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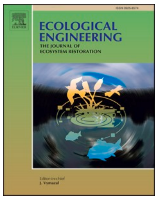

Wildflower strips in the agroecosystem for pollinator biodiversity restoration: Which plant species are capable of self-seeding?

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ABSTRACT

The success of wildflower strips for conserving pollinator biodiversity is often hampered by their poor sustainability, attributable to the short duration lifespan of the sown species. This three-year experiment aimed to: i) select the plant species that survived the agronomic disturbance practices implemented and ii) verify which crop management approach favoured their sustainability. Six experimental strips along the longest edges of the adjacent wheat crop were sown during the fall of 2019. The annual wildflower species that showed the best performances in emergence dynamics and seedling growth were some wildflowers derived from segetal weeds that are presently rare in conventional agroecosystems. The species *Centaurea cyanus*, *Agrostemma githago, Glebionis coronaria* among others attained the phenological stage of flowering most consistently, and also had the lowest mortality rates in the plant community studied. Despite preparing a stale seedbed, weeds were the most significant obstacle to the sustainability of the strips over time. Soil harrowing at the end of the summer lifecycle led to better plant survival performances (10.9 %) compared to senescent plant shredding (4.8 %). Harrowing also resulted in a greater wildflower survival the following year, as well as a higher number of pollinator visits. Honeybee visits were decreased by wildflower strip thinning over time, probably due to their typical constancy in the daily foraging choice for the same abundant species. A similar reduction was observed by the Lepidoptera. In contrast, generalist pollinators (i.e. Syrphidae, Bombyliidae, solitary bees and Coleoptera) were the least demanding pollinators in terms of the plant biodiversity of the sustainable wildflower strip. Harrowing led to a greater biodiversity of both wildflowers and pollinators (Shannon index, H′), and a lower weed dominance (Simpson index, D), compared to shredding. In summary, some segetal wildflowers could be incorporated into sustainable wildflower strips as they are self-seeding.

1. Introduction

Restoring agroecosystem biodiversity, which has been progressively eroded by both intensive cropping systems (Robinson and Sutherland, 2002) and climate change (Altieri et al., 2015), is one of the most important agronomic challenges of the new millennium (Barral et al., 2015). Indeed “ecological transition” is commonly used terms in agricultural policy planning (Langlais, 2023), combining biodiversity and agronomic sustainability as long-term productivity goals of agroecosystems.

In the complex dynamics of biodiversity decline within the agroecosystem, the feedback reduction in the mutualistic relationships (mutual benefit) between wildflowers and pollinators is of concern (Bretagnolle and Gaba, 2015). While most invasive weeds are self- and/or wind-pollinated (Gaba et al., 2017), wildflowers are essentially insect-pollinated and have little interference with the crops (Pinke et al., 2022). Consequently, they constitute an “ecosystem service” for bees and other pollinators. In practice, most common weeds that survive in highly disturbed agroecosystems, through conventional cropping systems, are characterized not only by their high competitiveness but also by the absence of mutualism (in terms of pollen movement and seed-set) from the surrounding pollinator biodiversity. The high competitiveness of the few dominant weed species (Storkey and Neve, 2018) has led to a marked decline in the biodiversity of both agroecosystems (Rollin et al., 2016) and natural grasslands (Farmilo and Moxham, 2023).

Unfortunately, this biodiversity decline is not merely an ecological problem but also an agronomic problem. In fact, it is now scientifically evident that the level of plant biodiversity is synonymous with agroecosystem sustainability over time (Crowder and Jabbour, 2014), also in terms of crop biocontrol (Dively et al., 2020; Hatt et al., 2017; Bischoff

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et al., 2022). Perennial species are especially quick in replacing annual flora, thereby dominating the post agronomic disturbance "ecological successions" (Sojneková and Chytrý, 2015).

A key element of biodiversity is provided by pollinators (Schulp et al., 2014), which enable the fertile seed-set of both wild flora (Benvenuti and Mazzoncini, 2021) and insect-pollinated crops (Vanbergen and Initiative, 2013). The most deliberated agro-ecological problem is the increasing decline in the most widespread global pollinators, namely the honey bees and (Neumann and Carreck, 2010).

An effective agronomic strategy in restoring agroecosystem biodiversity (promoting the increase of both plant and animal species) is to sow wildflowers strips alongside food crops (Korpela et al., 2013). This sowing can increase the pollination rate of insect-pollinated crops (Garibaldi et al., 2014). However, it is of even greater importance for the long-term survival of pollinators in the case of extensive (not insect-pollinated) cultivation with crops such as corn and winter wheat. Extensive cropping over large areas in the absence of biodiversity provides no food resources (pollen and/or nectar) for pollinators.

Unfortunately, the success of wildflower strips is often hindered both by the occurrence of a marked seed dormancy period of the various species and their overall, short duration lifespan over time, thus requiring subsequent re-sowing. Seed dormancy can be resolved by increasing the seed dose of those wildflower species with a lower germination (Baskin and Baskin, 2005), and/or by seed treatment that breaks the dormancy. However, sowing a wildflower mixture does not necessarily result in a vegetation cover with the same composition, as certain species may either establish poorly or not at all (Scheper et al., 2021). Furthermore, even wildflower strips with excellent emergence performances can be destined towards a rapid disappearance due to strong interferences by weeds (Schnee et al., 2023). Consequently, the sustainability of wildflowers over time is the largest overall agronomic problem due to the weed dynamics. Moreover, weeds are considerably more suited to self-seeding and to tolerating the agronomic disturbances typically carried out in the agroecosystem. Therefore, it is crucial to select insect-pollinated species with the greatest efficacy in restraining weed invasiveness and to carry out a suitable self-seeding that will enable its survival in the following years. Although commercial wildflowers, are characterized by excellent attractiveness performances for pollinators (Nichols et al., 2019), they do not appear to be suitable for wildflower strips that are sustainable over time. The reason is that they have not co-evolved with the typical agronomic disturbance management practices. To the contrary, ancient insect-pollinated weeds, which today are either rare or have even disappeared in conventional agroecosystems, may constitute an important plant resource in terms of pollinator survival. In other words, these wildflowers may represent a suitable choice in restoring biodiversity in anthropized environments (Kütt et al., 2016).

It is also not clear what agronomic management practice or technique at the end of the wildflower life cycle could guarantee the best strip performance in terms of sustainability over time. It is important to verify whether, and how, the mechanical management of the senescent wildflower residues is capable of shifting the competitive weed-wildflower balance to the advantage of the latter. The fact that some wildflower weeds have survived in ancient agroecosystems, disturbed exclusively by mechanical management, augments the hypothesis that these species are suitable plant species for sustainable wildflower strips.

The purpose of the present three-year experiment was to: i) to identify the most effective annual wildflower species in terms of seedling growth and plant self-sowing despite weed interaction and ii) to verify which mechanical management practice of senescent residues better promotes both wildflower and pollinator biodiversity.

2. Materials and methods

2.1. Plant material

Twenty-five herbaceous species with annual life cycles, with the exception of *Lycnis flos-cuculi* (Table 1), were selected for this study. The selection was based on two factors: i) their typical survival in agronomically disturbed environments, and ii) their attractiveness to pollinators due to the flower shape, size, color, inflorescence architecture and scents (Chittka and Raine, 2006). The respective, showy corollas are shown in Fig. 1. In the summer of 2019, senescent flowers, or inflorescences, of each of the twenty-five wildflower species were collected from the above-mentioned agro-environments. The seeds were extracted in the laboratory from the respective senescent flower tissues. They were then cleaned, dried (max 12 % humidity), and kept in glass jars (50 % air relative humidity) at 20 °C.

2.2. Agronomic environment

The trials were carried out in the experimental fields of the Department of Agriculture, Food and Environment of Pisa University (43°40′39"N, 10°19″46"E), Italy. The soil was sandy-loam (sand 70 %; lime 18 %; clay 12 %; pH 7.5; organic matter 1.8 %).

The climate of this agro-environment is typically Mediterranean with about 800 mm of annual rainfall, mainly concentrated in the autumn

Table 1

Botanical and agro-ecological information (Pignatti, 1982) of the twenty-five species tested in the experimental wildflower strips.

Wildflower species	Botanic Family	Environment of seed collection	Chorology
Adonis annua L.	Ranunculaceae	Crop edges	Eur-Medit.
Agrostemma githago L.	Caryophyllaceae	Winter cereals	Eur-Siber
Anacyclus radiatus Loisel.	Asteraceae	Crop edges	Steno-Medit.
Anchusa hybrida Ten.	Boraginaceae	Arid grasslands	Steno-Medit.
Anthemis arvensis L.	Asteraceae	Grasslands	Steno-Medit.
Blackstonia perfoliata (L.) Huds.	Gentianaceae	Arid grasslands	Eur-Medit.
Centaurea cyanus L.	Asteraceae	Winter cereals	Steno-Medit.
Centaurium erythraea Rafn.	Gentianaceae	Arid grasslands	Paleotemp.
Consolida regalis Gray	Ranunculaceae	Winter cereals	Eur-Medit.
Echium plantagineum L.	Boraginaceae	Pastures	Eur-Medit.
Glebionis coronaria (L.) Spach	Asteraceae	Pastures	Steno-Medit.
Glebionis segetum (L.) Fourr.	Asteraceae	Winter cereals	Eur-Medit.
Legousia speculum-veneris (L.) Chaix.	Campanulaceae	Grasslands	Eur.Medit.
Lycnis flos-cuculi L.	Caryophyllaceae	Grasslands	Eur-Siber.
Matricaria inodora L.	Asteraceae	Winter cereals	Sub-Cosmop.
Nigella damascena L.	Ranunculaceae	Winter cereals	Steno-Medit.
Orlaya grandiflora (L.) Hoffm.	Apiaceae	Arid grasslands	Cent.-Europ.
Papaver hybridum L.	Papaveraceae	Arid grasslands	Medit.-Turan.
Papaver rhoeas L.	Papaveraceae	Arid grasslands	Eur-Medit.
Silene armeria L.	Cariophyllaceae	Arid grasslands	Centr.-Europ.
Silene conica L.	Cariophyllaceae	Arid grasslands	Eur-Asiat.
Silene gallica L.	Cariophyllaceae	Arid grasslands	Eur-Medit
Tordylium apulum L.	Apiaceae	Crop edges	Steno-Medit.
Vaccaria hispanica (Mill.) Rauschert	Caryophyllaceae	Crop edges	W-Asiat.
Verbascum blattaria L.	Scrophulariaceae	Grasslands	Eur-Asiat.

Fig. 1. Flowers of the twenty-five tested wildflowers species: 1 = *A. annua* L. 2 = *A. githago*. 3 = *A. radiatus*. 4 = *A. hybrida*. 5 = *A. arvensis*. 6 = *B. perfoliata*. 7 = *C. cyanus*. 8 = *C. erythraea*. 9 = *G. coronarium*. 10 = *G. segetum*. 11 = *C. regalis*. 12 = *E. plantagineum*. 13 = *L. speculum-veneris*. 14 = *L. flos cuculi*. 15 = *M. inodora*. 16 = *N. damascena*. 17 = *O. grandiflora*. 18 = *P. hybridum*. 19 = *P. rhoeas*. 20 = *S. armeria*. 21 = *S. conica*. 22 = *S. gallica*. 23 = *T. apulum*. 24 = *V. hispanica*. 25 = *V. blattaria*. The vertical bar indicates 1 cm.

and spring periods. Annual minimum and maximum daily air temperatures fluctuate around the following ranges in the different months: February 2/10 °C, March 5/15 °C, April 10/18 °C May 14/24 °C, June 18/28 °C, July 20/30 °C, August 20/30 °C, and September 16/26 °C, min/max respectively.

Rectangular strips (2 × 50 m) were chosen in an area dedicated to wheat cropping. These areas were selected as the experimental plots based on their uniform weed distribution during the previous years. Sticks were fixed to the ground to delimit the six experimental strips along the longest edges of the adjacent wheat crop.

2.3. *Stale seedbed preparation*

In the late summer (August) and early autumn (October) of 2019, two “stale seedbed preparation” interventions were carried out to reduce the number of viable seeds in the soil. Both interventions consisted of two passages with a rotary harrow on each of the six previously delimited experimental strips. The first tillage procedure “forced” the previous seedbank to germinate by aerating the soil. The second tillage then mechanically eliminated the resultant weeds after the weed seedling emergence.

2.4. *Weed seed bank evaluation*

At the end of October 2019, after the stale seedbed preparation, the weed seed bank was analysed. In each of the 6 experimental strips, 30 soil cores were randomly collected from the shallowest soil layer (15 cm). Seed extraction was carried out, using a pressure adjustable hydrojet (20–120 bar), according to an already adopted methodology (Benvenuti et al., 2021).

2.5. *Wildflower field sowing*

The above-mentioned annual wildflower mix (only exception L. *flos-cuculi*) was sown in each of the six strips in the first ten days of November of 2019. To obtain a uniform plant density in the wildflower community, the seed dose of each species was calculated according to previous experiments (Bretzel et al., 2012). To obtain a uniform plant density in the wildflower community, the seed dose of each species was calculated according to previous experiments (Bretzel et al., 2012) in the directly proportional way to their 1000-seed weight and inversely to their germinability analysed in the laboratory according to standard procedures (Benvenuti and Macchia, 2006). The overall seed dose of the mix was of 5 g m^{-2} (corresponding to about 700 seeds m-2 in total).

After the manual seeding, light rolling was carried out to optimize the seed-soil contact and permit uniform seed germination and seedling emergence.

2.6. *Agronomic management*

After attaining the phenological stage of complete senescence (September 2020 and 2021, respectively), the wildflower strips were subjected to two agronomic management techniques after plant senescence: i) soil harrowing or ii) vegetation shredding. Three replicate strips (2 m × 50 m) for each technique were carried out. A randomized block was adopted as the experimental design.

2.7. Flowering dynamics

For each of the six wildflower strips, ten randomly selected plants of each species were marked with paper labels to evaluate the flowering dynamics in order to carry out surveys on the same plants over time. Data were expressed as flowering period (beginning and end) throughout the experimental period. Data for each wildflower species were collected weekly.

2.8. Evaluation of flower visitors

The quantity and biodiversity of the pollinators (insects that repeatedly visited the flowers) were analysed during the full flowering period of May over the experimental three-year period (2020, 2021, and 2022). May was selected as this was the month when all the wildflower species were in the full flowering phenological stage. Data were collected by placing a 1 m^2 plastic frame (sub-plot) along each experimental plot (three for each). Pollinators landing on the flowers inside this area (with evident feeding of pollen and/or nectar) were observed, identified, and counted. Pollinators were grouped into: honey bees (*Apis mellifera*), solitary bees, bumblebees, Syrphidae, Bombyliidae, other Diptera, Lepidoptera and Coleoptera. This evaluation was carried out weekly throughout the month of May at the following times: morning (from 10:00 to 12:00 h) and early afternoon (from 14:00 to 16:00 h). Observations lasted five minutes (in each of the aforementioned morning and afternoon evaluations) for each of the six strips (three sub-plot of 1 m^2 for each experimental plot). The total number of pollinator visits for each wildflower strip was expressed as pollinator visits m^{-2} h^{-1}, and the percentage of the relative pollinator groups was calculated.

2.9. Weed and wildflower evaluation

During February 2020, seedling emergence analyses were carried out in each plot (strips 2 × 50 m) to evaluate the plant density of both wildflowers and weeds (seeded and pre-existing flora respectively). In each experimental strip, a metal rectangle (50 × 50 cm) was placed randomly and the seedlings (10 counts for each strip) of the various species identified. The same survey was also repeated in the same manner in May (full flowering) in each of the three experimental years (2020, 2021, and 2022).

The data were processed as absolute density (plants m^{-2}) and then transformed into relative density (%) in order to calculate the biodiversity and dominance indexes of the various plant communities. In the third and last experimental year, destructive analyses (3 m^2 for each experimental plot) were also carried out to evaluate the above-grown weed biomass. The dry weight of each species was obtained by placing the plant material (cut at ground level) in a ventilated oven at 60 °C. When the tissues were completely dry (average drying time of one week), each weed sample was weighed.

2.10. Calculation of dominance and diversity indexes of weed, wildflower and pollinator communities

Data of the wildflowers and the related pollinators were used to calculate the Shannon diversity index (H′) as follows:

$$H' = -\sum_{i=1}^{k} p_i log p_i$$

where k is the number of plant or pollinator species, and p_i is the fraction of individuals belonging to the i^{th} each wildflower community or pollinator species.

In addition, the Simpson's index of dominance (D) of weeds was calculated, as shown below:

$$D = \sum (n_i/N)^2$$

where n_i is the number of individuals of a specific plant community, and N is the total number of weeds.

2.11. Statistical analyses

All the experiments used a randomized complete block design and were all conducted with three replicates. The variables analysed were: i) total visitors (No. $flower^{-1}$ h^{-1}) and ii) plant and pollinator biodiversity among the several categories (bees, solitary bees, bumblebees, Diptera Syrphidae, Diptera Bombyliidae, other Diptera, Lepidoptera and Coleoptera), iii) Plant density and dry weight of both wildflowers and weeds.

After the homogeneity test of variance, the arcsine transformation of the data was performed and expressed as a percentage to normalize their distribution (Steel and Torrie, 1980). All data (transformed percentages and untransformed not percentage data) were subjected to the analysis of variance (ANOVA) using Duncan's Multiple Range test ($p < 0.05$ and/or $p < 0.01$) for mean separation (least-significant difference, LSD). For each statistical analysis, CoHort (Minneapolis, MN) was used.

3. Results

3.1. Bio-agronomic performance of wildflowers after sowing

Despite sowing the same number of seeds per square meter, the emergence dynamics of the twenty-five wildflower species differed markedly (Table 2). The species showing the best seedling emergence performance were *G. coronaria* (23.7 plants m^{-2}) *A. githago* (22.4 plants m^{-2}), *Anthemis arvensis* (22.1 plants m^{-2}), *Glebionis segetum* (20.5 plants m^{-2}) and *C. cyanus* (19.4 plants m^{-2}), respectively. Conversely, the poorest seedling emergence species included *Consolida regalis* (4.3 plants m^{-2}), *Adonis annua* (5.2 plants m^{-2}), *Legousia speculum-veneris* (5.6 plants m^{-2}), *Blackstonia perfoliata* (5.4 plants m^{-2}), *Centaurium erythraea* (5.1 plants m^{-2}), and *Orlaya grandiflora* (7.2 plants m^{-2}), respectively. All the remaining species showed intermediate values between those mentioned above. Overall, the emergence rate (number of seeds/ emerged seedlings %) of the approximately 700 seeds sown per square meter was almost 50 %. However, not all emerged plants flowered. Of the 345.0 emerged seedlings per square meter, only 258.4 grew to reach the flowering stage. The different wildflower species showed different performances. Of interest, the same wildflowers that displayed the highest densities of flowering plants were also the same showing the best densities of emerged seedlings. The range fluctuated from 21.5 plants m^{-2} for *G. coronaria* to 1.8 plants m^{-2} for *C. erythraea*.

A comparison of the numbers of emerged seedlings and flowering plants highlighted the relative percentage mortality rate, which ranged from 64.7 % for *C. erythraea* to 1.3 for *A. githago*.

All twenty-five wildflower species reached the phenological stage of flowering between March and August (Table 3). The earliest wildflower species (March) included *Papaver hybridum*, *Silene conica*, *Silene gallica* and *Tordylium apulum,* respectively, while the latest (flowering until August) was *C. regalis*. Despite these differences in the flowering calendar, all the species tested showed full flowering in the month of May. May was, thus, considered the most suitable period to monitor the wildflower abundance and pollinator activity during the three-year experimental period.

3.2. Weed seedbank analysis

Table 4 shows the botanical composition of the weed seed bank detected in the “strip plots” used for the experiments. As expected,

Table 2
Agronomic performance of the twenty-five species sown in mixture for seedling emergence, attainment of the phenological stage of flowering and relative mortality rate (dead plants before flowering with to respect to emerged seedlings). Different letters of the total values indicate statistical differences ($p < 0.05$) according to the Duncan's LSD test. Values are followed by ± standard error.

Wildflower species	Seedling emergence	Flowering plants	Plant mortality (%)
	Plants m^{-2}		
Adonis annua L.	5.2 ± 0.4	2.1 ± 0.1	59.6 ± 3.1
Agrostemma githago L.	22.4 ± 2.3	22.1 ± 2.2	1.3 ± 0.1
Anacyclus radiatus Loisel.	13.2 ± 1.4	9.8 ± 0.7	25.8 ± 2.1
Anchusa hybrida Ten.	12.6 ± 1.4	7.9 ± 0.8	37.3 ± 3.0
Anthemis arvensis L.	22.1 ± 2.2	19.8 ± 1.6	10.4 ± 0.2
Blackstonia perfoliata (L.) Huds.	5.4 ± 0.4	2.1 ± 0.2	61.1 ± 4.1
Centaurea cyanus L.	20.4 ± 1.8	18.3 ± 1.2	10.3 ± 1.3
Centaurium erythraea Rafn.	5.1 ± 0.4	1.8 ± 0.1	64.7 ± 5.1
Consolida regalis Gray	8.7 ± 1.3	5.8 ± 0.4	33.3 ± 0.4
Echium plantagineum L.	8.6 ± 1.9	7.7 ± 1.2	10.5 ± 0.7
Glebionis coronaria (L.) Spach	28.3 ± 0.4	22.5 ± 2.3	20.5 ± 1.1
Glebionis segetum (L.)Fourr.	23.6 ± 0.6	18.6 ± 2.1	21.2 ± 0.8
Legousia speculum-veneris (L.) Chaix.	5.6 ± 0.3	2.5 ± 0.2	55.4 ± 4.7
Lycnis flos-cuculi L.	16.4 ± 1.4	14.3 ± 0.4	12.8 ± 1.1
Matricaria inodora L.	20.9 ± 1.9	16.4 ± 1.4	21.5 ± 1.1
Nigella damascena L.	21.3 ± 2.4	15.1 ± 1.8	29.1 ± 2.1
Orlaya grandiflora (L.) Hoffm.	7.2 ± 0.6	4.3 ± 0.4	40.3 ± 3.8
Papaver hybridum L.	8.3 ± 0.7	3.6 ± 0.2	56.6 ± 5.1
Papaver rhoeas L.	15.6 ± 1.4	13.6 ± 1.4	12.8 ± 1.1
Silene armeria L.	11.3 ± 1.2	3.5 ± 0.1	69.0 ± 5.4
Silene conica L.	13.6 ± 1.4	9.7 ± 0.5	28.7 ± 2.3
Silene gallica L.	15.2 ± 1.6	9.2 ± 0.8	39.5 ± 3.1
Tordylium apulum L.	13.5 ± 1.2	7.4 ± 0.6	45.2 ± 3.3
Vaccaria hispanica (Mill.) Rauschert	18.7 ± 1.5	11.3 ± 1.0	39.6 ± 3.2
Verbascum blattaria L.	16.9 ± 1.4	12 ± 0.8	29.0 ± 2.1
Total	360.1 ± 34.1 a	261.4	**Mean** 27.4 ± 2.3

despite the stale seedbed preparation, the shallowest soil layer (0–15 cm) still retained over 6000 seeds m^{-2} belonging to 27 different species. *Chenopodium album* and *Setaria viridis* were the predominant species, as these alone exceeded 1000 seeds m^{-2} with a relative density of 19.4 and 17.8, respectively. *Galium aparine*, *Lolium multiflorum* and *Echinochloa crus-galli* also showed approximately 400–500 seeds m^{-2}. A small number of seeds was found for the perennial species (*Cyperus rotundus* and *Plantago lanceolata*, 24.6 and 22.5 seed m^{-2}, respectively), with the exception of *Rumex crispus* with 300 seeds per m^{-2}.

3.3. Wildflower survival and weed dynamics after the different agronomic management techniques

As expected, a decline in the wildflower numbers was evident in the second and third years following sowing, in comparison to those recorded during the first experimental year (Table 5).However, this decline varied according to the different species and was also shown to vary as a function of the agronomic management. The shredding of senescent wildflower strips significantly decreased ($p < 0.05$) the survival dynamics during the subsequent years. Conversely, harrowing led to a greater survival of the wildflower community. A marked ability to survive was shown by *A. githago*, *A. arvensis*, *C. cyanus*, *G. coronaria*, *G. segetum*, *Matricaria inodora* and *P. rhoeas,* respectively. The survival rate of the latter species exceeded 20 % after three years after sowing. Conversely, some species such as *A. annua*, *Anchusa hybrida*, *B. perfoliata*, *C. erythrea*, *L. speculum-veneris*, *O. grandiflora*, *P. hybridum*, *S. conica*, *S.gallica*, *T. apulum* and *V. hispanica* showed a poor ability to survive over time, especially in the case of shredding. This wildflower decline was offset by a dramatic increase in weeds. From less than about 50 plants m^{-2} in the first year, the number of weeds increased to around hundred plants m^{-2} three years after wildflower sowing (Fig. 2). Moreover, the agronomic management practices showed an evident and statistically significant ($p < 0.01$) effect. The shredding of senescent wildflower residues showed a greater and more rapid weed increase ($p < 0.01$), compared to that found with harrowing carried out at the end of summer. In this latter case (Fig. 3A), the most invasive species, in the third experimental year, were *C. album*, *G. aparine*, *P. echioides* and *S. viridis,*belonging to the four different botanical families of Chenopodiaceae, Rubiaceae, Asteraceae and Poaceae, respectively. In contrast, in

Table 3
Calendar of the flowering dynamics of the tested wildflowers during the experimental periods.

Wildflower species	Flowering period (months of the year)											
	JAN	FEB	MAR	APR	MAJ	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Adonis annua L.				●	●							
Agrostemma githago L.				●	●	●						
Anacyclus radiatus Loisel.					●	●	●					
Anchusa hybrida Ten.				●	●	●						
Anthemis arvensis L.				●	●	●						
Blackstonia perfoliata (L.) Huds.				●	●	●	●					
Centaurea cyanus L.				●	●	●						
Centaurium erythraea Rafn.					●	●	●					
Consolida regalis Gray					●	●	●	●				
Echium plantagineum L.				●	●	●						
Glebionis coronaria (L.) Spach				●	●	●						
Glebionis segetum (L.)Fourr.				●	●	●	●					
Legousia speculum-veneris (L.) Chaix.				●	●	●						
Lycnis flos-cuculi L.				●	●	●						
Matricaria inodora L.					●	●	●					
Nigella damascena L.				●	●	●						
Orlaya grandiflora (L.) Hoffm.				●	●	●						
Papaver hybridum L.			●	●	●							
Papaver rhoeas L.				●	●	●						
Silene armeria L.				●	●	●						
Silene conica L.			●	●	●							
Silene gallica L.			●	●	●							
Tordylium apulum L.			●	●	●							
Vaccaria hispanica (Mill.) Rauschert				●	●							
Verbascum blattaria L.					●	●						

Table 4
Botanical information and density (absolute and relative) of the weed seedbank (0–15 cm), sampled before the sowing of the experimental wildflower strips. Values are followed by ± standard error.

Species	Botanic family	Life form[1]	Seed bank	
			Absolute density (seeds m^{-2})	Relative density[3] (%)
Abutilon theophrasti Medik.	Poaceae	T	25.8 ± 3	0.4
Amaranthus retroflexus	Amaranthaceae	T	144.5 ± 25	2.3
Anagallis arvensis L.	Primulaceae	T	85.4 ± 12	1.4
Avena sterilis L.	Poaceae	T	25.9 ± 4	0.4
Bromus sterilis L.	Poaceae	T	12.6 ± 2	0.2
Cerastium glomeratum Thuill.	Caryophyllaceae	T	321.4 ± 23	5.2
Chenopodium album L.	Chenopodiaceae	T	1233.7 ± 145	19.8
Cyperus rotundus L.	Cyperaceae	G	24.6 ± 2	0.4
Echinochloa crus-galli L. Beauv.	Poaceae	T	425.2 ± 15	6.8
Euphorbia helioscopia L.	Euphorbiaceae	T	12.8 ± 2	0.2
Fumaria officinalis L.	Papaveraceae	T	14.7 ± 3	0.2
Galium aparine L.	Rubiaceae	T	528.8 ± 3	8.5
Lamium purpureum L.	Lamiaceae	T	114.3 ± 14	1.8
Lolium multiflorum Lam.	Poaceae	T	465.4 ± 38	7.5
Picris echioides L.	Asteraceae	T	144.7 ± 18	2.3
Plantago lanceolata L.	Plantaginaceae	H	22.5 ± 3	0.4
Poa annua L.	Poaceae	T	74.6 ± 15	1.2
Polygonum aviculare L.	Polygonaceae	T	212.8 ± 21	3.4
Polygonum convolvulus L.	Polygonaceae	T	58.7 ± 14	0.9
Raphanus raphanistrum L.	Brassicaceae	T	112.2 ± 9	0.8
Rumex crispus L.	Polygonaceae	H	285.5 ± 18	4.6
Senecio vulgaris L.	Asteraceae	T	111.9 ± 14	1.8
Setaria viridis L. Beauv.	Poaceae	T	1133.8 ± 152	18.2
Sinapis arvensis L.	Brassicaceae	T	257.4 ± 35	4.1
Sonchus oleraceus	Asteraceae	T	15.7 ± 2	0.3
Stellaria media L. Vill.	Caryophyllaceae	T	216.2 ± 26	3.5
Veronica persica Poiret	Scrophulariaceae	T	214.2 ± 23	3.4
		Total	6235.3 ± 562	100.0

1 T = Therophyte; G = Geophyte; H = Hemicryptophyte.

the case of shredding (Fig. 3 B), the most invasive weeds mainly belonged to the Poaceae botanical family (*E. crus-galli*, *S. viridis* and *L. multiflorum*). In addition, the number of *C. album* (annual weed) was drastically reduced, while that of *R. crispus* (perennial weed) increased.

3.4. Pollinator flower-visits during the three-year experimental period

Throughout the three-year experiment, the wildflower strips were visited by all categories of pollinators: bees, solitary bees, bumblebees, *Diptera Syrphidae*, *Diptera Bombyliidae*, and other Diptera, Lepidoptera and Coleoptera groups (Fig. 4). During the first year, the number of flower visits was very high (Fig. 5), showing values of around 150 visits m^{-2} h^{-1}. However, the number showed a definite decrease in the following years, especially after shredding. In the second year after sowing and one year following shedding, there was a notable decrease in the number of flower visits (below 50 m^{-2} h^{-1}). This was significantly different ($p < 0.01$) from the situation in the wildflower strips managed with soil harrowing, in which the highest presence of pollinators (over

Table 5
Survival of the twenty-five wildflower species after the implementation of diversified agronomic management techniques (harrowing or shredding) carried out in September 2020 and 2021, respectively. Data are expressed as a percentage of the plant density with to respect to the seedling density detected after the sowing carried out in the first experimental year. Different letters indicate statistical differences within each wildflower species according to the Duncan's LSD test. Single or double asterisks indicate statistical differences between the agronomic disturbance techniques according to the same statistical test.

Survived wildflowers[1]	Agronomic disturbance		Statistical significance[2]
	Harrowing	Shredding	
	Survival[1]		
	%		
Adonis annua	2.2 d	0 d	n.s.
Agrostemma githago	35.3 a	13.5 a	**
Anacyclus radiatus	3.3 d	1.3 c	*
Anchusa hybrida	4.5 d	0.8 d	*
Anthemis arvensis	20.5 a	12.6 a	*
Blackstonia perfoliata	1.5 d	0 d	n.s.
Centaurea cyanus	25.8 a	8.5 b	**
Centaurium erythraea	1.1 d	0 d	n.s.
Consolida regalis	3.8 d	0.5 d	*
Echium plantagineum	15.2 b	2.3 c	**
Glebionis coronaria	23.5 a	15.8 a	**
Glebionis segetum	25.7 a	13.5 a	*
Legousia speculum-veneris	2.6 d	0 d	n.s.
Lycnis flos cuculi	5.4 c	8.2 b	n.s.
Matricaria inodora	28.2 a	12.6 a	*
Nigella damascena	16.3 b	5.8 b	**
Orlaya grandiflora	3.2 d	2.1 c	n.s.
Papaver hybridum	2.5 d	0 d	n.s.
Papaver rhoeas	23.7 a	8.5 b	**
Silene armeria	2.1 d	1.4 c	n.s.
Silene conica	2.5 d	3.1 c	n.s.
Silene gallica	2.8 d	3.5 c	n.s.
Tordylium apulum	1.1 d	2.6 c	n.s.
Vaccaria hispanica	3.5 d	0 d	n.s.
Verbascum blattaria	6.4 c	3.0 c	*
Mean	10.9	4.8	**

F = 11.32; d.f. = 33.

[1] With respect to the initial plant density after the emergence of the first year.

[2] n.s. = not significant, * = significant for p < 0.05, ** = significant for $p < 0.01$.

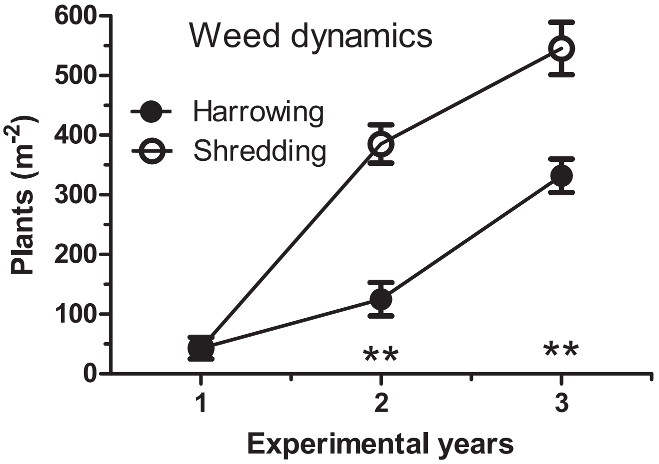

Fig. 2. Weed dynamics (derived from the pre-existing weed seed bank) after diversified agronomic management (harrowing or shredding) of senescent plants carried out at the end of summer. Single or double asterisks indicate statistical differences ($p < 0.05$ or $p < 0.01$ respectively) according to the Duncan's LSD test. Vertical bars indicate the ± standard error of the means.

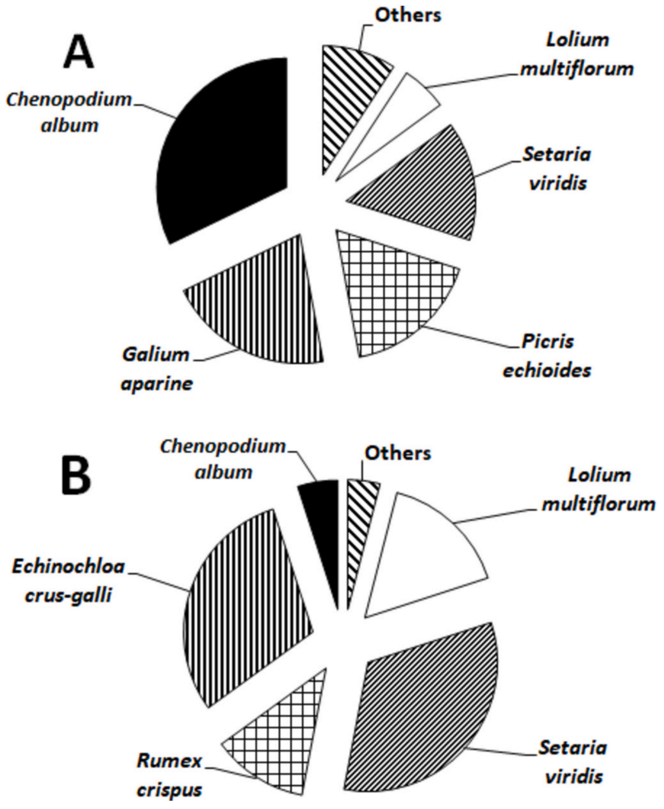

Fig. 3. Relative density (percentage of the total plant dry weight) of weed species at the end of the trial (third year) after agronomic management consisting of either harrowing (A) or shredding (B) of senescent wildflower strips.

50 m^{-2} h^{-1}) was detected.

During the third experimental year, after two consecutive years under the two agronomic management practices, respectively, the differences between harrowing and shredding decreased, although they were still statistically significant ($p < 0.05$). Both techniques reported values below 50 m^{-2} h^{-1}. This pollinator decrease was not the same in all the examined pollinator categories (Table 6). The bees were the most strongly reduced category over time both following harrowing (survival of 13.5 %) and, even more so, after shredding (survival of only 4.4 %), showing highly significant ($p < 0.01$) statistical differences. Other pollinator categories that were significantly reduced by the aforementioned wildflower decline were the Lepidoptera (only 8.1 and 4.9 m^{-2} h^{-1} individuals after harrowing or shredding, respectively) and bumblebees (only 16.6 and 6.6 individuals m^{-2} h^{-1} after harrowing or shredding, respectively). Minor reductions were found for solitary bees and the Diptera, but above all for the Coleoptera.

3.5. Dynamics of indexes of wildflower and pollinator biodiversity and weed dominance

During the three-year experimental period, the wildflower strips showed not only the aforementioned decreases but also a progressive reduction in biodiversity (Fig. 6A), evaluated using the Shannon Index (H′). The choice of agronomic management technique was also involved in modulating this decrease. In particular, shredding decreased the plant diversity the most, showing significant differences ($p < 0.01$) to harrowing management in both the second and third years after sowing. On the other hand, during the same three-year experimental period, weed dominance (Simpson Index, D) significantly increased (Fig. 6B). This increase was statistically significant ($p < 0.05$) in the second year and then even more so ($p < 0.01$) in the third year. Shredding favoured the dominance dynamics of the weed communities to a greater extent than

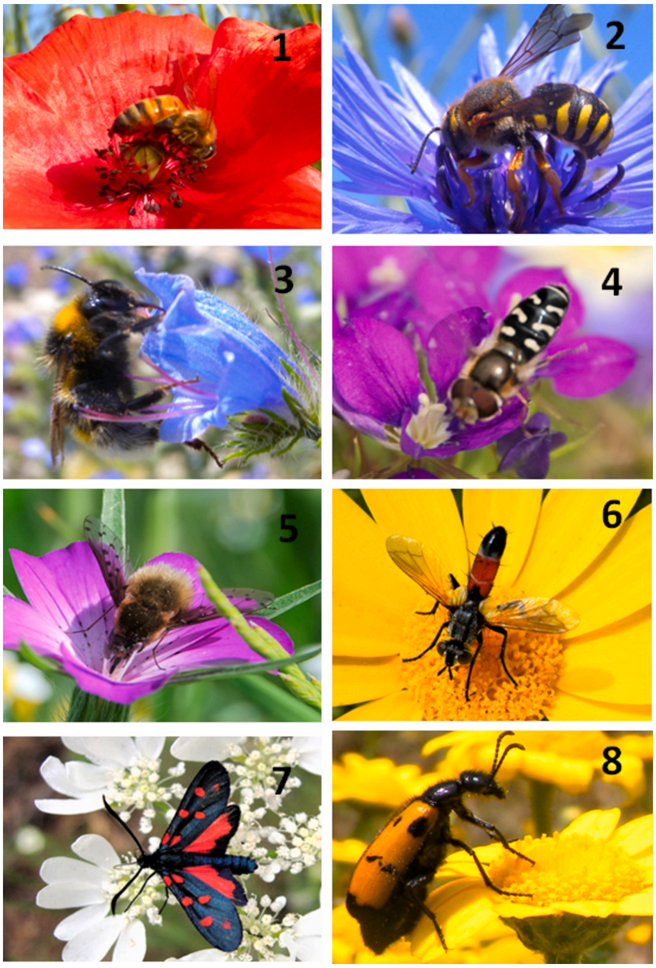

Fig. 4. Pollinator groups observed on the wildflower strips during the three-year experimental period: 1 = Honey bee (on *Papaver rhoeas*). 2 = Solitary bee (on *Centaurea cyanus*). 3 = Bumblebee (on *Echium plantagineum*). 4 = *Diptera syrphidae* (on *Legousia speculum-veneris*). 5 = Diptera bombyliidae (on *Agrostemma githago*). 6 = Other diptera (*Tachinida* on *Glebionis segetum*). 7 = Lepidoptera (on *Orlaya grandiflora*). 8 = Coleoptera (on *Anacyclus radiatus*).

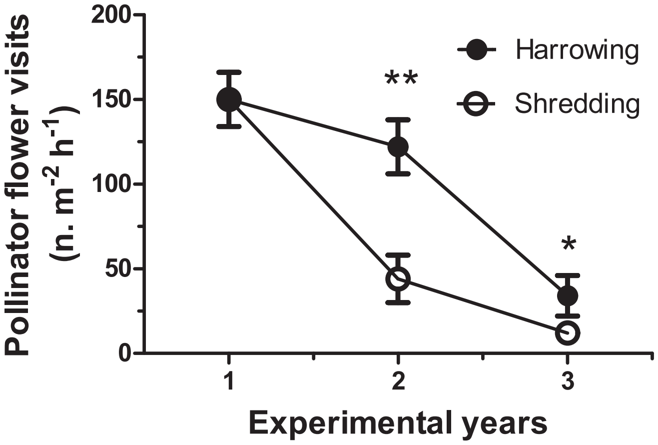

Fig. 5. Dynamics of pollinator visits on the wildflower strips during the three-year experimental period after diversified agronomic management (harrowing or shredding) of the senescent plants. Single or double asterisks indicate statistical differences ($p < 0.05$ or $p < 0.01$ respectively) according to the Duncan's LSD test. Vertical bars indicate the ± standard error of the means.

Table 6
Survival of the eight pollinator groups after a two-year period of diversified agronomic management (harrowing or shredding). Data are expressed as a percentage of the pollinator density, three years after sowing, with to respect to the pollinator density detected during the first experimental year. Different letters indicate statistical differences within each wildflower species according to the Duncan's LSD test, Single or double asterisks indicate statistical differences between the agronomic disturbance according to the same statistical test.

Pollinator groups	Agronomic disturbance		Statistical significance[2]
	Harrowing	Shredding	
	Survival[1]		
	%		
Honey bees	6.5 a	2.2 a	**
Solitary bees	26.2 c	15.1 b	*
Bumblebees	12.6 b	6.6 a	*
Diptera Syrphidae	21.1 c	19.5 c	n.s.
Diptera Bombyliidae	22.4 c	13.4 b	*
Other Diptera	25.5 c	22.2 d	n.s.
Lepidoptera	8.1 a	4.9 a	*
Coleoptera	33.0 d	24.6 d	*
Mean	23.1	15.6	*

F = 14.52; d.f. = 28.

[1] With respect to the initial pollinator density during the first year.

[2] n.s. = not significant. * = significant for $p < 0.05$. ** = significant for $p < 0.01$.

harrowing.

The pollinator biodiversity was associated with wildflower biodiversity (Fig. 6C). The decrease in biodiversity was more marked and significantly significant ($p < 0.01$ or $p < 0.05$) in the case of shredding. In contrast, soil harrowing partially reduced the decrease in pollinator biodiversity.

4. Discussion

4.1. Bio-agronomic performance of wildflowers after sowing

Although the wildflower mix was balanced, as the quantity of each species was inversely proportional to the relative unit weight and germinability, the effective seedling emergence of the various species showed a marked difference. Some species such as *A. annua*, *B. perfoliata*, *C. erythrea*, *C. regalis*, *L. speculum-veneris*, *O. grandiflora* and *P. hybridum* showed rather low emergence dynamics with between 5 and 10 seedlings per square meter. This appeared to be due to two factors: i) unpredictable induction of secondary dormancy after sowing (Baskin and Baskin, 2004), and ii) diversified germination inhibition mediated by the soil matrix surrounding the buried seeds (Benvenuti, 2023). In contrast, other species such as *A. githago*, *A. arvensis*, *G. coronaria*, *G. segetum*, *M. inodora* and *N. damascena* showed a very satisfactory emergence rate of more than 20 plants per square meter. All other species showed agronomically satisfactory emergence rates of between 10 and 20 seedlings per square metre.

Unfortunately, not all the emerged seedlings reached flowering, as commonly occurs in complex seeded wildflower communities (Hitchmough, 2000). The species with the highest density of flowering plants were the same (mentioned above, *A. githago,* etc.) as those showing the highest emergence rates. In practice, the more vigorous "ecological niche-occupation" was crucial for various species to establish themselves in the plant community. This is due to the early competitive (Adler et al., 2018) and allelopathic (Arroyo et al., 2018) interactions between both wildflower species and weeds. The most abundant species in the early growth stages tended to inhibit the most sporadic species. Consequently, the species showing the highest percentage of mortality were, almost always, those that had shown poor seedling emergence.

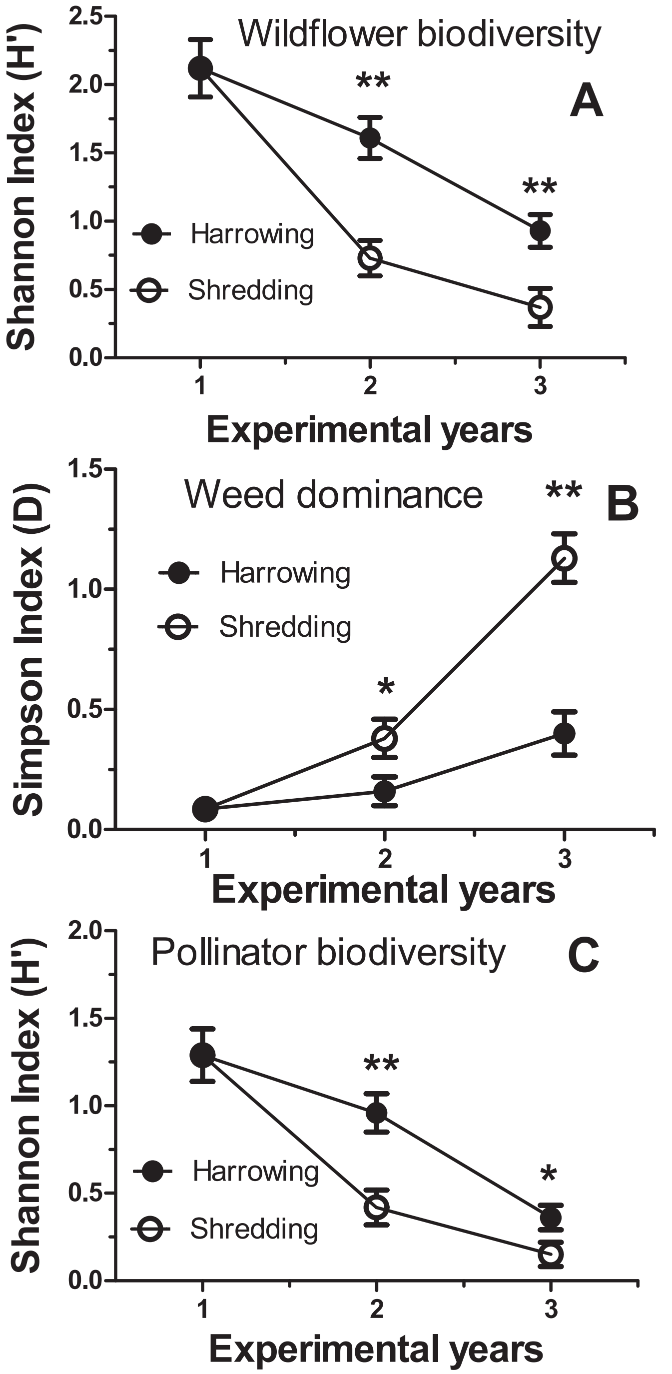

Fig. 6. Dynamics of wildflower biodiversity (Shannon index. A), weed dominance (Simpson index. B) and pollinator biodiversity (Shannon index. C) after agronomic management consisting of either harrowing (A) or shredding (B) of senescent wildflower strips. Single or double asterisks indicate statistical differences ($p < 0.05$ or $p < 0.01$ respectively) according to the Duncan's LSD test. Vertical bars indicate the ± standard error of the means.

As expected, the different flowering dynamics depended on the earliness or lateness of the various wildflowers. Despite the marked precocity of *P. hybridum*, *S. conica*, *S. gallica* and *T. apulum* and the lateness of *C. regalis*, the flowering peak of the wildflower strips occurred in May.

In terms of the "ecosystem service" for pollinators (Sutter et al., 2018), most of the wildflowers tested appeared to satisfy the food needs (pollen and nectar) of the pollinators during the spring. Therefore, the wildflower mixture appeared to be suitable for improving plant biodiversity alongside the wheat crops since, with the exception of some weeds (Rollin et al., 2016), pollinators usually have no available food resources, attributable to the lack of entomogamous species.

4.2. Weed seedbank composition

A weed seed bank in the shallowest soil layer (0–15 cm) containing approximately 6000 seeds m^{-2} was shown to conform to what can be considered a substantially widespread level of potential infestation (Graziani et al., 2012) in agroecosystems managed with conventional cropping systems. Many of the twenty-seven species identified in this study were limited in number, and were characterized by a low level of competitiveness due to their small size and/or their prostrate habitus. These included *Anagallis arvensis*, *Euphorbia helioscopia*, *Fumaria officinalis*, *Lamium purpureum*, *Plantago lanceolata*, *Poa annua*, *Polygonum aviculare*, *Stellaria media* and *Veronica persica*. In contrast, there were very low numbers of other weeds which clearly affects wildflower-weed competitiveness. The most prevalent species were *C. album* and *S. viridis*, both in terms of abundance (over 1000 seeds m^{-2}), and also in the degree of competitiveness towards the surrounding species (Moechnig et al., 2003). A further agronomic concern also stemmed from species such as *E. crus-galli*, *G. aparine*, and L. *multiflorum,* with around 400–500 seeds m^{-2} in the shallowest soil layer (0–15 cm). Additional species, although notoriously competitive, such as *Abutilon theophrasti*, *Amaranthus retroflexus*, *Raphanus raphanistrum* and *Sinapis arvensis*, were present in small numbers and as such did not pose a significant agronomic threat. The presence of weed species with a perennial cycle, such as *R. crispus*, *P. lanceolata* and *C. rotundus,* are capable of vegetative propagation. This renders the floristic evolution even more unpredictable in the future.

4.3. Wildflower survival and weed dynamics after the different agronomic management techniques

There are two crucial aspects for identifying agro-ecologically sustainable wildflower strips: i) the agronomic management techniques adopted, and ii) the choice of the most suitable species to sow. With regard to agronomic management practices, at the end of the life cycle harrowing proved to be of great importance in favouring the survival of the various wildflower species. Of great interest, the selected species were shown to be weeds that were once widespread in traditional agroecosystems before the "green revolution". Nowadays, these species are rare (Richner et al., 2015). Their survival was attributable to their resilience to agronomic disturbances carried out by soil tillage. The survival dynamics of these species are favoured by the cyclical burial of crop residues as these create the ideal conditions for soil surface recolonization through the germination and emergence of the periodically buried seeds. In contrast, shredding results in a mulch of the senescent wildflower strip which hinders the germination of the unburied seeds lying on the soil surface. After shredding, some species, such as *A. annua*, *B. perfoliata*, *C. erythraea*, *L. speculum-veneris*, *P. hybridum* and *V. hispanica*, were shown to completely disappear three years after sowing.

Unfortunately, despite the success after the first year of harrowing in strip management, not all species showed a satisfactory level of survival. There was a substantial reduction in the numbers compared to the first year. Nonetheless, in contrast to shredding, all species survived, albeit in small numbers.

The extreme difficulties in surviving extensive management conditions highlighted the survival ability of a few species, as was already observed in other agroecosystems (Kowalska et al., 2023). In the third experimental year, seven species (*A. githago*, *A. arvensis*, *C. cyanus*, *G. coronaria*, *G. segetum*, *M. inodora* and *P. rhoeas*), retained more than 20 % of their original density detected in the first year. The use of these species, together with harrowing at the end of the life cycle, was considered a positive outcome in terms of planning sustainable wildflower strips over time. We were surprised to discover that several of these species were precisely those that were once widespread in traditional agroecosystems (Sutcliffe and Kay, 2000), and which are now in decline following subsequent intensification cultivation practices. In this regard, it is worth highlighting the almost complete disappearance of *C. cyanus* and *A. githago,* which were once very widespread in ancient agroecosystems (Jauzein, 2001).

Undoubtedly, a real difficulty in the survival of the various wildflower species was attributed to the invasiveness of the pre-existing weed seed bank. In the first experimental year, thanks to the preliminary stale seedbed preparation, the weed density was below 50 plants m-2. Unfortunately, in the following year the weed density more than doubled after harrowing, and greatly increased (about 400 plants m-2) after shredding. In the third year, the weeds further established themselves at very high levels under both management practices. Of the two techniques, shredding was decidedly less sustainable.

At the end of the three-year experimental period, the weed composition differed markedly between the two types of agronomic management practices. In the case of harrowing, about three quarters of the weed community was composed of the annuals, *C. album*, *G. aparine* and *P. echioides*. Conversely, in the case of shredding, the prevailing botanical weed composition was formed by the Poaceae, such as *E. crus-galli*, *S. viridis* and L. *multiflorum*. This is probably based on the fact that growth of the Poaceae are favoured by an accumulation on the soil surface of annually produced seeds. This typically happens in cases of no-till cropping systems where grasses become the most widespread weeds (Leguizamón et al., 2009). As regards shredding, there was a notable increase in *R. crispus*, probably attributable to the ability of this perennial species to regrow from buds located on the soil surface that were not damaged by shredding. In summary, harrowing was shown to be the most favourable agronomic management technique, which led to a greater survival of the tested wildflowers. Shedding was significantly less sustainable over time.

4.4. Pollinator flower-visits during the experimental three-year period

During the spring of the first experimental year, a high number of flower-visits (about 150 visits m^{-2} h^{-1}) was observed. The pollinator abundance was also accompanied by their high complexity (Shannon index H', $p < 0.01$), as all the selected insect categories were found. This confirmed the marked efficacy of wildflower strips as a conservation strategy for pollinators in different agro-environments (Haaland et al., 2011; Schmidt et al., 2022; Scheper et al., 2021). However, it was noted that the success progressively decreased over the following two years, attributable to the aforementioned decline in wildflowers. The choice of agronomic management also impacted on the overall decline. In the second year, harrowing led to a greater wildflower survival and higher number of pollinators. In contrast, in the same year, shredding strongly reduced the wildflower density and consequently, the presence of pollinators. In the third year, there was a drastic decline in pollinators to a few dozen visits m^{-2} h^{-1} in both agronomic managements systems, but more specifically to that in which shredding was practiced.

The pollinator decline was not uniform for all the different categories, with some being affected more than others. At the end of the third year, honey bees suffered the greatest reduction compared to the first year. This appears to be attributable the behavioural characteristic of honey bees. The latter neglect the scarce blooms of some wildflowers since their "constancy" (Grüter et al., 2011) involves daily flower-visits to the same species. In other words, honey bees are generalist pollinators, but are demanding in choosing species with abundant blooms. Instead, the marked decrease in Lepidoptera appears to be due to the degree of specialization linked to their particular mouthparts (Krenn et al., 2005), which means they choose the most productive species in terms of flower shape (Schiestl and Johnson, 2013), nectar quantity (Wallisdevries et al., 2012), and composition (Mevi-Schütz and Erhardt, 2005). In practice, the increased rarefaction or even disappearance of some species of wildflowers that are rich in nectar and/or characterized by particular amino acids could be the cause of their greater decline.

The other categories (solitary bees, Diptera and Coleoptera) were reduced to a lesser extent in the third year, probably as these species are generalists in the choice of flowers to visit. The Coleoptera was the least reduced category as their food consists of pollen. Moreover, the consumption of pollen does not involve any specialization (Bernhardt, 2000).

In summary, the role of wildflower strips as a tool for pollinator conservation, has a duration of two years after sowing, but only if the agronomic management of their senescent residues is carried out through soil harrowing. However, sustainable wildflower strips can be implemented in the future in two modes: i) use of a wildflower mix formed only by species that are the most suited to survival (i.e. *A. githago*, *C. cyanus*, *A. arvensis*, *G. segetum*, *G. coronarium*, *M. inodora* and *P. rhoeas*), and ii) implementation of an additional stale seedbed preparation to ensure the further reduction in the pre-existing weed seed bank.

4.5. Dynamics indexes of wildflower and pollinator biodiversity and weed dominance

The initial biodiversity of wildflower strips, highlighted by the Shannon index, declined especially after shredding. Soil harrowing after wildflower senescence was the only technique to limit the decrease in wildflower numbers in the second experimental year. This modality of soil management appears to be crucial not only for creating the best conditions for the wildflowers to self-sow (i.e. acceptable germination due to suitable seed-soil contact), but also as a tool to hinder weed aggressiveness especially in the case of perennial species. In addition to increasing the number of weeds, shredding decreased their biodiversity rendering the weed community oligo-specific. In fact, the increase in grasses had a strong impact on the drastic increase in the dominance index (Simpson, D). Conversely, harrowing showed less of an increase in the dominance of broadleaf species. Nonetheless, weed dynamics, both in terms of the quantity and dominance of a few species, is the largest critical issue which severely limits the sustainability of wildflower strips over time (Benvenuti and Bretzel, 2017). Finally, the biodiversity dynamics of pollinators confirmed how their quantitative decline was also highlighted by the decline in their complexity. An acceptable level of pollinator biodiversity was only maintained in the second year with management based on soil harrowing. In the third year, although differences still evident between the different agronomic management techniques, the pollinator biodiversity collapsed to negligible levels from an agro-ecological point of view.

5. Conclusions

The future planning of wildflower strips could be based not only on the choice of species that perform ecosystem services for pollinators, but also by those that persist over time. The present study individuated seven species that were effective at surviving in the strips, in a Mediterranean environment, alongside the edges of a wheat crop. The most suitable species were ancient weeds, today definable as rare wildflowers, (*C. cyanus*, *A. githago*, *A. arvensis*) that only survived in eco-friendly agroecosystems. These species appeared to be resilient to the agronomic disturbance of harrowing at the end of the growth cycle. Moreover, harrowing was found to be optimal for the selected annual cycle species. Future experiments are necessary to investigate the optimal management of perennial wildflower strips. Further knowledge of what makes wildflower strips sustainable over time will be of crucial importance in the conservation of plant-pollinator biodiversity, both within the agroecosystem and in surrounding ecosystems.

CRediT authorship contribution statement

Stefano Benvenuti: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

I declare that my manuscript have not any financial and personal relationships with other people or organizations that could inappropriately influence (bias) their work. (Declarations of interest: none).

Data availability

Data will be made available on request.

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