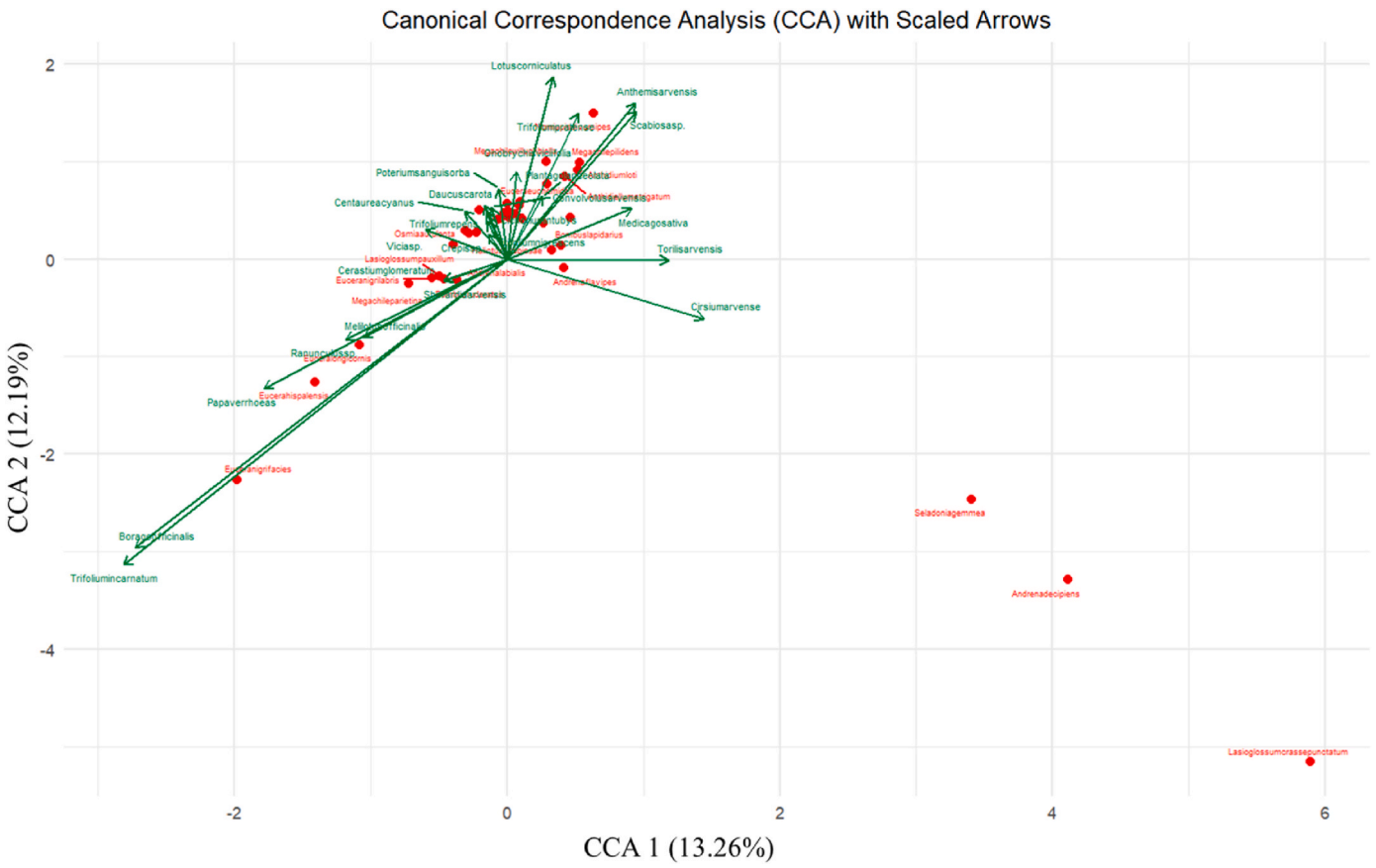

Fig. 8. Canonical Correspondence Analysis (CCA) for the wild bee and flowering plant communities in the "Bramasole" area; red dots represent bee species, green arrows plant species.

2016; BeesWasps & Ants Recording Society, 2013e). It flies from May until late summer, males prefer yellow Asteraceae species while females have been reported to visit *Lotus corniculatus* blooms (BeesWasps & Ants Recording Society, 2013e). In our monitoring, specimens were observed foraging mainly on the latter species and only sporadically on *Ranunculus* sp. L., 1753 and *Centaurea cyanus* L. *Epeolus cruciger* (Panzer, 1799) was a further NT species. This cuckoo bee of the family Apidae can exploit about four species of *Colletes* in Italy, among which the most common are *Colletes hederae* Schmidt and Westrich, 1993 and *C. succintus* (Linnaeus, 1758). Although we did not find species belonging to the genus *Colletes*, the presence of the parasite indicates their presence in or close to the experimental areas (BeesWasps & Ants Recording Society, 2013b). *L. costulatum* (Kriechbaumer, 1873) and *L. pygmaeum* (Schenck, 1853) are also considered NT species. *L costulatum* is oligolectic for *Campanula* L., 1753, although high pollen counts of *Galium* L., 1753 and Cichorioidea were also found in the pollen loads analysed by Westrich (1989), suggesting probable polylectic behaviour in environments without *Campanula* (Scheuchl and Willner, 2016). In our case, the specimens were observed on various plant species including Fabaceae and Asteraceae while *Campanula* was found sporadically in our study areas. *L. pygmaeum* is reported to be polylectic and found mainly on Fabaceae and Lamiaceae. Both these species are likely to be found in habitats with dry and sandy or argillaceous soils (Scheuchl and Willner, 2016).

Among the seed commercial mixtures developed for the Mediterranean area, we searched for those with a high diversity of nectariferous and/or polleniferous species whose flowering would succeed each other from early spring to autumn, to cover the needs of species with a different flight time, and that offered ranges of colours and floral symmetries suited to the ecological traits of diverse pollinator species (Balzan et al., 2014b). Moreover, since the study areas are located within detention basins of two of the main tributaries of the Arno River, plants should be resistant to water stress. Also, thanks to the contribution of spontaneous flowering species (usually not the same as in the control plots dominated by grasses), the sown experimental plots provided an overall sufficiently high and prolonged flower coverage compared to the control plots. In Mediterranean regions, the shortage of flowers during the dry season is one of the factors causing nutritional stress for pollinating insects (Bartual et al., 2018).

In both areas involved in the study, the total abundance and biodiversity of wild bees were significantly influenced by the sowings. The control plots representing the surrounding environment did not undergo any treatment and were dominated by grasses that left little space for wild flowering species. After our interventions and in the following three years, the sown plots attracted significantly larger numbers of bees than the controls, and in both experimental areas, the total number of species was approximately tripled compared to the control. These results indicate that sowing entomophilous plants within this kind of marginal area can be very effective. At the same time, the sowed plots showed that increasing the number of flowering plant species leads to an increase in the number of bee species. As in the study by Wood and colleagues (2017), a higher specific richness of flowering plants was matched by a higher specific richness of wild bees. In this analysis, we focused not only on the sown species but also on the flowering spontaneous plants we found in the sown plots. This is because most of the spontaneous species "intruding" into our sown plots were not the same as those present in the control but possibly species present in the seed bank of the experimental areas whose germination and flowering were made possible due to the harrowing of the soil to prepare the seedbeds of our mixtures. Although, as expected, the presence of Fabaceae species played a fundamental role in supporting a rich and abundant bee community, the CCAs highlight the need for a great variety of flower

symmetries. Many species of Andrenidae, Halictidae and Colletidae are particularly dependent on wild blooms (Michez et al., 2019). Among the intrusive species, we found that *Lathyrus* species, *T. campestre, Polygonum aviculare, Linum bienne* and *C. arvense* are common species offering trophic resources to particular solitary bee species. Species of larger body size and with a long ligule, such as those belonging to the families Apidae and Megachilidae clustered mainly near Clovers (either spontaneous and sown) and other Fabaceae and Boraginaceae. The different clustering between these two groups may also be due to indirect phenomena such as interspecific competition or differences in pollen production and preferences. In both areas, *T. incarnatum* and *B. officinalis* aggregated far from the other plant species and attracted different bee species. This may be due to the very early and abundant blooming, offering resources to species that flicker in early spring (e.g. species of *Eucera*, *Andrena* and *Osmia*). Even if the ANOVA test on our CCA models was not significant and may limit the inferential strength of the analyses, the converging evidence from alternative validation approaches (Bootstrap and Procrustes tests) indicates that the observed associations between plant and bee species are not simply artefacts of random variation. Furthermore, the ANOVA non-significance is not unusual in ecological ordination studies with a high number of response species (in each area we sampled more than 100 species), and therefore the CCA findings may be interpreted cautiously, as exploratory evidence of plant–bee community associations useful for selecting plant mixtures for conservation purposes.

In conclusion (see Table 5), we have shown that marginal and disturbed lowland areas have a strong potential to host diverse and numerous communities of wild bees if trophic resources are increased through the seeding of suitable herbaceous plants and that a high number of flowering plant species is crucial to increase the bee community diversity. Therefore, seed mixtures must have a reasonable number of flowering species to be effective. In addition to nectar and pollen production, these species must guarantee flowering diversity over a long period throughout the year. Fabaceae are an excellent group of species, as they produce abundant flowering over a long time and are also soil-improving species. However, in addition to Fabaceae, Asteraceae, such as *C. intybus* and *H. echioides* (or some *Picris* L., 1753 species) and Apiaceae (*Daucus carota* L., 1753) are needed as a resource for small-bodied and short ligula species. Finally, the importance of early flowering species, such as some Boraginaceae is fundamental to supporting early bee species immediately after the winter period. Mowing once a year may be useful to limit grasses and make room for sown flowers or wild spontaneous blooms.

This study represents a pilot project for the development of guidelines for the management of a particular type of area with a view to contributing to maintaining the richness and diversity of pollinating insects. Italy, like other Mediterranean countries, hosts a large number of pollinator species, often distributed in fragmented areas within anthropized landscapes. Flood detention basins and unmanaged riparian areas, which may extend over relatively large surfaces, even in urbanised contexts, can be managed to favour connections between source areas naturally offering rich trophic resources and nesting sites for diverse pollinator communities. Adopting such management practices at the regional or national level by the public bodies that manage the hydrographic network and areas adjacent to watercourses could therefore contribute to the conservation of pollinating insects, as similar practices already adopted in agriculture.

This work, albeit on a local scale, has been able to: support the theory of biodiversity-ecosystem function by demonstrating a positive link between floral richness and wild bee diversity; refine the theory of community assembly by highlighting the disproportionate role of certain plant species as key floral resources in the structuring of bee communities; contribute to an ever-expanding theoretical framework that integrates biotic and abiotic factors in the formation of pollinator communities; last but not least, it has contributed to gathering knowledge about more than 150 species of wild bees for which the biological and ecological characteristics are still unknown or poorly investigated, in addition to data on the presence and status of these populations in one of the most biodiverse country of the Mediterranean region (recalling that at European level more than 55 % of wild bee species are still classified as “Data Deficient” (Nieto et al., 2014)). These insights could guide future research on the interactions between plants and pollinators in many natural and anthropogenic ecosystems. In this regard, future research should also monitor the long-term development of the vegetation within the sown areas and evaluate the management interventions needed to maintain their effectiveness over time.

Table 5
Main hypotheses of the study, indicating the experimental methods and the results obtained for each objective.

Objective/hypothesis	Methods	Results
Is the sowing of entomophilous plant mixtures actually effective in supporting wild bees in marginal riparian areas?	Sowing of three different mixtures of entomophilous plants in the spring and autumn of 2022.	The sown plots provided food resources for a longer period and supported a greater abundance of wild bees than the unseeded control plots.
How does the number of flowering species affect the diversity of the bee community?	Monitoring for three years (2022–2024), the sown plots and the wild bees.	For each additional flowering species, the species richness of wild bees increased by about 16 %.
Which plant species are most likely to support the bee community in these areas?	Studying the plant-pollinator interaction in the sown plots and in the control plots for three consecutive years (2022–2024).	Fabaceae species and early blooming plants, are most likely to influence the wild bee community.

4.1. Limits of this study

Although this work involved monitoring two areas for consecutive years with a very high sampling effort and an equally high resolution of bee species identification, the experimental design had some limitations. The study was strongly requested by the authority managing these territories (CBMV3), but interventions were only possible in public areas. Management of these areas must first consider their role as occasional detention basins, so the plants allowed should have specific features: a non-planting root system, low and non-woody stems, resistance to water stress, low maintenance needs, and self-seeding. As far as possible, we chose non-ornamental and non-alien plant species that were as consistent as possible with the surrounding vegetation. Seeding and management of the areas were conducted by CBMV3, so the experimental plots had dimensions facilitating the work of large machinery. All these factors did not allow for smaller but more numerous experimental plots. However, these limitations, being the same for most floodplains, allowed us to develop “soft” pollinator-friendly management guidelines.

CRediT authorship contribution statement

Oana Catalina Moldoveanu: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Martino Maggioni:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Daniele Vergari:** Writing – review & editing, Supervision, Conceptualization. **Francesca Romana Dani:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Conceptualization.

Funding

Open access funding was provided by Università degli Studi di Firenze within the CRUI-CARE Agreement. O.C.M. acknowledges the

support of Programma Operativo Nazionale Ricerca e Competitività n. B11B21004740007. F.R.D. and M.M. acknowledge the support of the NBFC to the University of Florence, funded by the Italian Ministry of University and Research, PNRR, Missione 4 Componente 2, "Dalla ricerca all'impresa", Investimento 1.4, Project CN00000033.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Not applicable.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.127496.

Data availability

All data analysed for this paper are available in the Supplementary Materials.

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