Using the response – effect trait framework to quantify the value of fallow patches in agricultural landscapes to pollinators.

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Abstract

Questions: What is the role of managed fallow habitats in providing resources for pollination services in agricultural landscapes? How is resource provision affected by fallow management and landscape structure? Can the resulting variation in the value of fallows to pollinators be explained using the response-and-effect trait framework?

Location: Four semi-arid Mediterranean agricultural regions (NE Iberian Peninsula).

Methods: Landscape complexity, fallow field age and management practices were identified as the explanatory factors that interact which each other and affect the provision of resource for pollination communities. A trait-based approach was taken to model the system. Plant traits were selected on the basis of their response to abiotic factors (response traits) and those that influence the interaction with pollinators (effect traits). Plant community characterization was calculated based on both taxonomic and functional indices. The linkages between the selected plant traits on contrasting fallows were analyzed using community-weighted mean Redundancy Analysis (CWM-RDA).

Results: The presence of semi-natural areas in the landscape was shown to enhance the value of fallows for pollinators, providing a source of diverse flower forms. In contrast, we found that field edges act as a relatively poor reservoir for flowering plant species in these areas. Land-use practices promoting mid-successional plant communities that support the coexistence of diverse life forms with overlapping flowering periods and a range of flower morphologies had the greatest potential to support a diverse pollinator community.

Conclusions: An early-herbicide application (February) combined with shredding were identified as the best fallow-practices for enhancing resources for pollinators. The construction of our framework will help policy makers to identify management recommendations that will result in the most beneficial plant communities for pollinators in fallows.

Keywords: Fallow lands, Agri-environmental schemes, Functional traits, Ecosystem services, Pollinator attractiveness, Environmental filters.

Nomenclature: de Bolòs et al. (2005)

Introduction

In recognition of the unintended environmental consequences of the drive for increased productivity of agricultural land, the European Union's Agri-Environmental Regulation Initiative has promoted various Agri-Environmental Schemes (AES) to enhance levels of biodiversity on farmland (Whittingham 2011). Leaving land fallow is one option available in these schemes and is one of the most promising approaches for supporting and enhancing biodiversity in agro-ecosystems (Toivonen et al. 2013; Ma & Herzon 2014). In contrast to perennial field margins, fallows present the opportunity to manage large areas in field centres that provide a habitat for species adapted to disturbed environments (Butler 2009). Although the management of fallows has tended not to be primarily driven by the delivery of ecosystem services, these non-crop habitats are important landscape elements which may reinforce key ecosystem services such as pollination or biological control in the context of optimizing the multi-functionality of AES habitats (Kuussaari et al. 2011; Toivonen et al. 2013).

Because fallows are located in the main area of crop fields, characterized by regular disturbance, they provide a habitat for arable plant species that are functionally distinct from the more generalist species that tend to be found in the boundary features of arable landscapes. These arable plants (including many that could be classified as weeds) are more sensitive to perturbations and may also have a high intrinsic value as a component of biodiversity that provides distinct resources and functions in agroecosystems (Rotchés-Ribalta et al. 2015). The value of these floras on fallow lands will be influenced by the historical management pressure imposed on the field crop and on the specific conditions generated by the management of the fallow. A poor seed bank resulting from intensively managed land will require seeds from outside the field to increase plant diversity; therefore the surrounding landscape may also play a key role, acting as a reservoir for propagules (Kohler et al. 2008). A complex landscape, with a high percentage of natural and semi-natural habitats, is likely to act as a refuge for weed species that are most sensitive to intensive agriculture and also offer a great amount of resources for pollinator insects (Smart et al. 2002; Gaba et al. 2010; Solé-Senan et al. 2014).

Declining weed abundance has been identified as a driver of both pollinator declines and losses of pollination services (Steffan-Dewenter & Westphal 2008; Nicholls & Altieri 2012). Therefore, providing greater plant biodiversity on farmland through the provision of areas of land managed specifically for this aim is likely to increase the provision of a range of ecosystem services and utilizing fallow land avoids the negative impact arable weeds have on crop yield. However, it is difficult to quantify the enhancement of pollinator habitat (Whittingham 2011; Wratten et al. 2012) - all plant species do not contribute equally to the delivery of varied ecosystem processes and the sustainability and resilience of these processes may depend on aspects of diversity beyond the number of species present in a community (Stuart-Smith et al. 2013). Different pollinators promote selection for diverse floral forms that produce an array of "pollination syndromes", defined as a suite of floral traits that function as an advertisement and reward for pollinators (Fenster et al. 2004; Poveda et al. 2005). Changes in floral characters such as morphology, colour and odor or food quality can influence pollinator visits

(Wratten et al. 2012; Ricou et al. 2014). Developing models for quantifying the relative value of different habitats in the context of these floral traits is a clear research need for assessing contrasting habitats and management recommendations. Although the most often used management techniques to enhance pollinator habitat on farmland consist of field margin manipulation, the role of fallow land as a temporary patch habitat in dryland Mediterranean systems has been seldom explored.

The use of functional traits has been an important conceptual advance in linking biodiversity with ecosystem processes and associated services (Ma & Herzon 2014). A conceptual framework has been developed by Lavorel & Garnier (2002) that differentiates traits associated with response to environmental and management filters – response traits - from those that determine the effect of that change in the functional signature of the plant community on ecosystem services - predicted by effect traits. The overlaps or correlation between relevant response and effect traits will determine the extent to which an environmental or management driver will impact ecosystem functioning. This framework has recently been extended to systems where services are delivered by higher trophic groups (Lavorel et al. 2013; Solé-Senan et al. 2017).

The goal of this study was to populate this framework based on plant species abundance measured in experimental fallows in four semi-arid regions of the NE Iberian Peninsula, modelling the effects of landscape, age of fallow and field management as a series of filters acting on plant biodiversity and pollinator insects. By selecting target traits, we set out to 1) examine the response of plant vegetation traits to environment and management factors and 2) explore the overlap and interaction with plant 'effect' traits to predict the potential impact of changes in management in contrasting landscapes on the potential value of the fallows to pollinators.

Material and methods

Study area and experimental design

Trials were located in the Catalan part of the Ebro basin (north-eastern Iberian Peninsula), an area with a flat or slightly undulating topography, Mediterranean continental climate and average annual rainfall of 350 mm. A total of four separate fallow lands with different ages were selected as study areas: Montcortes (41°42'35.22''N; 1°13'52.33''E) and Ballobar (41°32'55.37''N; 0°5'59.06''E), were new fallows following an annual crop rotation and Balaguer (41°44'38.92''N; 0°45'21.63''E) and Mas de Melons (41°30'14.26''N; 0°42'40.18''E), have remained as fallows for five and four years before the start of the experiment respectively. All the study sites were selected because they were located in areas dominated by dryland cereal crops but represented different degrees of landscape complexity, from structurally simple –with high percentage of arable land- to more complex ones –with high percentage of semi-natural patches- (Appendix S1). All are also included in a special protection area of the Natura 2000 network, a key policy instrument for continental wide biodiversity protection in Europe.

We conducted a three-year field experiment (overthe 2012, 2013 and 2014 agronomic seasons, from October to June-July) to examine the succession of plant communities on fallow lands and the impact of contrasting management. The different starting points of the fallow fields allowed us to test the impact of management in the context of different natural successional stages,from more ruderal to more competitive communities. In each of the four study sites, one fallow field was divided into 21 plots of 200 m^2 as a randomized complete block design with three replicates for each of the treatments which reproduce some of the most common cultural practices carried out in fallow lands. The following treatments were applied: 1) chisel plough -a minimum tillage resulting in soil disturbance down to ten cm, 2) shredding – cutting and removal of the biomass-, 3) herbicide spray – glyphosate at 1.5 lha^{-1} dose- and 4) alfalfa sowing. The treatments had different timings: “early dates” – February, for chisel and herbicide, “late dates” –April: again for chisel, herbicide and shredding, and October for alfalfa sowing. Additionally, some plots were untreated (control), giving a total of seven treatments repeated three times in each study area: early chisel, late chisel, early herbicide, late herbicide, late shredding, early alfalfa and untreated control. At the end of each agronomic season (October), the vegetation of all experimental plots was cut in order to remove an excess of organic matter while maintaining the cumulative effect of the previous treatments.

Vegetation sampling

Plant data were collected from five quadrats of 0.25 m^2 located on each experimental plot in May, 15-20 days after the last management was done and when AES restrictions came into force. Coverage of each species was visually estimated as a percentage of the area of the entire quadrat (Appendix S2). Vegetation richness was recorded as the number of plant species identified in each quadrat.

Landscape/habitat information

Data on landscape structure variables were obtained from an aerial orthophoto SIGPAC (http://sigpac.mapa.es/fega/visor/) taken during the experimental period and measured within circles with a radius of 500 m around the centre of each experimental field, identified as the appropriate scale at which weeds are most strongly associated with landscape structure (Gaba et al. 2010; Marshall et al. 2006). After checking that the non-crop elements of the landscape had not change substantially during the study period, two landscape variables were calculated: percentage of semi-natural habitats and length of field edges, which previous studies have shown are relevant to plant diversity and weed community composition in the study area, providing quantified information regarding the surrounding habitat (Solé-Senan et al. 2014). Semi-natural habitats were identified as all non-cropped land uses and edge length was calculated by summing all the boundaries of the fields in that area.

Selection of plant traits

According to the model proposed by Lavorel et al. (2013), we first identified the plant traits that we expected to respond directly to the environmental and management drivers described above (response traits) (Appendix S3). Growth form together with flowering onset were included as they have been associated with persistence in disturbed habitats (McIntyre et al. 1995; Cornelissen et al. 2003; Gunton et al. 2011) and have been related to management practices, specifically the intensity of tillage (Fried et al. 2012). Seed dispersal plays an important role as it affects plant colonization, related to landscape structure and disturbance level, therefore modulating community assembly in space and time (McIntyre et al. 1995; Critchley et al. 2004). Plant height and Specific Leaf Area (SLA, the ratio of leaf surface to leaf dry mass) were both expected to respond to intensity of disturbance with disturbed environments being characterised by shorter plants with higher SLA, associated with faster resource use strategies *sensu* Westoby (1998). Plant height and SLA are also related to plant competition, which will vary with the succession stage.

Secondly, we classified the plant traits that can influence interactions with pollinator communities (effect traits) in the context of the traits of the pollinators themselves (trophic response traits, *sensu* Lavorel et al. 2013) (Appendix S3). It has long been noted that changes in floral features are highly linked with this function (Wratten et al. 2012; Ricou et al. 2014);so-called "pollination syndromes" (Fenster et al. 2004), such as corolla morphology and colour. These were therefore selected as traits that determine pollinator response. Discrimination between different corolla shapes is associated with accessibility (Gómez et al. 2008), distinguishing among generalists (pollinated by several to many animal species from different taxa) and specialist (pollinated by one or a few taxonomically similar animal species) flowers (Ashworth et al. 2004). This is likely to be correlated with morphometric parameters of pollinators (body size and mouthparts length) (Fenster et al. 2004). Flower colour is also a plant effect trait that will determine pollinator response. It is related to UV reflection and the ability of perception, thus it is associated with visual attractiveness (Menzel & Shmida 1993; Ricou et al. 2014). Finally, flowering duration also influences pollination visitation, determining reward (nectar and/or pollen) availability period (Bosch et al. 1997).

Trait values for each of the species were obtained from the literature and from open access databases (Appendix S3). We acknowledge the potential importance of intra-specific variability in determining functional diversity (Albrecht et al. 2012) and the benefit of measuring traits directly in the contrasting treatments. However, although this may affect the conclusions based on plastic traits such as SLA and height, many of the traits we included in our analysis (such as flower morphology and growth form) are categorical and will be largely unaffected by intra-specific differences.

Plant community characterization was calculated based on taxonomic and functional indexes. Two taxonomic metrics were selected: the total species richness (S) and the Shannon entropy index (H), presented as the exponential of Shannon-Weaver index. With this transformation, species are weighted in proportion to their frequency in the sampled community (Appendix S2) and thus it can be interpreted as an equivalent number of species in the community if they were all equally common and facilitates the interpretation and comparison of diversity among communities (Jost, 2006). To assess the functional approach we used the community-weighted mean (CWM) trait value (Garnier et al. 2004), which expresses the mean trait value in the community weighted by the relative abundance of the species. Furthermore, as a complementary metric, we quantified the degree to which trait values differ in a community by functional diversity (FD). We measured the variation in traits by using Rao´s quadratic diversity, combining multiple traits into one FD index (Moretti et al. 2013). Unlike CWM, which is calculated per each trait separately, FD is based on multiple traits. The Rao coefficient has recently been identified as a useful metric for comparing functional studies of contrasting biological communities and has the flexibility to combine dissimilarity data from single traits into a compound value from multivariate analysis of multiple traits (Ricotta and Moretti 2011).

Statistical analysis

Species richness, H, and FD (Rao) indexes were used to explain variation in plant communities between the different habitats and landscapes (Appendix S4). We performed General Linear Mixed Models (GLMM) with Poisson error distribution to investigate the relationship with landscape features and fallow-age taking into account only data from control plots. The effect of field treatments on diversity and species richness were tested, using all data, by a Linear Mixed Model (LMM) and a post-hoc Tukey´s pairwise comparison was utilized to determine differences among treatments. Locality and plot were included as random factors in both analysis to control the different historical management and the independence of the samples.

To quantify the innate correspondence between response-effect traits values in the study species pool, a Principal Components Analyses (PCA) was carried out to characterize the patterns of correlations among them. Variance in trait values between species was standardized to zero mean and unit standard deviation to give them all equal weight in the analysis before performing the PCA. To assess how the variability of individual traits changes along the environmental factors (effects of landscape, age since fallow and field treatments) we performed a CWM-RDA analysis following Kleyer et al. (2012). This technique uses multiple linear regressions (ordinary least squares) among response variables (traits) and predictors (environmental data). Because *Medicago sativa* was sown in some treatments, this species was excluded from the analysis in alfalfa plots, therefore only testing the indirect effect of the cultivation and additional competition on the background flora. Locality and plot were included as covariables.

T-value biplots were constructed from the CWM-RDA analysis for each of the explanatory variables (effects of landscape, age since fallow and field treatments) using the Van Dobben method (terBraak and Looman, 1994). Previous studies have used these ordination diagrams to disentangle plant species relationships (Madrigal et al. 2011; Schmitt et al. 2010). The ordination is based on reduced-rank regression, combining multiple regressions between species traits and a particular site factor, and the model defined by the CWM-RDA. Van Dobben circles indicate those traits with a strong relation to the explanatory variables tested (t-value < |2|).

Statistical analyses were performed with the R program, 3.0.2 (R Foundation for Statistical Computing, Vienna, AT) with the lme4package (http://CRAN.R-project.org/package= lme4) and with CANOCO 5.0 for Windows (Microcomputer Power, Ithaca, NY, US).

Results

An increase of Shannon entropy index (H) and species richness was observed as the percentage of semi-natural habitat in the landscape increased and the fallows became older, in this case also for FD (Rao); there was no relationship with total length of field boundary (Table 1). Post-hoc Tukey test results from LMM analysis did not find any association for either the taxonomical indices (H and species richness) or for the functional diversity index (FD Rao) between different treatments (data not shown). However, the late management interventions (chisel and herbicide) resulted in lower values of H and richness. In contrast, shredding and early herbicide were the treatments with highest values, more similar to those of the control. As regarding FD, the highest values were related to early-herbicide and late-chisel treatments (Fig. 1).

The first PCA axis accounted for 26.23 % of the variance and identified a trade-off between plant traits which was related to a successional gradient from more ruderal to competitive plant strategies (Fig. 2). Species with a low PCA1 score were characterized by a high SLA, early flowering or annual life cycle, graminoid forms, white-greenish-brownish flower colours with anemophilous and open entomophilous shapes. In contrast, species with a high PCA1 score had a perennial life form, late flowering time, tall stature, autochory seed dispersal, zygomorphic and tubular corollas, and yellow and blue flower colours. The contrasting plant strategies reflected in the multivariate analysis provide a useful framework for interpreting the response of the plant communities to different management treatments and potential value to pollinators. Trait relationships from Van Dobben circles results have been summarized in Table2, for those plant traits which response to the environmental factors (response traits), and in Table 3 for the traits underpinning interactions between plants and pollinators (effect traits/trophic response traits). The results are summarized in the following sections:

Landscape features and age since fallow (Tables 2 and 3)

Fallows within landscapes with a high percentage of semi-natural habitats had a community with a higher proportion of legumes, autochory seed dispersal and later flowering species, characteristics correlated with zygomorphic corolla and blue flower colour. A greater length of field edges promoted a community dominated by annual graminoid species and an anemochory and unassisted seed dispersal, related positively with characteristics as white-greenish-brownish flower colours and negatively with purple and yellow corolla ones and long flowering duration. A successional pattern was evident in that older fallows had plant communities more dominated by perennial forbs, such as hemicryptophytes and geophytes, and species with autochoric seed dispersal. These traits in turn were positively correlated with tubular corollas and yellow flower colour, and negatively correlated with open entomophilous corollas and purple colour.

Field management practices (Tables 2 and 3)

Among field management treatments, a promotion of annual plants by early interventions was observed together with the presence of shrubs on the early-herbicide treatment. Late herbicide and shredding increased the presence of perennial forms (mainly hemicryptophytes). Graminoids forms were more prevalent on early-chisel and alfalfa treatments than forbs. A late flowering onset was observed on the early-herbicide practices while in late herbicide treatments, a positive relation with taller plants and early flowering time was observed. The characteristics of plant communities resulting from the different field treatments were correlated with traits which are likely to determine pollinator interaction such as anemophilous corollas, positive related with alfalfa, chisel and shredding practices. Early-herbicide and shredding treatments were positively correlated with open entomophilous corollas and negatively with tubular ones, as was observed in alfalfa and early-chisel treatments. Yellow flowers showed a positive correlation to late-herbicide and other flower colours (such as greenish and brownish) were positive correlated with alfalfa, chisel treatments and shredding. Finally, a longer period of flowering was related to late chisel and early herbicide treatments.

Discussion

We aimed to better understand how altering fallow habitats by environmental or human-associated disturbances can influence the functional trait composition of the vegetation selecting between different plant ecological strategies. From the shifts in response and effect traits we predicted changes in the attractiveness for pollinators. Following the response-effect framework (Appendix S5), we now discuss: 1) the functional response of plant communities to environmental and management drivers and 2) the overlap with flowering traits that determine the value of fallows for pollinators.

Response of fallow plant communities to environmental and management drivers

Understanding the processes determining the variation of biological communities in habitats managed as part of agri-environment schemes requires analyses at multiple scales. Although particular management strategies may benefit certain species, it has been shown that landscape characteristics also play an important role in determining plant and pollinator diversity in managed ecosystems (Carvalheiro et al. 2011). Any change in species composition also needs to be related to functional characteristics since a reduction in functional diversity implying a substitution of specialist species by generalists, leading to a functional homogenization of the communities and a potential increase in competition among pollinators for resources (Clavel et al. 2010; Tadey 2015).

Areas of semi-natural habitat and field margins represent areas of least disturbance within arable systems, acting as a sink which provide shelter and refugia for plant species which are unable to persist in the harsh conditions of intensely cultivated habitats (Fried et al. 2009) and as a source, allowing immigration of plant species either to crop fields or new uncultivated patches as fallow lands (Gabriel et al. 2005; Tscharntke et al. 2005; Kleijn et al. 2011). These habitats generally have lower fertility than fertilised arable fields and are more likely to harbour legumes, a plant morphology which is predicted to increase under these conditions (van Elsen 2000); in our study, legume species of the *Coronilla*, *Medicago* or *Retama* genera were found at greater frequency in landscapes with a greater proportion of semi-natural habitat. The relative ecological stability of semi-natural areas is also reflected in the presence of species with late time of first flowering (Pinke & Gunton 2014) or autochory seed dispersal. Autochory is a short-distance dispersal mechanism and the low colonizing capacity over space suggests that species are in an optimal area. An increased proportion of semi-natural habitat in the landscape surrounding the fallows was reflected in a greater representation of these traits in the field centres and an overall increase in taxonomic and functional diversity. Contrary to our expectation and to the trend with an increase of semi- natural areas around fallow-fields, more field edges in the landscape did not show any relation either with the taxonomic indices or with the functional diversity (FD (Rao)). In our study system, field edges were not managed for biodiversity and only provided extremely narrow boundaries with no capacity to buffer negative effects from neighbouring areas due to the high intensity of agricultural practices

(Aavik & Liira 2010; Ma et al. 2002) resulting in a dominance of annual grasses. There may, therefore, be potential to combine improved field margin management with the appropriate management of fallows to add value to both components of the agricultural landscape.

Studies of successional dynamics in managed ecosystems have highlighted that old communities tend to be more competitive, leading to uniform landscapes which provide fewer niches for weeds or insects (Lososová et al. 2006; Kuussaari et al. 2011). Our results show a contrasting trend, with older fallows having a higher taxonomic and functional diversity and coexistence of species with dissimilar functionality. Low disturbance rates, the chance to develop different resource acquisition strategies or unpredictable natural regeneration have all been suggested as causes of the persistence of a diversity of flower species with high resource value (Wratten et al. 2012). It may be, however, that as the fallows age further, the dominance of a few, more competitive species may increase and that we mainly observed mid-successional communities with a combination of earlier ruderal and later competitive strategies. Succession of the vegetation with fallow age also revealed a gradient of plant strategies as noted by Garnier et al. (2004). Early fallow stages, immediately following agricultural disturbances, had a community dominated by opportunistic ruderal species with traits associated with fast growth: annual life cycle and high SLA. Anemochory seed dispersal is related most strongly to the ability of a species to colonize new patches that may be a long distance from the source population (Dupré & Ehrlén 2002; Kohler et al. 2008). Hemicryptophytes and geophytes appear as the dominant life forms on late successional fallow stages mainly represented by Asterceae family (*Crepis*, *Silybum* or *Carduus*) and autochory seed dispersal, indicative of competitive plant communities.

Among the management regimens tested in this study, early herbicide application is the one that led to a habitat occupied by both annual and woody plants, diversifying vegetation structures and so, ecological strategies. Glyphosate is a non-selective contact herbicide that controls a wide range of weeds. However, phanerophytes, chamaephytes and most of the hemicryptophytes are the least harmed, leading to a more heterogeneous habitat. The role of these biological forms, in contrast to annual herbaceous plants, resulted in a sparse and patchy habitat with a lower density of vegetation. Previous studies have shown that periodicity of flowering is adapted to the intensity and frequency of soil disturbances in herbicide treatments (Gaba et al. 2013). Tillage promoted pioneer annual plants with fast life cycles (Sojneková & Chytrý 2015). It is also noteworthy that the annual graminoid dominance on alfalfa and early-chisel, was related to early soil disturbance, while late-chisel managements are characterized by a predominance of perennial rhizomatous/stoloniferous graminoids such as *Cynodon dactylon* which permit an effective colonization of bare ground sites (Kahmen et al. 2002). Although we have shown that the effect of herbicides can be interpreted in the context of a disturbance regime and so related to plant traits, it is also the case that herbicide selectivity will also play a major part in the structuring of communities in agricultural landscapes. These effects may ultimately have to be modelled at the level of individual species.

Interaction of response and effect traits

Identifying key plant traits which influence the interaction with pollinators will be useful for understanding the effect of the responses of communities to environment and management discussed aboveon pollination services. Pollinators were not directly measured in this study, however, well established published relationships between flowering traits and attractiveness to pollinators allow us to predict the impact of the landscape and treatments on the value for different plant communities to pollinators.

In our study, the increase of legumes on fallows in landscapes with a higher proportion of semi-natural habitats was linked with zygomorphic corolla and blue flower colour, well-known syndromes of complex flowers that are associated with pollination by long-tongued bees (Corbet 1995; Fenster et al. 2004). However, the high functional divergence on these fallows may indicate that, although pollinators specializing in zygomorphic flowers would be expected to be promoted, these fallows also support plants which provide resources to generalist pollinators. The presence of these patches of relatively high-contrast habitat types, or 'ecotones', is predicted to enhance the value of managed fallows for pollinators. Moreover, semi-natural habitats provide a place to nest and hibernate for the major pollinator groups (Batáry et al. 2011), making them an essential element in the landscape. But, not all the so-called ecotones´ elements in the landscape were acting in the same way on the fallow floras with a high proportion of field boundaries having a deleterious effect on resource provision for pollinators. The high level of disturbance generated by the farm practices has led to an impoverishment of the habitat value of field edges, acting as a source of undesirable kind of species such as graminoids. The Poaceae family is considered to be inaccessible and so less frequently visited by pollinators (Ricou et al. 2014), leading to a reduction of flower features which promote pollinator-plant interactions (Fenster et al. 2004).

Along the age-gradient succession, the dominance of more generalist flower features in early stages such as open entomophilous corollas is notable and suggests that, at this stage, all pollinator fauna may be functionally equivalent (Fenster et al. 2004). As expected, different successional stages were not functionally equivalent and one approach to management would be to design interventions that aim to maintain communities in the successional stage that delivers the most value to pollinators. We suggest, maintaining mid-successional communities would be optimal for supporting a wide range of pollinators in our system. To achieve this type of habitat, intermediate levels of disturbance may be required (Wratten et al. 2012). In this regard, early-herbicide treatments were beneficial because they promoted a heterogeneous habitat structure allowing a high coexistence of life forms and so an overlapping of flowering periods. The increased abundance of flowers with open entomophilous corollas as opposed to anemophilous ones (that tended to dominate in other management treatments) was another important component of the floras adapted to this treatment. However, the role of pesticides in agriculture in causing pollinator declines is well documented, especially where spraying time coincides with flowering time (Nicholls & Altieri 2012). Here the application was made in early February, out of the flowering peaks of most of the species. Open entomophilous and anemophilous corollas were promoted by shredding management, while anemophilous ones dominated in chisel and alfalfa treatments, resulting in poor habitat quality in terms of attractiveness for pollination. Alfalfa is generally considered as a temporary pollinator-friendly cover crop (Wratten et al. 2012) because of its beneficial flower features. Nevertheless, this area presents a low productivity index (Oñate et al. 2007) and alfalfa crops without an irrigation supply, often fail. At the same time, the early soil removal caused by the alfalfa sowing is favoring the development of Poaceae species, the less attractive family for insects.

A landscape perspective is needed to achieve conservation goals on fallow lands. While local effects of management can be detected over small scales that share a similar environment, deriving more general rules of plant community assembly in fallows is dependent upon regional scales that aggregate environmental heterogeneity. In order to achieve this, an important distinction between the landscape elements must be made. As a next step to further assess ways to enhance pollinator habitats in fallow lands, a validation of the results of the study would be desirable to determine the relationships between our predictions and information on insect species´ abundance and diversity. Also, here we have tested the field practices which are most commonly developed in these of non-crop habitats; however other management options could also be applied. Since livestock tend to promote vegetation heterogeneity, selective grazing could be suggested as an alternative management practice in fallows. If sowing is an option, an important issue to take into account to enhance its efficiency is to have a good knowledge about the abundance and diversity of groups of pollinator in the region before choosing plant species (Pywell et al. 2011). The use of herbicides in a conservation study often causes controversy and, although chemical application could presumably be beneficial for some target species, future assessment of its potential damage to insects or wildlife in general is first required.

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Supporting Information

Appendix S1. Summary of the site characteristics.

Appendix S2. List of species encountered and average abundance in relation to field practices applied in the study.

Appendix S3. Summary of plant response and effect traits used in the analysis.

Appendix S4. Summary of the mean species richness, Shannon diversity index (H) and functional diversity index (Rao) (±S.E.) per field treatment.

Appendix S5. The response–effect trait framework based on Lavorel et al. (2013).

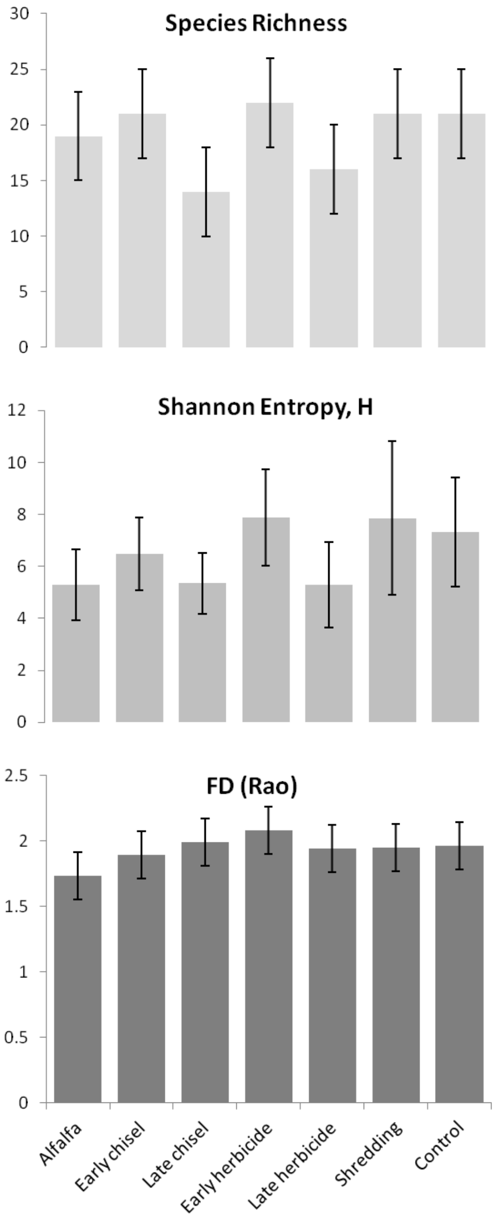

Fig. 1. Mean of species richness, Shannon entropy index (H) and Functional diversity index (Rao) per field treatment. Error bars show SE.

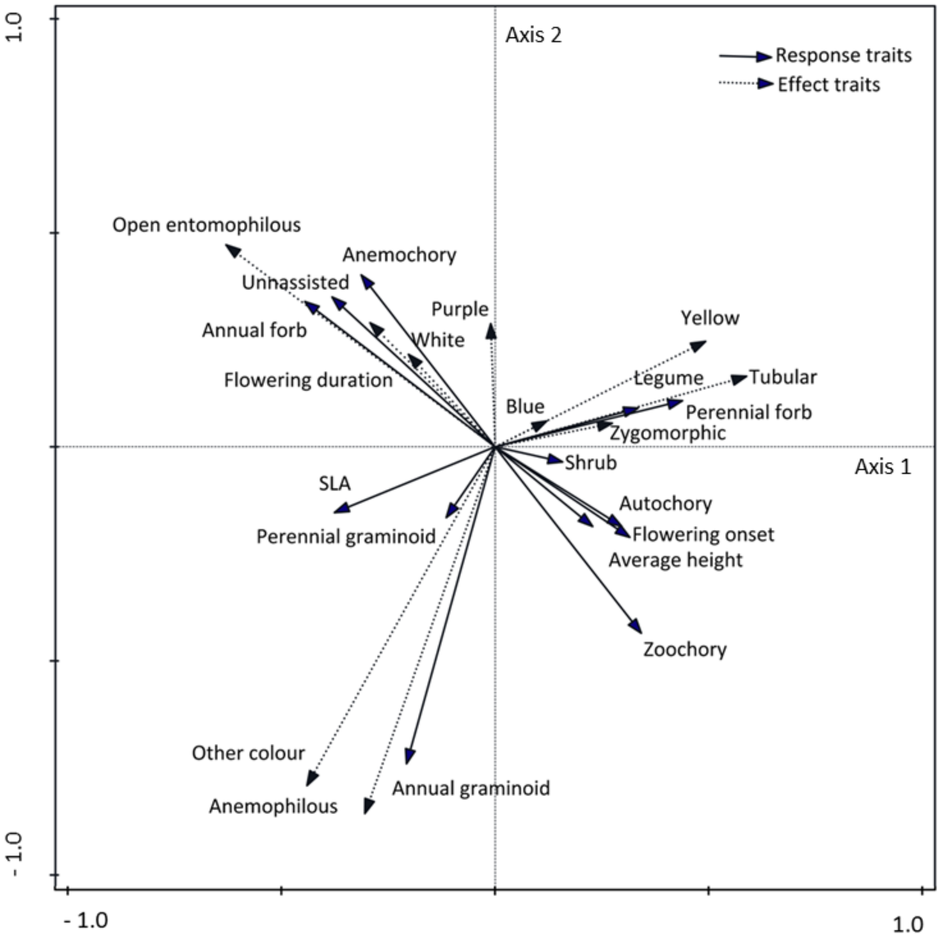

Fig. 2. Correlation among plant functional traitsrepresented by a Principal Components Analysis. Percentage variance accounted for first two axes = 36.3%. Primary axis for the response traits represents trade-off between ruderal traits (fast cycle of life, high specific leaf area, annuality) and competitive traits (late flowering time, perennial life-forms, tall stature) and for the effect traits is associated with the complexity of floral structures, traits related with generalists pollinators (white-greenish-brownish flower colours, anemophilous and open entomophilous corollas) and traits linked with more specialists insects (yellow and blue flower colours, zygomorphic and tubular corollas).

Table 1. General linear mixed model (GLMM) of the changes in species richness, Shannon diversity index (H) and functional diversity index (Rao) in relation to landscape features (percentage of semi-natural habitat and length of field edges) and age since fallow using Poison error distribution and including location and plot as random factors.

Environmental factors	**Indexes**	**F**
Semi-natural habitat	Richness	7.75***
	H	5.74**
	FD (Rao)	3.14
Edges length	Richness	0.01
	H	0.18
	FD (Rao)	0.27
Age since fallow	Richness	1.18*
	H	1.41*
	FD (Rao)	2.97*

* P <0.05; ** P <0.01; ***P<0.001

Table 2. Summary of Van Dobben circles results for response plant traits, representing the positive (represented by a +) or negative (represented by a -) relation to the abiotic variables.The traits that are not acting as a response to the abiotic filters according to the framework described in Appendix S5 are represented by grey blocks.

		Abiotic filters								
		Landscape features		Age of fallow	Field managements					
		Semi-natural habitats	Length of field edges		Alfalfa	Earlyc hisel	Late chisel	Earlyherbi cide	Late herbicide	Shredding
Growthform	Annual forbs							+	-	
	Perennial forbs		-	+	-	-			+	+
	Annual graminoids		+	-	+	+				
	Perennial graminoids						+			
	Legumes	+								
	Shrubs							+		
Seeddispersal	Anemochory		+	-	▨	▨	▨	▨	▨	▨
	Autochory	+		+	▨	▨	▨	▨	▨	▨
	Zoochory				▨	▨	▨	▨	▨	▨
	Unassisted		+		▨	▨	▨	▨	▨	▨
	Average height	▨	▨	▨					+	
	SLA	▨	▨	-						
	Flowering onset	+						+	-	

Table 3. Summary of Van Dobben circles results for effect plant traits, representing the positive (represented by a +) or negative (represented by a -) relation to the abiotic variables.

		Abiotic filters								
		Landscape features		Age of fallow	Field managements					
		Semi-natural habitats	Length of field edges		Alfalfa	Earlychisel	Late chisel	Earlyherbicide	Late herbicide	Shredding
Corolla shape	Anemophilous		+		+	+	+			+
	Open entomophilous			-				+		+
	Tubular			+	-	-		-		
	Zygomorphic	+								
Flowercolour	Purple		-	-						
	Blue	+								
	Yellow		-	+					+	
	White		+							
	Other colour		+		+	+	+			+
	Flowering duration		-				+	+		

Supporting Information to the paper

Robleño, I. et al. Using the response – effect trait framework to quantify the value of non-crop patches in agricultural landscapes to pollinators. *Applied Vegetation Science*.

Appendix S1.

Summary of the site characteristics.

Location	**Semi-natural habitats* (ha)**	**Length of field edges (m)**	**Age of fallow**		
			2012	2013	2014
Mas de Melons	20.1	8981.3	4	5	6
Montcortes	1.7	8575.4	1	2	3
Balaguer	4.5	8322.9	5	6	7
Ballobar	5.2	9588.6	1	2	3

*500 m buffer = 78.54 ha (100%)

Supporting Information to the paper

Robleño, I. et al. Using the response – effect trait framework to quantify the value of non-crop patches in agricultural landscapes to pollinators. *Applied Vegetation Science*.

Appendix S2.

List of species encountered and average abundance in relation to field practices applied in the study. Nomenclature follows de Bolòs et al. (2005).

Species	**Control**	**Alfalfa**	**Shredding**	**Early-chisel**	**Early-herbicide**	**Late-chisel**	**Late-herbicide**
Adonis microcarpa	0.0373	0.0427	0.0193	0.0107	0.0220	0.0823	0.0003
Aegilops geniculata	0.0250	0.0167	0.0050	0.0067	-	-	-
Allium sp.	-	0.0377	0.0067	0.0017	0.0267	0.0017	0.0190
Amaranthus albus	0.0067	-	-	0.0037	-	0.0033	-
Amaranthus blitoides	-	0.0017	0.0130	-	0.0253	0.0723	0.0137
Amaranthus retroflexus	0.0007	0.0007	0.0107	-	-	-	0.0003
Anagallis arvensis	0.1412	0.2007	0.1353	0.1020	0.4107	0.1263	0.1807
Anacyclus clavatus	10.849	5.1547	4.5027	5.3407	6.3060	3.2150	4.9110
Anthemis arvensis	-	-	-	0.0067	-	-	-
Astragalus sesameus	0.0038	-	-	-	0.0010	0.0667	0.0033
Atractylis humilis	-	-	-	-	-	0.0017	-
Avena barbata	-	-	0.0033	-	-	-	-
Avena sterilis	0.0277	0.1800	0.0467	0.1473	0.0733	0.0350	0.0383
Bromus diandrus	2.3678	1.8003	0.2170	4.8220	0.3403	0.3010	2.3277
Bromus hordeaceus	-	-	-	0.0100	-	-	-
Bromus madritensis	-	-	0.0100	-	0.0067	-	-
Bromus rubens	0.1808	-	0.0007	0.1700	0.0350	0.0300	0.0067
Bupleurum semicompositum	0.1398	0.0263	0.3740	0.0017	1.2393	0.0870	0.0747
Calendula arvensis	0.0075	0.0133	0.2033	0.0833	0.0040	0.0350	0.0287
Capsella bursa-pastoris	-	0.0057	0.0007	0.0240	-	0.0690	-
Carduus bourgeanus	0.0033	-	-	-	0.0017	0.0023	-
Carthamus lanatus	0.1180	0.1390	0.2233	0.0200	0.1940	0.2033	0.0233
Carduus tenuiflorus	0.2283	-	0.0170	0.0083	0.0010	-	0.0150
Centaurea aspera	0.2067	0.1550	0.1817	0.1250	0.0600	0.1657	0.0167
Centaurea melitensis	0.5572	0.2530	0.1520	0.1440	0.1563	0.2183	0.1550
Centaurea solstitialis	0.2818	0.1483	0.1193	0.0023	0.0457	0.2633	0.1233
Cerastium glomeratum	-	0.0067	0.0050	0.0087	-	-	0.0100
Chenopodium album	-	-	0.0070	0.0003	0.0003	0.0037	-
Chenopodium vulvaria	0.0560	0.0840	0.0790	0.1303	1.1593	0.3037	0.1127
Chondrilla juncea	0.1100	-	0.1733	0.0133	0.0350	0.0493	0.0133
Cirsium arvense	-	-	-	0.0007	0.0047	0.0067	0.0017
Cnicus benedictus	-	-	0.0017	-	-	0.0057	-
Convolvulus arvensis	0.3482	0.2467	0.3450	0.4507	0.9260	0.4310	0.2383
Conyza sp.	-	-	-	-	0.0103	0.0007	-
Coronilla minima	-	-	0.0333	-	-	-	-

Species	**Control**	**Alfalfa**	**Shredding**	**Early-chisel**	**Early-herbicide**	**Late-chisel**	**Late-herbicide**
Coronilla scorpioides	0.6158	0.2837	0.0017	0.0133	0.0270	0.0197	0.1443
Crepis capilaris	-	-	0.0040	-	0.0017	0.0117	-
Crepis foetida	-	-	0.0033	-	-	-	-
Crepis pulchra	0.0783	0.1133	0.0867	0.0833	0.0667	0.3433	0.0833
Crepis sancta	-	-	0.0267	0.2600	-	-	0.0067
Crepis sp.	1.4577	0.3243	1.9413	0.3020	0.9523	0.4117	0.8400
Crepis vesicaria subsp. *taraxacifolia*	2.0638	0.1530	1.7633	0.5700	0.5440	0.9950	1.9230
Crucianella angustifolia	0.0033	-	-	-	-	-	0.0117
Crupina vulgaris	-	0.0017	-	-	0.0037	0.0033	-
Cynoglossum cheirifolium	0.1133	0.0003	0.0727	-	0.0233	-	0.0067
Cynodon dactylon	0.1607	-	0.3617	-	1.2040	0.1600	0.2067
Delphinium gracile	-	0.0017	-	-	-	-	-
Desmazeria rigida	-	-	-	0.0017	-	-	-
Diplotaxis erucoides	2.2863	0.3317	2.1487	3.1910	1.5520	3.6033	1.4823
Dipcadi serotinum	-	-	0.0167	-	-	-	-
Echium plantagineum	0.0167	-	-	-	-	-	0.0100
Echium vulgare	0.0500	-	0.0017	-	-	-	-
Erodium ciconium	0.1083	0.0217	0.3733	0.0100	0.0633	0.1737	0.0883
Erodium cicutarium	0.0667	0.0137	0.1123	0.0550	0.2493	0.0780	0.4320
Erodium malacoides	0.1590	0.0250	0.3943	0.1100	0.2710	0.5350	0.6517
Erucastrum narsturtiifolium	0.0743	0.0337	0.0040	0.0167	0.4423	0.1083	0.0933
Eruca vesicaria	1.9170	0.2883	1.2050	2.8500	1.6640	1.1100	1.3480
Eryngium campestre	0.4917	0.0407	0.0613	0.0367	0.1613	0.0770	0.1603
Euphorbia exigua	0.0037	-	-	-	0.0017	-	-
Euphorbia falcata	0.0138	-	0.0083	0.0067	0.0020	0.0003	0.0123
Euphorbia helioscopia	-	-	0.0277	-	0.0017	-	0.0060
Euphorbia segetalis	-	-	-	-	-	0.0033	-
Euphorbia serrata	0.0817	0.1677	0.1260	0.1923	0.2333	0.0087	0.0223
Filago pyramidata	0.4387	0.2547	0.6163	0.0317	0.2677	0.3393	0.1567
Fumaria officinalis	0.2907	0.6117	0.1807	0.7617	0.2733	0.2610	0.1903
Fumaria parviflora	0.0333	0.0627	0.0110	0.0117	0.0003	0.0100	0.0117
Galium aparine	-	0.0133	-	-	0.0003	-	-
Galium parisiense	1.0547	0.2370	0.5613	0.1260	1.5793	0.3323	0.6397
Galium tricornutum	0.2878	0.3237	0.0433	0.4653	0.2950	0.1533	0.1487
Geranium sp.	0.0313	0.1117	0.0350	0.1520	0.0237	0.0143	0.0290
Glaucium corniculatum	0.0485	0.2803	0.1123	0.1353	0.1193	0.0493	0.0360
Hedypnois cretica	0.0310	0.0043	0.3893	0.0117	0.0240	0.0437	0.0373
Heliotropium europaeum	0.0003	0.0037	0.0023	0.0043	0.0747	0.0100	0.0187
Herniaria hirsuta subsp. *cinerea*	0.6310	0.1940	0.3173	0.1633	0.9413	0.4880	0.6947
Hippocrepis ciliata	0.0020	0.0033	-	-	0.0010	-	-
Hippocrepis comosa	0.0185	0.0003	0.0007	0.0023	0.0100	0.0117	-
Hippocrepis multisiliquosa	0.0220	-	-	-	-	-	-
Hordeum murinum	0.0347	-	0.0390	0.1857	0.0220	0.0223	0.0470
Hordeum vulgare	0.0333	-	0.0100	0.0167	0.0250	-	0.0167
Hypecoum procumbens	-	0.0017	-	0.0050	0.0067	0.0003	-

Species	**Control**	**Alfalfa**	**Shredding**	**Early-chisel**	**Early-herbicide**	**Late-chisel**	**Late-herbicide**
Kochia scoparia	0.0033	-	0.0050	0.0650	0.5803	-	0.0070
Koeleria phleoides	0.0833	0.0050	0.0250	0.0003	0.0983	0.0033	0.0083
Lactuca serriola	1.4362	0.1390	1.2793	0.5573	1.7237	1.5350	1.0553
Lamium amplexicaule	-	-	-	-	0.0070	-	-
Leontodon taraxacoides	0.0092	-	0.0167	0.0167	-	0.0100	0.0133
Linaria micrantha	0.0037	0.0013	0.0287	0.0040	0.0087	0.0200	0.0037
Linum strictum	-	-	-	0.0033	-	-	-
Lithospermum arvense	-	-	-	-	-	0.0010	-
Lolium rigidum	3.9578	5.7407	2.4338	6.1990	3.3557	3.3367	2.8683
Malcolmia africana	0.0770	0.3827	0.2273	0.1483	0.1423	0.0217	0.0430
Malva sylvestris	0.5007	-	0.0233	0.0333	0.1333	0.6650	0.7967
Marrubium vulgare	0.0067	-	0.0767	-	0.0700	0.0067	0.0100
Matricaria chamomilla	-	-	-	0.0100	-	-	-
Medicago orbicularis	-	-	-	-	-	-	0.0100
Medicago sativa	-	-	0.0070	0.0170	0.0003	0.0003	0.0033
Medicago tribuloides	-	-	-	-	0.0067	-	-
Muscari comosum	-	-	-	0.0050	0.0033	0.0133	0.0277
Muscari neglectum	0.0010	0.0100	0.0017	-	-	0.0017	-
Nigella damascena	-	0.0033	-	-	-	-	-
Pallenis spinosa	0.2068	0.0017	0.0613	0.0733	0.0050	0.1970	0.0200
Papaver hybridum	0.3203	0.2483	0.1673	0.0207	0.2570	0.0200	0.2060
Papaver rhoeas	9.8872	12.3873	12.1477	5.3693	9.3210	2.8747	7.5267
Picris echioides	0.0067	-	-	-	-	0.0100	0.0017
Plantago afra	-	-	-	-	-	0.0060	-
Plantago albicans	0.0050	-	0.0150	-	0.0927	0.0067	0.0100
Plantago coronopus	0.0067	-	0.0167	-	0.0100	0.0010	-
Plantago lagopus	0.2970	-	0.5267	0.0290	0.1580	0.2080	0.0890
Plantago lanceolata	0.0150	-	0.0150	0.0103	0.0013	0.0373	0.0743
Platycapnos spicata	0.0037	-	-	-	0.0003	0.0100	0.0233
Polygonum aviculare	0.0010	0.0230	0.0007	0.0247	0.0003	0.0040	0.0017
Rapistrum rugosum	-	-	-	-	0.0167	-	-
Reseda lutea	0.0925	0.0433	0.1567	0.0133	0.1790	0.0133	0.1533
Reseda phyteuma	0.0200	0.0367	0.1400	0.0067	0.2153	0.0083	0.0203
Retama spherocarpa	-	-	-	-	0.0100	0.0033	-
Roemeria hybrida	0.0257	0.0593	0.0783	0.0770	0.0407	0.0490	0.0703
Salsola kali	0.0278	0.1203	0.1530	2.6260	3.0133	0.1657	0.0263
Salsola vermiculata	-	-	-	-	0.0667	-	-
Santolina chamaecyparissus	0.0500	-	-	-	0.0003	-	-
Sanguisorba minor	-	-	-	0.0033	-	-	-
Scabiosa stellata	-	0.0017	-	-	0.0033	-	-
Scorzonera hispanica	-	-	-	-	-	0.0167	-
Scorzonera laciniata	0.7583	0.0477	0.3487	0.2580	0.2890	0.4873	0.3933
Senecio vulgaris	0.0050	0.0133	0.0100	0.0103	0.0287	0.0440	0.0147
Seseli tortuosum	0.3577	0.0007	0.4960	-	0.3983	0.1000	0.1873
Silybum marianum	0.5948	0.1090	0.1300	0.3867	0.0017	0.0333	0.0267
Silene vulgaris	0.2143	0.0417	0.5053	0.0727	0.0843	0.3283	0.2347

Species	Control	Alfalfa	Shredding	Early-chisel	Early-herbicide	Late-chisel	Late-herbicide
Sisymbrium crassifolium	0.0500	-	0.0500	-	-	-	0.0907
Sisymbrium irio	-	-	-	-	0.1000	0.0133	-
Sisymbrium orientale	0.0333	-	0.0333	-	0.2667	0.0100	0.0367
Sisymbrium runcinatum	0.0173	0.1283	0.0223	0.1267	0.3203	0.0700	0.0183
Sonchus asper	0.0887	0.0350	0.1310	0.0567	0.1883	0.1477	0.0903
Sonchus oleraceus	2.3985	0.6067	2.9463	2.4343	1.8507	1.7583	2.4733
Sonchus tenerrimus	0.0700	0.0533	0.0967	0.0183	0.2340	0.1597	0.0813
Spergularia diandra	-	-	0.0167	-	-	-	-
Stellaria media	-	-	-	-	-	0.0003	-
Tragopogon dubium	-	0.0067	0.0067	-	-	-	-
Trigonella mospeliaca	0.0920	-	-	0.0023	0.0003	0.0183	0.0057
Veronica hederifolia	0.0067	0.0257	-	0.1000	-	0.0117	0.0033
Verbena officinalis	-	-	-	-	0.0233	-	-
Veronica polita	-	0.0067	-	0.0067	-	0.0667	-
Verbascum thapsus	-	-	-	-	-	-	0.0833
Vicia peregrina	-	0.0017	-	-	-	-	0.0100
Vulpia ciliata	-	0.0017	-	-	-	-	0.0033

Supporting Information to the paper

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Appendix S3.

Summary of plant response and effect traits used in the analysis.

Response Traits	Categories	Source*	Effect traits	Categories	Source*
Growth form	Annual forbs Perennial forbs Annual graminoids Perennial graminoids Legumes Shrubs	a	**Flower shape**	Anemophilous corolla Open entomophilous Tubular Zygomorphic	a
Seed dispersal	Anemochory Autochory Zoochory Unassisted	b	**Flower colour**	Purple Blue Yellow White Other colour (greenish-brownish)	a
Average height	continuous	a			
SLA	continuous	c			
Flowering onset	1-12	a	**Flowering duration**	1-12	a

Average height (cm); SLA (mm^2 mg-^{1}); Flowering onset/duration (month)

*(a) de Bolòs O., Vigo J., Masalles R.M., & Ninot J.M. 2005. *Flora Manual Dels Països Catalans*, 2nd ed. Pòrtic, Barcelona.

*(b) Kleyer, M., Bekker, R.M., Knevel, I.C., Bakker, J.P., Thompson, K., Sonnenschein, M., Poschlod, P., Van Groenendael, J.M., Klimes, L., (…) & Peco, B. 2008. The LEDA Traitbase: A database of life-history traits of the Northwest European flora. *Journal of Ecology* 96: 1266–1274.

*(c) Kattge, J., Díaz, S., Lavorel, S., Prentice, I.C., Leadley, P., Bönisch, G., Garnier, E., Westoby, M., Reich, P.B., (…) & Wirth, C. 2011. TRY - a global database of plant traits. *Global Change Biology* 17: 2905–2935.

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Appendix S4.

Summary of the mean species richness, Shannon diversity index (H) and functional diversity index (Rao) (±S.E.) per field treatment.

Management	**Richness**	**H**	**FD (Rao)**
Alfalfa	19 ± 4	5.3 ± 1.4	1.73 ± 0.19
Early chisel	21 ± 4	6.5 ± 1.4	1.89 ± 0.18
Late chisel	14 ± 3	5.3 ± 1.2	1.99 ± 0.14
Early herbicide	22 ± 4	7.9 ± 1.8	2.08 ± 0.14
Late herbicide	16 ± 2	5.3 ± 1.6	1.94 ± 0.18
Shredding	21 ± 5	7.9 ± 3	1.95 ± 0.18
Control	21 ± 4	7.3 ± 2.1	1.96 ± 0.18

Not significant differences in post-hoc Tukey test results from LMM analysis

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Appendix S5.

The response–effect trait framework based on Lavorel et al. (2013). A) identifies the response of plant traits to the environmental driver of interest; B) identifies the trophic effect plant traits which affect to pollination; C) linkages among the different response and effect traits across trophic levels.