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Which conditions determine the presence of rare weeds in arable fields?

Roser Rotchés-Ribalta *, José Manuel Blanco-Moreno, Laura Armengot, Laura José-María, F.Xavier Sans

Departament de Biologia Vegetal, Facultat de Biologia, & IRBio Universitat de Barcelona, Av. Diagonal 643, 08028 Barcelona, Spain

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ABSTRACT

The intensification of agricultural management has caused some weed species to become rare in arable farming systems. It is difficult to disentangle which management practices are the least harmful for the conservation of rare arable weeds because of their sparse presence. In this research, we overcame the limitations of previous analyses of rare weeds by analyzing them in a large number of plots (1957) at the edges of multiple organic fields (304), which maximized the probability of detecting these species. We evaluated the relationships between farming practices and local site conditions and the presence of rare arable species that are characteristic of cereal fields.

We detected 46 of the 65 rare weeds that are known to inhabit the study area, but their frequency was very low. Cereal crops, either alone or in mixtures with legumes, enhanced the probability of finding rare weed species, while fertilization had a detrimental effect. Other management practices that were considered had no effect on the presence of rare arable weeds. However, selected rare species tended to fare better under particular local conditions and to be favored by specific management practices. In contrast, a significant amount of the variance of the rare weed presence was explained by farm-related and field-related random factors. Thus, the occurrence of rare arable species is apparently determined by stochastic factors that may be related to the local species pool that likely depends on the history of fields and farms. Therefore, conservation efforts should be focused on areas currently inhabited by rare arable species.

1. Introduction

Conserving arable weed species is somewhat problematic because their preferred habitat, arable fields, is primarily devoted to crop production (Fried et al., 2009). Increases in farming efficiency to enhance productivity have resulted in fields becoming less diverse, with few non-crop plants tolerated (Robinson and Sutherland, 2002). Agriculture has repeatedly been identified as one of the main causes of biodiversity loss worldwide (Elsen, 2000; Rich and Woodruff, 1996; Storkey et al., 2012). This is primarily due to the large cropland areas that are devoted to grow crops, which diminish non-crop habitats such as hedgerows and field margins, and the widespread use of pesticides and fertilizers (McLaughlin and Mineau, 1995). Therefore, conserving farmland biodiversity requires less intense farming practices (Tscharntke et al., 2005).

In recent decades, many arable weed species have suffered such a critical population decline that they have become rare or even locally extinct in many countries (Baessler and Klotz, 2006; Cirujeda et al., 2011; Fried et al., 2009; Storkey et al., 2012). Many of these species are found in the Red Data Lists of some European countries (Cheffings and Farrel, 2005; Kleijn and van der Voort, 1997 Türe and Böcuk, 2008), which constitutes the basis for most conservation strategies (Aboucaya et al., 2000; Kleijn et al., 2006). However, in Spain and other countries in the Mediterranean area, rare arable weed species are not included in the Red Data Lists or in conservation plans because these species are considered non-native and dependent on the maintenance of artificial habitats (Sáez et al., 2011). Conservation of rare arable species is crucial because of their intrinsic value as both components of biodiversity and key indicators of traditional and low-intensity agriculture. In addition, these rare species provide a greater variety of forms, compositions and functions than do the few crop species that dominate arable land and constitute a valuable resource for

* Corresponding author. Tel.: +34 934 021 471; fax: +34 934 112 842.
E-mail addresses: roser.rotches@ub.edu (R. Rotchés-Ribalta), jmblanco@ub.edu (J.M. Blanco-Moreno), larmengot@ub.edu (L. Armengot), ljosemaria@ub.edu (L. José-María), fsans@ub.edu (F.X. Sans).

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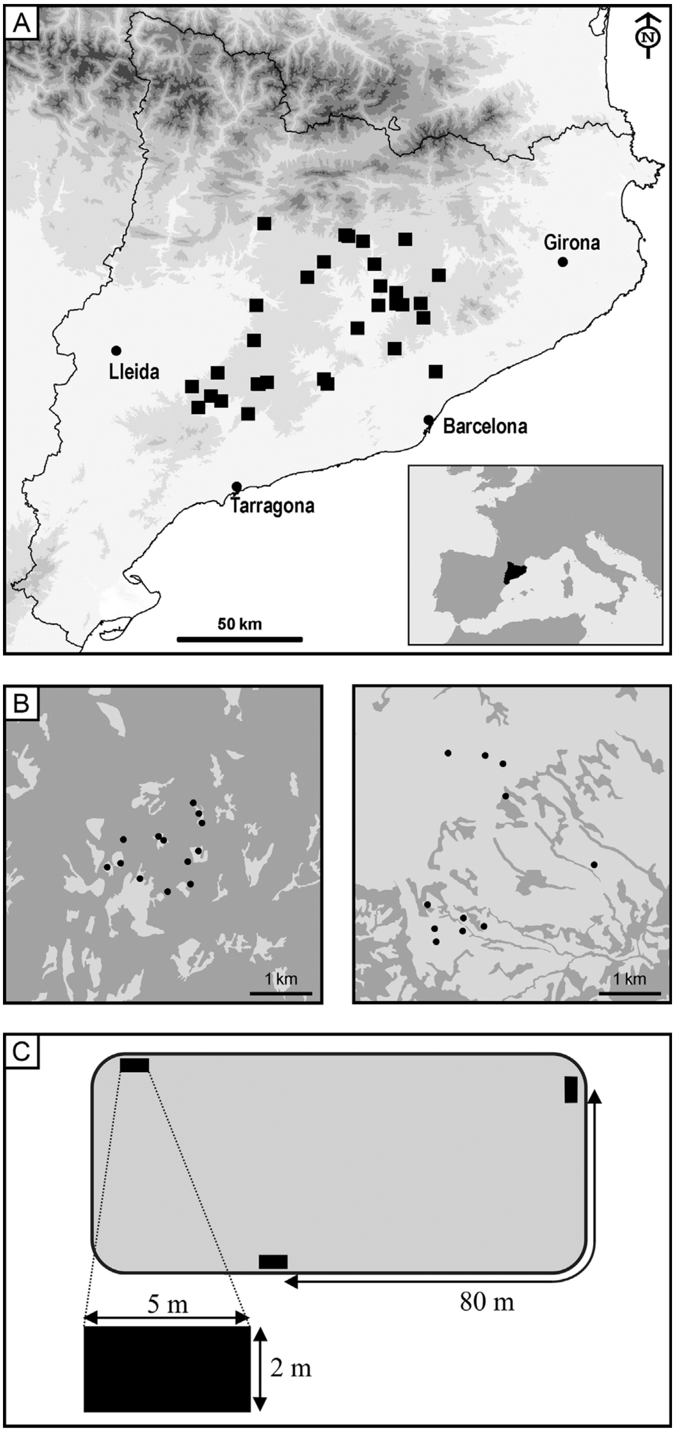

Fig. 1. (A) Locations of the 32 farms (squares) within Catalonia (NE Spain). Gray tones indicate elevation contours of 500 m. (B) Fields sampled (dots) at two farms taken as examples of complex (left) and simple (right) landscapes. Light gray represents arable habitats while dark gray includes other natural and semi-natural habitats. (C) Plots of 2 m × 5 m size spaced 80 m apart from each other were surveyed within each field.

pollinators, herbivores, predators and parasitoids (Caballero-López et al., 2010; Hawes et al., 2003; Tscharntke et al., 2005).

The distribution of arable weed species is determined by many parameters, among which history of land management and landscape composition, weather conditions, seed dispersal and other stochastic factors can play an important role (Ryan et al., 2010). Nevertheless, it is widely acknowledged that less intensive farming practices, such as those used in organic farming where herbicide and chemical fertilizer inputs are banned, tend to be beneficial for the richness and diversity of arable species (Cirujeda et al., 2011; Gibson et al., 2007; Kleijn et al., 2009), as well as the occurrence of rare arable weeds (Romero et al., 2008). However, there is considerable variation in management intensity among organic farms (Armengot et al., 2011a; Clough et al., 2007). This leads to highly versatile and seemingly contradictory effects of organic vs. conventional farming on diversity (Bengtsson et al., 2005). Thus, it may be appropriate to consider particular management practices to evaluate their impact on the presence of rare arable species.

Several studies have shown how weed species diversity is determined by the surrounding landscape, which acts as a refuge and source of propagules that can colonize crops (Gabriel et al., 2005; José-María et al., 2010; Poggio et al., 2010; Roschewitz et al., 2005; Solé-Senan et al., 2014). For this reason, it is important to consider the composition and amount of natural and semi-natural habitats that are adjacent to fields and landscape structure as factors that may contribute to variations in weed diversity.

The purpose of our research was to determine which field and local conditions are more suitable for the occurrence of rare arable species and to outline appropriate management practices that may promote their conservation. The specific objectives of this study were (1) to assess the effects of farming practices and local conditions on the occurrence of rare weed species within fields and (2) to investigate similarities between the responses of selected species to these variables. This study overcomes limitations of analysis that are related to low frequencies and usually affect studies of rare arable species, by surveying them in many plots at the edges of multiple organic fields where those species are most likely found (José-María et al., 2010; Kovács-Hostyánszki et al., 2011). Thus, this sampling method maximizes the probability of detection of each rare species (Thompson, 2004).

2. Material and methods

2.1. Study site

The sampling was conducted in 2011 in Catalonia, northeastern Spain (41°22′–42°06′N; 0°59′–2°12′E). We selected organically managed fields from 32 farms within an area spanning 100 km × 80 km (Fig. 1). The average (±standard error) altitude of the surveyed sites is 558 m a.s.l. (±30 m and ranging from 95 to 871 m a.s.l.). The fields have basic soils with loamy and clayish textures. The climate is Mediterranean, with mean annual temperatures of 12.6 ± 0.2 °C and an average precipitation of 637 ± 21 mm (Ninyerola et al., 2005). Average monthly temperatures are always positive, but frost can occur from December to February, and is normally restricted to a few hours per day. Natural habitats in the study area include pine (*Pinus halepensis* Mill. and *P. nigra* Arnold) and oak (*Quercus ilex* L. and *Q. faginea* Lam.) woodlands, shrublands, small stands of perennial-dominated grasslands, and riverine vegetation.

2.2. Plant survey

A total of 304 organically managed fields were surveyed during May and June 2011 (just before harvest). The selected fields had been sown in the previous growing season with the annual crops that are usually included in the winter cereal crop rotation (small grain cereals, legumes, ryegrass and crop mixtures containing cereals and legumes). To maximize the detection of rare arable weeds, the weed survey was restricted to the edges of the fields, which are defined as the first cultivated meters adjacent to field margins (Marshall and Moonen, 2002). The sampling plots (2 m × 5 m) were established 80 m apart at the edges of the fields

Table 1
Characterization of management, field and landscape descriptors and the local conditions of the sampled farms ($n = 32$), fields ($n = 304$) and plots ($n = 1957$). The mean and range (in brackets) of the continuous variables and the proportion of fields and farms with the stated practices for the discrete variables are shown.

Field management	
Years from conversion to organic management	9.67 [1,25]
Cereal ratio[a]	0.56 [0,1]
Soil tillage	
No till and no inversion tillage	199/304
Inversion tillage	105/304
Current crop	
Cereal	170/304
Mixture	87/304
Legume	17/304
Ryegrass	30/304
Seed origin	
Reuse seeds	192/304
Purchased seeds	112/304
Sowing time	
Autumn sowing	246/304
Spring sowing	58/304
Sowing density (kg ha^{-1})	154.81 [16.5, 384]
Type of N inputs	
No fertilization	119/304
Manure	167/304
Slurry	18/304
Amount of N inputs (kg ha^{-1})[b]	47.44 [0600]
Weed control	
No control	176/304
Tillage (pre-sowing control)	89/304
Harrowing (post-sowing control)	39/304
Animal husbandry	
No grazing	213/304
Grazing	91/304
Farm management	
Farm type	
Stockless farms	11/32
Mixed farms	21/32
Field and landscape descriptors	
Percentage of arable land (PAL)	46.58 [6.83, 100]
Field area (ha)	1.54 [0.16, 15.04]
Field shape (perimeter/area)	0.06 [0.01, 0.19]
Local conditions	
Crop cover (%)	51.97 [0100]
Weeds cover (%)	32.82 [0100]
Habitat of the adjacent margin	
Ruderal vegetation	813/1957
Grasslands	531/1957
Woody vegetation	517/1957
Other habitats	96/1957

[a] Calculated as the proportion of cereal crops in the 5-year rotational scheme of each field.
[b] Calculated using local tables of N content (Campos Pozuelo et al., 2004).

(Fig. 1). Thus, depending on the field size, a minimum of three and a maximum of ten plots were sampled per field. In each plot, we recorded the presence of rare arable weeds. These were defined as characteristic species of the phytosociological order *Secalietalia cerealis* Br.-Bl. 1936 (communities of dryland winter cereal fields in a Mediterranean climate on basic soils) that are considered rare in the study area (de Bolòs et al., 2005) (Table A1). These species are categorized into rare (r), very rare (rr) and extremely rare (rrr) according to their frequencies and abundances in relevés from various published sources and in herbarium collections. The nomenclature of plant species and their attribution to the phytosociological order follows that of de Bolòs et al. (2005). In each plot, we also recorded the habitat type of the adjacent margin and crop and total weed cover visually.

2.3. Explanatory variables considered

Farmers were interviewed to obtain information about their farming practices on each sampled field and farm during the 5 years preceding the sampling (Table 1). The selected variables reflect recent field management (number of years elapsed since conversion to organic farming and the cereal ratio, which is the proportion of cereal crops in the five-year rotational scheme) and current management during the period 2010–2011 (all other variables) of each field. The presence (mixed) or absence of livestock was used as a management variable at the farm level.

Some field descriptors, such as the area of the field and the shape of the field (perimeter-to-area ratio), were included in the model as covariates that may determine the presence of rare arable weeds in the fields. The percentage of arable land characterized within a 1 km radius around each field was considered as a landscape descriptor. We used the Catalan Habitats Cartography (Carreras and Diego, 2004) to calculate the percentage of arable land.

Local conditions at the sampling plot were also considered as variables that may determine the presence of rare arable species. These variables were the habitat type of the adjacent margin and the percentage cover of crop and weeds. Adjacent margins were categorized into ruderal vegetation, grasslands, woody vegetation (including shrublands and woodlands) and other habitats found in very low frequencies (including bare soil, arable land and wet ditch vegetation) (Table 1).

2.4. Analyses of the occurrence of rare weeds

The study was conducted at both the field ($n = 304$) and plot ($n = 1957$) levels. At the field level, we evaluated the probability of finding rare arable species in a field using the proportion of sampled plots per field that contained rare species. The effect of all recorded management variables (Table 1) on the probability of the presence of rare species in the field was analyzed using generalized mixed-effect models with a binomial error distribution, including farm as a random factor. The values of the response variable were included as binomial data using the number of sampled plots that contained rare species and the number of plots in which rare species were absent. Therefore, the total number of plots in each field was used to weight the probability that a rare species occurs in a field. Continuous explanatory variables were standardized (by subtracting the mean and dividing by their standard deviation) to homogenize their ranges of variation and facilitate the comparison of their effects based on regression coefficients. For the type of nitrogen inputs and weed control variables, orthogonal contrasts were fixed a priori to compare the different levels in a meaningful way (see Table 2). Because we did not find strong correlations between the explanatory variables, all of them were included in the model without interactions to carry out a general exploration of the rare arable species behavior.

At the plot level, we analyzed the probability of the presence of rare arable species within the plots at the field edges. Data on the presence of at least one rare species were evaluated to test the effects of local conditions (Table 1) using generalized mixed-effects models. Field and farm management variables, as well as field and landscape descriptors, were also considered in this model. We included farm and field (nested within farm) as random factors. Because the presence data were entered as binary information, we used a model with a binomial error distribution. Continuous explanatory variables were also standardized and, again, orthogonal contrasts were fitted for the type of nitrogen inputs and weed control variables.

To assess the goodness of fit of the models, we computed their coefficient of determination (R^2). These coefficients were expressed as the marginal R^2, accounting for the variance

Table 2
Effects of the field and farm management and field and landscape structure variables on the occurrence of at least one rare arable species at the field level. Estimated coefficients and their standard errors for the linear mixed models, degrees of freedom for each variable (DF) and *P*-values (*** when *P*-value < 0.001; ** < 0.01; * < 0.05 and · < 0.1) are shown.

	Estimate ± SE	DF	*P*-values
Field and farm management			
Years from conversion	−0.087 ± 0.148	254	0.559
Cereal ratio[a]	0.188 ± 0.370	254	0.612
Inversion (vs. no inversion) tillage	0.139 ± 0.335	254	0.678
Current crop			
Mixture (vs. cereal)	−0.104 ± 0.203	254	0.607
Legume (vs. cereal)	−0.897 ± 0.302	254	0.003**
Ryegrass (vs. cereal)	−1.407 ± 0.316	254	0.000***
Reuse (vs. purchased) seeds	−0.237 ± 0.228	254	0.299
Spring (vs. autumn) sowing	−0.295 ± 0.224	254	0.189
Sowing density[b]	0.121 ± 0.094	254	0.202
Type of N inputs			
Fertilized (vs. no fertilized)	−0.295 ± 0.152	254	0.052·
Slurry (vs. manure)	−0.296 ± 0.240	254	0.218
Amount of N inputs (log (N + 1))	0.307 ± 0.200	254	0.124
Weed control			
Control (vs. no control)	−0.065 ± 0.076	254	0.394
Tillage (vs. harrowing)	−0.038 ± 0.214	254	0.859
Grazing (vs. no grazing)	−0.242 ± 0.194	254	0.212
Mixed farms (vs. stockless farms)	−0.264 ± 0.422	30	0.532
Field and landscape descriptors			
Field area	0.214 ± 0.070	254	0.002**
Field shape (perimeter/area)	−0.025 ± 0.074	254	0.733
Percentage of arable land (PAL)	0.166 ± 0.119	254	0.164

Model deviance = 1231.1.
[a] Calculated as the proportion of cereal crops in the 5-year rotational scheme of each field.
[b] Standardized for each crop type.

explained by the fixed factors, and the conditional R^2, which is the variance jointly explained by both fixed and random factors (Nakagawa and Schielzeth, 2013).

2.5. Analyses of the occurrence of selected rare arable species

Analyses to assess the effects of both field and plot variables on the presence of each species were also performed using mixed-effects models with binomial errors. We considered only those rare species with more than 19 occurrences, which represents 1% of the sampled plots. This yielded 19 rare arable species. These analyses allowed us to ascertain whether the pattern of presence found for the pool of rare weeds responded to consistent patterns among species.

Moreover, we carried out a meta-analytic approach to combine the information from individual species' models of the 19 most frequent rare arable species based on the *P*-values of the estimated effects (Zaykin, 2011). The combination of *P*-values can be used to support a common hypothesis that has been tested in several studies (in our case, several species). We used the weighted Z-test, which is Stouffer's method (also known as the 'inverse normal' test) (Zaykin, 2011). For each variable, we used the inverse of the coefficient's estimated standard errors as weights, as recommended in Zaykin (2011). Two-sided *P*-values are generally inappropriate for the meta-analytic combination of *P*-values. Therefore, the individual *P*-values were converted to one-sided *P*-values before combination as follows: $P_{\text{one-sided}} = P_{\text{two-sided}}/2$ if the effect direction (either positive or negative) was the same as expected, and $P_{\text{one-sided}} = 1 - P_{\text{two-sided}}/2$, otherwise. Once they were combined, the results were converted back to two-sided as follows: $P_{\text{two-sided}} = 2P_{\text{one-sided}}$ if $P_{\text{one-sided}}$ is lower than 0.5 and $2(1 - P_{\text{one-sided}})$ otherwise.

For the analyses, we used R 3.0.3 (R Development Core Team, 2013) with the lme4 package (Bates et al., 2014) for the generalized mixed models and the MuMIn package for the R^2 calculation (Bartoń, 2013).

3. Results

3.1. Overview of rare arable weed communities

Overall, we recorded 46 characteristic arable species that are considered to be rare by de Bolòs et al. (2005). These species are included in a list of 65 rare arable species with a distribution area that matches the study area (Table A1, Supplementary data). This means that we were able to detect more than 70% of the rare arable weed species that may occur in the study area. We found at least one rare species in 1162 plots from the total of 1957 sampled plots. Nevertheless, most of the rare species (27 of 46) occurred in less than 1% of the surveyed plots, and many of them were present in only one or two plots. The most frequent species were *Kickxia spuria* (L.) Dumort. and *Galium aparine* subsp. *spurium* (L.) Simonk, and even these were recorded in less than 16% of the plots.

3.2. Rare arable species at the field level

The presence of rare arable weeds was significantly affected only by a few current management practices (Table 2). Cereal crops encouraged the presence of rare weeds belonging to the *Secalietalia cerealis* order (i.e., typical of winter cereal fields) more than legume or ryegrass crops. Fertilization had a slight negative effect on the occurrence of rare arable species. Larger fields tended to have a higher probability of sustaining rare weeds.

The fraction of the variance explained by the random factor farm was larger than that explained by the fixed factors. Conditional R^2 (0.28), which accounts for the variance explained jointly by fixed and random factors, was higher than the marginal R^2 (0.10) or the variance explained by all of the fixed factors. This difference indicates that the fraction explained by the random effects that depend on farm was more important.

3.3. Rare arable species at the plot level

The percentage of crop cover and especially of weed cover showed a significant positive relation with the presence of rare arable species (Table 3). On the contrary, the type of habitat in adjacent boundaries did not influence the presence of rare arable species. Among the field-level variables included in the plot-level

Table 3
Effects of local conditions on the presence of rare characteristic arable species sampled at the plot level. Estimated coefficients and their standard errors for the linear mixed model, the degrees of freedom for each variable (DF) and the *P*-values (*** when *P*-value < 0.001; ** < 0.01; * < 0.05 and · < 0.1) are shown. Field management practices and landscape structure were also included in the model but are not shown in the table.

	Estimate ± SE	DF	*P*-value
Local conditions			
Crop cover	0.196 ± 0.085	1648	0.022*
Weeds cover	0.380 ± 0.085	1648	0.000***
Habitat of adjacent margin			
Grasslands (vs. ruderal vegetation)	−0.314 ± 0.321	1648	0.329
Woody vegetation (vs. ruderal vegetation)	−0.050 ± 0.161	1648	0.756
Other habitats (vs. ruderal vegetation)	0.153 ± 0.167	1648	0.359

Model deviance = 2217.3.

Table 4
Number of species with positive (+) or negative (−) effect of each variable considered in the mixed-effect models for the presence of each rare arable species analyzed. The number of species with a significant effect is in parentheses. 'Combined *P*-value' represents the *P*-values of Stouffer's meta-analytic approach used to combine the information of each particular species model. The following notation is used for size of the *P*-values: *** when *P*-value < 0.001; ** < 0.01; * < 0.05 and · < 0.1.

	+	−	Combined *P*-value
Field and farm management			
Years from conversion	17 (6)	2 (0)	0.000***
Cereal ratio[a]	14 (0)	5 (0)	0.009**
Inversion (vs. no inversion) tillage	2 (0)	17 (1)	0.000***
Current crop			
Crop mixtures (vs. cereal)	9 (1)	10 (0)	0.281
Legume (vs. cereal)	7 (0)	12 (1)	0.044*
Ryegrass (vs. cereal)	2 (0)	17 (6)	0.000***
Reuse (vs. purchased) seeds	7 (0)	12 (0)	0.163
Spring (vs. autumn) sowing	0 (0)	19 (3)	0.000***
Sowing density[b]	16 (2)	3 (0)	0.000***
Type of N inputs			
Fertilized (vs. no Fertilized)	12 (0)	7 (0)	0.561
Slurry (vs. manure)	14 (0)	5 (0)	0.186
Amount of N inputs (log (N + 1))	12 (0)	7 (0)	0.597
Weed control			
Control (vs. no control)	11 (1)	8 (0)	0.12
Tillage (vs. harrowing)	6 (0)	13 (0)	0.362
Grazing (vs. no grazing)	3 (0)	16 (3)	0.000***
Mixed farms (vs. stockless farms)	13 (0)	6 (0)	0.889
Field and landscape descriptors			
Field area	15 (2)	4 (0)	0.003**
Field shape (perimeter/area)	4 (0)	15 (2)	0.001**
Percentage of arable land (PAL)	11 (1)	8 (1)	0.331
Local conditions			
Crop cover	11 (0)	8 (0)	0.222
Weeds cover	15 (3)	4 (0)	0.000***
Habitat of adjacent margin			
Grasslands (vs. ruderal vegetation)	8 (1)	11 (0)	0.26
Woody vegetation (vs. ruderal vegetation)	3 (0)	16 (1)	0.001**
Other habitats (vs. ruderal vegetation)	11 (2)	8 (0)	0.003**

[a] Calculated as the proportion of cereal crops in the 5-year rotational scheme of each field.
[b] Standardized for each crop type.

model, only ryegrass sown during the current growing season (vs. cereal-sown fields) showed a negative effect on the presence of rare species at the plot level (−1.31 ± 0.50, $P = 0.009$).

Random factors also largely influenced the presence of rare species at the plot level. The variability explained by all of the fixed factors (marginal R^2) was only 0.10. However, the conditional R^2 was 0.24 when farm was considered as the only random factor and 0.47 when farm and field were both considered as random factors, together with the fixed factors.

3.4. Patterns of presence of selected species

Analyses of the effects of both field and plot variables showed that very few of the assessed parameters significantly affected the presence of the 19 most common rare species when separately analyzed (Table 4). Only the presence of ryegrass crops, whichnegatively influenced the presence of rare species, and the years since the conversion to organic farming, which had a positive effect, affected up to six of the 19 species analyzed (Table 4). Analyses that accounted for all of the models of the 19 species revealed that weed cover at the plot level was beneficial to these rare arable species. In addition, these rare arable species were more likely to be found in larger fields that were under organic management for a longer time and that had a higher proportion of cereals in the rotation scheme. They appeared preferentially in fields sowed with cereal or crop mixtures instead of legumes or ryegrass and were not favored by spring sowing. Tillage with soil inversion and grazing after the preceding harvest determined a smaller presence of particular rare weeds. Rare weeds tended to not occur at the field edges that neighbored woody vegetation.

4. Discussion

4.1. Status of rare arable weeds

A large proportion of the rare arable species occurred at the edges of the organically managed fields. We detected more than 70% of the rare species that de Bolòs et al. (2005) listed as inhabiting the study area. This high percentage may be due to the large number of plots surveyed at the edges of fields and because the study was focused where these species are preferentially found. However, 40% of the total surveyed plots were completely devoid of rare species and, when the rare species were present they had extremely low frequencies. These data confirm the current scarcity of the studied species (Chamorro et al., 2007) while providing some hope for their conservation because many of them are still present in arable fields of Catalonia.

4.2. Presence of rare arable species in fields

One of the strongest agricultural filters on the presence of rare arable species was the standing crop type, which has also been reported in other studies (Fried et al., 2009; Marshall, 2009). Because rare arable weeds as defined in this study are specialists of winter cereal cropping systems, sowing cereals or a mixture containing cereals provides the conditions that favor the presence of these species (Kolářová et al., 2013).

Fertilized fields were marginally detrimental to rare arable weeds, as also reported by Storkey et al. (2012). Arable weeds and crop species compete for the same resources and hence tend to be mutually exclusive (Ponce et al., 2011; Critchley et al., 2006). This negative effect of fertilization on weed species usually acts indirectly by stimulating crop growth, which in turn decreases light penetration and reduces weed growth (Kleijn and Van der Voort, 1997).

The inclusion of field descriptors (field area and shape) and the proportion of arable land in the model allowed the possible effect of these parameters on the presence of these rare species to be discarded. Actually, only field areas contributed to an explanation of the presence of rare arable weeds. Larger organically managed fields were more likely to hold rare arable species than smaller fields with similar management, probably because they came from the historical amalgamation of smaller fields that may have enlarged the local species pool (Marshall, 2009). The presence of rare weeds may be primarily determined by the local species pool that is maintained by the buffer effect of the soil seedbank (Hiltbrunner et al., 2008).

4.3. Local site conditions favoring rare arable species

Despite the fact that weeds and crop species tend to be mutually exclusive (Ponce et al., 2011), both crop and weed species (including the rare ones) apparently are able to coexist at the edges of organic farming fields. This particular result may be related to the low crop cover values at the studied field edges (ca. 50% on average). At the edges of the fields, lower organic fertilizer inputs, poor soil conditions and sowing failure may strongly limit crop performance and reduce the importance of crop-weed competition (Dutoit et al., 2007; Romero et al., 2008). Thus, favorable conditions for the crop in organically managed field edges would also benefit weeds, which would in turn favor the presence of rare species.

We assumed a potential effect of the adjacent boundary on the presence of rare arable species at the field edge because, as other studies have indicated, this could act as a refuge for these species (Gabriel et al., 2005; José-María et al., 2010; Poggio et al., 2010; Roschewitz et al., 2005). Because rare characteristic arable species are found almost exclusively in arable habitats and require periodic disturbances, we expected that the adjacent habitat that could best act as a refuge would be a ruderal one. On the contrary, we also expected that more competitive vegetation at the adjacent boundary, such as woody vegetation, would be detrimental for the presence of rare arable species. However, our results indicated no effect of any of these habitats on the presence of rare arable weeds.

4.4. Species-specific responses

Overall, very few of the many parameters we considered actually influenced the presence of the particular rare arable species that were analyzed. Most studies have found that management practices exert an important influence on the presence and diversity of arable weed species in arable fields (Albrecht, 2003; Armengot et al., 2011b; José-María et al., 2010). However, the occurrence of rare arable species may instead respond to stochastic factors that have led them to appear and remain at particular sites. In light of these results, we could assume that the presence of these species and the determination of their rarity are the result of specific traits of each species (Pinke and Gunton, 2014; Storkey et al., 2010), which would be an interesting point to consider in future conservation studies.

Nevertheless, with the meta-analysis we are able to detect an overall trend of these 19 rare arable species to appear under particular conditions and be favored by specific farming practices. This highlights a similar response of these species to the variables considered. Cereal crops or mixtures containing cereals and legumes, both in the current season and at high frequencies in a rotation scheme, benefited these rare arable species because the autumn sowing time of cereals is perfectly coupled with their germination requirements (Saatkamp et al., 2011). Slight annual periodic soil disturbances without soil inversion tended to favor the presence of rare arable weeds by generating the appropriate conditions for germination of seeds without burying them into the soil (Gruber and Claupein, 2009).

These rare weeds were more likely to appear in those spots with high weed cover, indicating that suitable local conditions for weeds in general were also appropriate for the rare ones. Therefore, practices that enhance weed diversity within crop fields would also be suitable for rare arable species conservation (Romero et al., 2008). Cropland edges are prone to be negatively affected by competing neighboring vegetation because it reduces the availability of soil nutrients and light through belowground competition and shading. That is why globally the 19 rare species tended to be excluded at the crop edges adjacent boundaries that were dominated by more competitive vegetation such as woodlands and shrublands. The significant effects of the other types of adjacent boundaries must be interpreted with caution because they were represented in very few samples.

4.5. Importance of random factors

Farm and field random factors significantly increased the explained variance in the occurrence of rare characteristic weeds over the fixed factors. Field effect was more important than farm effect, but even the farm alone explained more variance than did all of the fixed factors together. The importance of the random factors suggests that the occurrence of rare species is controlled by factors other than the local conditions that were considered, field and farm management and field descriptors or landscape simplification, and depends to a large extent on the farms and fields themselves. Although we were able to find a trend of particular rare arable species to appear under certain conditions, the importance of the random factors on the overall presence of these species is evident. Therefore, the presence of rare arable species at a particular site would be determined, to a large extent, by the diversity of the seeds that remain in the soil seedbank, which is largely set by the field management history (Hiltbrunner et al., 2008).

5. Conclusions

Our data reinforce the fact that rare characteristic arable species occur at the edges of organically managed fields. Nevertheless, these species face an actual threat because they are found at very low frequencies. Therefore, the moment is right to take action for their conservation, taking into account that many of them are still present in organic arable cropping systems.

The foundations for the conservation of rare arable species must consider very particular management parameters, such as the promotion of sowing winter cereal crops and fine-tuning fertilization. Particular rare arable species showed a trend to appear preferentially when autumn sowing took place or when no inversion tillage was conducted. Nevertheless, the inconsistencies between the overall occurrence analysis and the meta-analysis reflect the difficulty in understanding the role of farming practices in explaining their conservation status. For this reason, it would be interesting to promote further research on the ecological requirements at the species level to develop appropriate conservation strategies.

The presence of rare arable species was highly explained by field and farm random factors, which are the result of the variability in the local species pools. Therefore, conservation efforts based on specific practices to favor rare weeds should focus on those areas where the species are currently settled.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2015.01.022.

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