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RESEARCH ARTICLE

How long does it take to establish a field boundary with a small proportion of weeds? An example in semi-arid conditions

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Abstract
Context Field boundary (FB) establishment and conservation have been promoted to enhance biodiversity in agroecosystems. However, weeds can colonize these areas during the revegetation process, which might be a problem for adjacent fields. Data is necessary to facilitate acceptance of these structures by farmers.
Objectives This work takes advantage of a unique opportunity to describe the plants establishing in a set of new FBs. The main aims were to describe species composition in a six-year period and to detect if FBs can be a weed source for surrounding agricultural land.
Methods Data was collected in ten FBs in a semi-arid environment in north-eastern Spain (eight metres in width) created from 2003 to 2007 in a farm owned by the CITA Research Centre. Vegetation was recorded in spring in years 2006–08 and 2011–13 covering a time sequence that ran from establishment until an age of 10 years. The same data was recorded in adjacent winter cereal field centres (FCs) and existing boundaries of neighbouring commercial farms (CFBs) established decades earlier.
Results Plant ground cover and total species richness increased rapidly in the FBs, remaining stable after approximately the fourth year. Different analysis confirm that vegetation in the FBs was different from that found in the FCs and CFBs; 10 years was

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probably a too short period for the FBs to develop a similar vegetation composition to that of the CFBs.
Conclusions Data of this example support that establishing new FBs can promote plant diversity without infesting the surrounding fields with weeds.

Keywords Field margin · Succession · *Lolium rigidum* · *Papaver rhoeas* · Agri-environmental schemes

Introduction

Agri-environmental schemes (AES) have been adopted in several European countries to encourage farmers to establish field margins. The objective is generally to increase biodiversity, including that of arable weeds (Walker et al. 2007). An AES was developed in the Spanish region of Aragon over the years 2007–2013 (BOA 2009) to protect field boundaries, i.e., non-cultivated strips both next to roadways and between fields separating pieces of land, as well to promote the establishment of new ones. Unlike margins established in other AESs, these boundaries were not allowed to be seeded, weeded, or fertilized for at least the initial five-year period of the AES commitment. Grazing was allowed as the only boundary management practice, while applying herbicide, tilling or burning was forbidden. In the period 2008–10, 627 farmers applied for this AES, affecting 12,700 ha (S. Murillo, pers. comm.). This AES was designed mainly to prevent the disappearance of still existing field boundaries (FBs) in the semi-arid Aragon area, where intensification threatens their existence, by protecting them and encouraging the establishment of new FBs in the area. In many areas of Spain these structures have already eliminated increasing arable land but in some others such as in the Zaragoza province they still exist.

Unfortunately, no local data is available and the expected plant species succession in the newly established FBs is unknown. Therefore, it is uncertain whether these FBs could be a source of weed infestations in the adjacent fields, annual species such as *Papaver rhoeas* L., *Lolium rigidum* Gaud., *Avena sterilis* subsp. *ludoviciana* (Durieu) Nyman or *Bromus diandrus* Roth or perennials such as *Cirsium arvense* (L.) Scop. being a priori the most troublesome ones (MAAMA 2015). Due to lack of funding, the AES was discontinued and the essential information was not collected.

Simplification and intensification of the agricultural landscape is considered to be one of the main reasons for the alarming loss of insect species worldwide (Sánchez-Bayo and Wyckhuys 2019). Several work suggest that it is important to preserve and to increase the area of semi-natural habitat to halt the loss of biodiversity (Billeter et al. 2008); experimental data show that connectivity is more important than area for plant species richness in linear landscape elements (Thiele et al. 2018). Thus, FBs seem to be appropriate environments where biodiversity could increase again, provided diverse vegetation is established offering food and habitat to pollinators, birds, reptiles and small mammals (Cirujeda and Pardo 2020). Moreover, rare arable weeds might find in edges and boundaries a habitat in which to survive and reproduce (Solé-Senan et al. 2014).

Long-term studies on margin vegetation conducted in the UK show that when new margins are established, annual weeds are a short-lived problem (Smith et al. 2010) and their occurrence should decline in the long term. However, the occurrence of several perennial weeds in the field margins of farms in the Netherlands necessitated the adoption of management strategies such as mowing and removing the cuttings to avoid their proliferation (De Cauwer et al. 2008; Tarmi et al. 2011). Conversely, in Spain it has been demonstrated that few weeds occur in FBs exceeding 3 m width when they form a bank separating plots in steep landscapes, especially when they are covered with > 60% woody and evergreen perennials (Cirujeda et al. 2019). However, it is not known how long it takes for perennial vegetation to dominate newly established FBs in semi-arid conditions. Data could contribute to farmers' decisions to establish new FBs because generally they still consider FBs as a source of weeds.

Short-term successions may vary depending on the soil type and the precise position of the set-aside plots with respect to source habitats (Boatman et al. 2011). In the surveyed area, pseudo-steppe vegetation is expected to colonize the new FBs with perennial grasses and small shrubs (Puente Cabeza 2004). Some authors describe how vegetation composition is subject to year-to-year fluctuations in response to changing weather conditions and successional processes (Smith et al. 2010). Additionally, as rainfall patterns alter plant community dynamics and succession (Morecroft et al. 2004), year of establishment may also have an influence on the final vegetation in the FBs. Rainfall fluctuations are especially important in semi-arid regions (Ries et al. 2017), so it is important to conduct long-term experiments in such climatic regions. Generating such information would be useful especially for legislators wishing to promote natural vegetation in FBs to increase biodiversity in agricultural ecosystems, particularly in semi-arid regions where very scarce data has been collected on this topic so far. Data is necessary to be able to have an idea of the types of species that would replace the former annual weeds after installing new FBs.

Seed availability from the nearest adult plants seems to be one of the most limiting factors for vegetation recovery in Australian semi-arid fields (Scott and Morgan 2012). Even when a nearby seed source exists in a forest, seeds may enter only three metres into adjacent cropland (Devlaeminck et al. 2005). Moreover, most annual anemochorous species do not disperse seeds more than a few metres from the mother plant (Buisson et al. 2006). Thus, these species are supposedly unable to revegetate newly established FBs from a greater distance. Additionally, on land that has been used as agricultural fields for decades or even centuries with at least one annual tillage operation, this practice may have reduced the seed bank of the species, which are not adapted to agricultural conditions and may thus show a lack of vegetation recovery (Scott and Morgan 2012). Under Mediterranean conditions in France, it has been demonstrated that soil properties, above-ground vegetation, and soil seed banks are still impacted by cultivation done more than a century ago, even after abandonment of the practice. Therefore, species richness is higher in old grasslands than in formerly cultivated fields (Forey and Dutoit 2012).

For all the above reasons, plant establishment in margins of agricultural fields in semi-arid regions, where patches of natural vegetation are scattered, is expected to be slow. Even in the UK, with higher water and nutrient availability, Pywell et al. (2002) reported that lack of seed source was the key factor limiting the assembly of diverse grassland communities in the short term.

Pollinators or other beneficial insects are effectively attracted by artificially sown plants in intensive agricultural crops such as fruit orchards or horticultural plantations (Nicholls and Altieri 2013; Buhk et al. 2018). However, few studies try to determine the attractiveness of natural field margins to insects or other wildlife as a way of increasing agrobiodiversity (examples: Balzan and Moonen 2014; Guiller et al 2016; Morrison et al. 2017). Also, few studies are available describing the revegetation process of newly established FBs *sensus* Smith et al. (2010) for the UK, and none for semi-arid conditions.

The objectives of this work were: 1) to describe the changes in plant ground cover, species richness, proportion of forbs and monocotyledonous species, and of annuals and non-annuals during the first 10 years of FBs newly established in different years, 2) to describe the abundance and frequency of dominating arable weeds and species considered non-weeds in these FBs, 3) to compare the results with those found in FBs of commercial fields established decades ago (CFBs) and adjacent field centres (FC), in semi-arid conditions and 4) to analyse the vegetation distribution in all three environments. Besides the age, another difference between FBs and CFBs is that the FBs did not receive herbicide nor fertilizer drift from the adjacent organically-managed fields but that CFBs could receive both.

These objectives will contribute to verify the following hypotheses: 1) Plant ground cover will increase in FBs over time; 2) Plant succession is similar regardless of the year of establishment of an FB; 3) Weed species abundance and frequency decline over time in FBs, with an increase in perennial non-weed species; 4) Vegetation in FBs is different from that found in FCs; and 5) Vegetation in FBs after 8–10 years is similar to that found in CFBs.

Materials and methods

The main part of the work comprised surveying FBs of different ages for six years. Additionally, other environments, i.e. adjacent FCs and CFBs in nearby locations (at a distance of 5–15 km), were included for purposes of comparison.

Study sites and experimental design

The study of the FBs and the adjacent FCs was performed on a 322 ha farm called El Vedado Bajo del Horno owned by the Centro de Investigación y Tecnología Agroalimentaria de Aragón (CITA Research Centre) at Zuera (Zaragoza province, north-eastern Spain) and in FBs of commercial fields in the nearby locations of Zuera and Leciñena (Zaragoza province) (called CFBs hereafter).

The climate of the area is semi-arid, with a mean annual rainfall of 346 mm (Oficina del Regante, SARGA, 2016). The dry period is from May to September; in these months the evaporation is higher than the recorded low rainfall (Supplementary Figure S1). Most rainfall is recorded in autumn and spring when also most annual plant emergence occur. During the study years mean monthly temperature in Zuera was 14.6 °C; the mean of the monthly maximum temperatures was 21.1 °C and that of the minimum monthly temperatures, 8.4 °C. Rainfall distribution varied between years (Table 1). The winters of 2008 and 2012 were especially dry, as was the subsequent spring of 2012. In contrast, spring 2013 was unusually rainy (Table 1). A strong NW wind (the so-called *cierzo*) is common in the area, blowing along the Ebro valley with the consequence of drying out the soils rapidly.

Sudden storms with heavy rainfall may happen, causing severe erosion problems, as described for other areas with a semi-arid climate (Ries et al. 2017). Additionally, the fields on the experimental farm are big and there is scarce vegetation in the hilly landscape between the fields, so run-off water is largely unobstructed.

Field boundary establishment

The need to reduce water flow motivated the establishment of uncultivated FBs eight metres wide next to the roadways as of 2003, with the installation of two new margins each year until 2007 (10 in total). Those stripes had been previously commercial farmland. FB establishment started each year after the cereal harvest in July; stubble was not ploughed into the soil as is usually done in the area and remains were instead kept on the soil surface. These FBs were located between coordinates 41º52′55.15’’N/ 0º39′32.17’’W north and 41º50′26.74’’N/ 0º38′28.83’’W south; 41º52′37.27’’N/ 0º40′25.30’’W west and 41º51′20.47’’N/ 0º38′29.07’’W east. The maximum distance between the FBs was 5 km. No other similar initiative has been reported in the area and the AES applicants in 2008–10 mostly inscribed existing CFBs, so these FBs provided a unique opportunity to describe revegetation processes starting in different years (Fig. 1, Photos 1, 2).

FCs and CFBs

Barley (*Hordeum vulgare* L.) and durum wheat (*Triticum durum* L.) are the most frequent crops in the area, often grown only every two years, due to the scarce water availability. Additionally to the sampled FBs, vegetation in two different FCs was surveyed each year in cropped fields (not in fallow land).

In years 2013 and 2014, additionally, field boundaries located in nearby commercial farms separating field portions were sampled (CFBs). These CFBs have remained the same for decades and vegetation

Table 1 Monthly rainfall (mm) and number of days with rainfall (in number) at the location of Zuera (Zaragoza, Spain)

	Jan-spring sampling 2006	Jan-spring sampling 2007	Jan-spring sampling 2008	Jan-spring sampling 2011	Jan-spring sampling 2012	Jan-spring sampling 2013
Rainfall (mm)	108.8	132.7	140.4	117.9	75.2	156.0
Days with rainfall	37	34	47	29	23	57
	Sep05-winter sampling 06	Sep06-winter sampling 07	Sep07-winter sampling 08	Sep10-winter sampling 11	Sep11-winter sampling 12	Sep12-winter sampling 13
Rainfall (mm)	106.6	153.0	57.1	171.1	90.4	325.1
Days with rainfall	26	49	38	46	31	79

Rainfall recorded in September until the winter sampling is considered to permit the autumn and winter plant emergences while rainfall recorded from January until the spring assessment is considered to enable the spring growth of the plants emerged in autumn and of the perennials. Source: Oficina del Regante, Sarga, Aragón Government

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
FB1 FB2	Created	ns	ns	3	4	5	ns	ns	8	9	10	ns
FB3 FB4	-	Created	ns	2	3	4	ns	ns	7	8	9	ns
FB5 FB6	-	-	Created	1	2	3	ns	ns	6	7	8	ns
FB7 FB8	-	-	-	Created	1	2	ns	ns	5	6	7	ns
FB9 FB10	-	-	-	-	Created	1	ns	ns	4	5	6	ns
FCs	ns	ns	ns	<1	<1	<1	ns	ns	<1	<1	<1	ns
CFBs	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	>20	>20

Fig. 1 Year of field boundary (FB) creation, age of the FBs, FCs and CFBs (in years), and sampling dates. *NS* not sampled

Photo 1 one of the field boundaries (FB) of the Vedado farm, in this case created in 2005, the picture was taken during the spring sampling period two years after creation

can thus be considered climax for FBs in the area. They were selected in the nearby locations of Zuera and Leciñena (between coordinates 41º54′8.87’’N/ 0º38′51.23.42’’W north and 41º47′33.79’’N/ 0º32′36.03’’W south; 41º54′8.87’’N/ 0º51′23.42’’W west and 41º47′33.79’’N/ 0º32′36.03’’W east), as close as possible to the newly established FBs in order to allow realistic comparisons. The maximum

Photo 2 one of the samples commercial field boundaries (CFB); in this case, *Lygeum spartium* was dominant

distances between the FBs and CFBs were 5, 9, 15 and 9 km between the northernmost, southernmost, westernmost and easternmost sampled FB and CFB, respectively.

Vegetation sampling

Similarly to the methodology of Aavik et al. (2008) and of Rostami et al. (2016), four permanent 2 × 2 m quadrats were chosen randomly in each of the described FBs, with a separation of at least 20 m between them. The quadrats were placed near the inner-field edge of the 8 m strips, at a distance of 6–8 m from the outer edge of the field, to avoid excessive influence of the roadways. Total plant ground cover (%) was assessed in winter (February or March) and in spring (late April or early May) in six years (2006–08 and 2011–13). Additionally, in the spring assessments, each plant species was identified and its individual percent ground cover recorded. In total, plant ground cover was assessed at 12 moments, and species records were made on 6 occasions. Winter assessments aimed to describe the vegetation of the autumn-emerged plants before the spring growth; spring assessments aimed to describe the main plant development in the year, provided there was enough rainfall. Data for FB 6 in 2008 was lost because of uncontrolled sheep grazing despite the fences installed in 2007.

For the FCs, two adjacent cereal fields were chosen each year and weeds assessed at least 20 m from the boundary in four sampling quadrats of the same dimensions as in the FBs, distributed randomly following the same methodology.

Vegetation in the CFBs was recorded in May 2013 and 2014 in three quadrats that were as wide as the boundary and 2 m in length. These boundaries had not been disturbed directly for decades, although they may receive fertilizer and herbicide drift from the nearby fields. The chosen CFBs had been included in the AES in years 2008–10. Plant species identification was based on *Flora Europaea* (Tutin et al. 1964–1980) and on local floras, i.e. Puente Cabeza (2004) and De Bolòs et al. (1990).

Data analysis

After identification, the percentage of plants belonging to the different botanical families was calculated for the FBs, FCs and CFBs. In this case, data from all the quadrats was pooled together to give a global view of the found plant species.

Plants were classified into monocotyledonous or forbs and into two life-form groups, i.e. annuals and non-annuals, and into weeds (frequent species in cereals) and non-weed species (at least not-troublesome species) , following Carretero (2004). Finally, plants were organized into four groups considering life-forms and weediness: (i) annual arable weed species, (ii) biennial and perennial arable weed species, (iii) annual non-weed species and (iv) biennial and perennial non-weed species. The percentage of plant species belonging to the different groups was calculated for each quadrat (results in Tables 5, 6 and Supplementary Tables 1, 2).

As also found in other areas of Spain (Romero et al. 2008; Solé-Senan et al. 2014), botanical diversity was high within FBs established during the same year, so each one was analysed separately; data of the four quadrats of each FB were the replicates for that FB. Data was tested for normality and homoscedasticity and was transformed when needed following $\arcsin(\sqrt{x}/100)$ to satisfy these criteria. Analyses of variance (ANOVA) were performed on annual, forb and total species richness, and Student–Newman–Keuls (SNK) mean separation tests were performed to detect differences, using R version 4.03 (R Foundation for Statistical Computing, Vienna, Austria). Similarly, ANOVAs and mean separation tests were conducted for each sampling date separately, comparing in this case the different FBs to investigate the effect of boundary establishment year on species richness. Secondly, the dominance of species was studied. When conserving or installing new FBs next to their fields, farmers fear that weeds (especially *Bromus diandrus* Roth.) might grow there and later infest the fields. For this reason, plants appearing at a density of ≥ 10% plant ground cover were identified for each of the four weediness and life-form groups. The Integrated Pest Management guide published by the Spanish Ministry of Agriculture is more restrictive and considers 2% as a general economic threshold within a cereal field for a particular species or for the sum of those species (MAAMA 2015). However, Gerowitt and Heitefuss (1990) established the general economic threshold within a cereal field at 5–10% cover for broad-leaved species. We thus considered 10% because 2% is considered for the field centre, so 10% for the boundaries seems to be demanding enough. The number of appearances of weed species exceeding 10% plant ground cover in the sampling squares was determined for each year and a regression for this value vs. the age of each sampling quadrat was calculated.

Finally, a multivariate analysis was performed to describe the vegetation composition in the different FBs in comparison with the vegetation found in the adjacent FCs and in the CFBs. Vegetation distribution was tested by carrying out a canonical correspondence analysis (hereafter CCA) with Canoco 5.0 (Smilaurer and Leps, 2014). The explanatory variables were the environments (FB, CFB and FC) and years of establishment (0 for FC, 0–10 for FBs and 20 for CFB). The basic data unit was quadrat-year.

Results and discussion

General results

The FBs harboured the highest species richness and greatest diversity of botanical families, followed by the CFBs and, as expected, the lowest values were for the FCs (Table 2). One reason for this could be that the width of the FBs (8 m vs 2 m in CFB and FC) favoured the establishment of more species despite the fact that only 2 m were sampled in all cases. Curiously, Rostami et al. (2016) found higher species richness within agricultural fields (43 species) compared to non-crop field edges (37) and within-field edges (30) in Iran.

In all three environments, *Asteraceae* and *Poaceae* were the most or second most well-represented families, the third and fourth families being *Fabaceae* and

Table 2 Species and family numbers found in the field boundaries (FBs), commercial field boundaries (CFBs) and field centres (FCs)

	FBs	CFBs	FCs
Total species number	126	70	33
Families number	23	18	13
Asteraceae	32	19	7
Poaceae	19	15	3
Fabaceae	16	(5)	(2)
Brassicaceae	9	7	4
Papaveraceae	(7)	5	6

The four families with most species of each environment are presented (in parentheses, number of species in that family despite not belonging to the 4 most represented families)

Brassicaceae for FBs and CFBs but *Papaveraceae* and *Chenopodiaceae* in FCs (Table 2).

Plant ground cover

Plant ground cover in winter was generally lower than in spring and both data sets showed an overall increase with growing FB age (Fig. 2 A, B) (confirming hypothesis 1). Winter and spring cover data was plotted in two different graphs to facilitate the overview. These results are in the range of those observed by Boatman et al. (2011), who found around 50% plant ground cover in FBs < 2 years old, increasing to 80% in older FBs.

In most of the FBs, cover tended to decrease in the dry winters of 2008 and 2012. In 2008 it was significantly lower than in the previous winter of 2007 for FBs 5 and 8, as it was for winter 2012 compared to 2011 for FBs 2, 7 and 8 (Fig. 4A, B, Table 1). For the newest FBs 9 and 10, the most significant changes were found for the first years compared to the last ones, FB age being more important than those two dry periods.

On the other hand, weed ground cover tended to increase in most FBs during the exceptionally rainy spring of 2013, being significantly higher than in the previous spring for FB 5, only. High stone content in the soils (mean of $75 \pm 1.61\%$ of the soil weight) implies low water retention capacity of the soils. This could explain the decline in vegetation cover in the dry seasons; water infiltration has been found to be a key factor to assure vegetation restoration (Masson et al. 2015), supporting these observations. Thus, although there were evident unusual rainfall situations, the effect on plant cover seemed to be less in 2012 and 2013, very probably because the FBs were older and vegetation thus more stable than in 2008 (Fig. 2A, B).

When analysing plant ground cover of the FBs for each sampling date individually, lower values were found for the younger boundaries compared to the older ones until spring 2008. Later, only FB 3 had a lower ground cover than the rest in winter and spring 2011, so the differences were ironed out. No notable differences were found in FBs aged 4–8 years and 6–10 years, showing that ground cover generally did not increase significantly after the fourth year of establishment, regardless of the particularities of each sampling quadrat and of the FB establishment year, confirming hypotheses 1 and 2.

In the younger FBs plant ground cover was scarce in the first winter after establishment but increased rapidly in the first spring (FBs 7, 8), confirming hypothesis 1. This process was especially slow for FBs 9 and 10, very probably because the dry winter of 2008 coincided with the first year of margin establishment and probably lengthened the time needed to achieve a constant ground cover (Fig. 2A, B, Table 1). In the older FBs no significant increases or decreases were observed for FB 1 and FB 2 being aged 3 years or older, and for FB 3 and FB 4 being aged 2 years or older; in the younger boundaries, FB 5-FB 8, ground cover was stable after 1–2 years. In FB 9 and FB 10, established in 2007, significantly lower ground cover was found in the first year compared to the fourth and subsequent years (Fig. 2A, B), indicating rapid initial ground cover, which remained stable for 9 or 10 years. Thus, concerning hypothesis 2, the year of boundary set-up might have an influence on initial cover especially if that year has exceptionally low or high rainfall, but initial differences seem to even out in the subsequent years.

The differences between FBs were probably due to site-specific characteristics of each FB, including soil texture, moisture, position in the landscape, etc.; also the unique individual historical trajectory of each particular site has been demonstrated to be relevant for the expected succession for Mediterranean regions (Buisson et al. 2006). FB 4 occupies a low-lying position in the landscape favouring the presence of more run-off water and nutrients; moreover the soil of this FB had the lowest stone content ($66 \pm 5.8\%$ of the soil weight). These characteristics probably explain the larger plant ground cover values in this FB compared to all the others, even during the dry winter of 2008. However, the differences between FBs, including FB 4, were gradually smoothed out. The plant ground cover decline observed in FB 6 in winter 2008 was due to sheep grazing, which was visible in the form of lower weed ground cover for several years (Fig. 3). Buisson et al. (2006) observed that sheep grazing might be insufficient to initiate vegetation recovery; in fact in this case it caused a substantial plant ground cover decrease for several years.

Total species richness

Total species richness in the FBs increased gradually and stabilized between the first and fifth year of establishment, depending on the FB (Table 3). Only in the younger FBs 5, 7, 8, 9 and 10 was species richness found to be significantly higher 5 or 6 years after establishment compared to earlier years, while the older FBs 1–4 did not show any significant differences in species richness in the sampled years (Table 3). Initial differences observed in the first years of the creation of the FBs thus seemed to be ironed out (hypothesis 2). Overall, significantly more species were recorded in spring 2007, 2011 and 2013, possibly due to the favourable climatic conditions in those years (Table 1).

When data was analysed for each sampling moment separately, species richness was statistically the same in 2011–13, i.e., when comparing FBs aged between 4 and 9 years; the only exceptions were again FB 4 and FB 6, very probably for the above-mentioned reasons. The results are similar to the observations of Bazzaz (1975) in set-aside land in the USA, where species richness stabilized after the fourth year of abandonment.

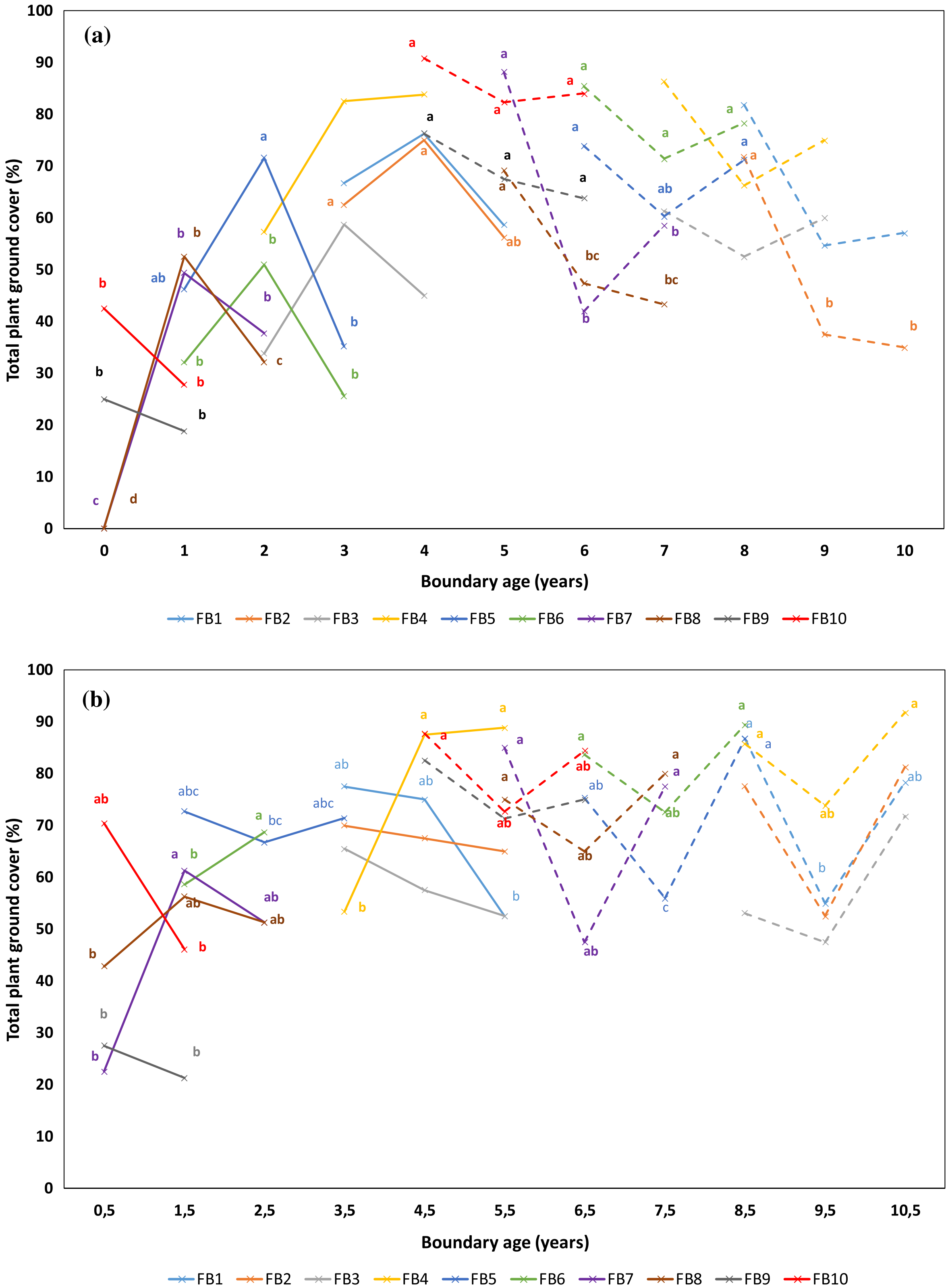
In most FBs, plant richness stood at more than 15 and even in some cases surpassed 20 species, which is much higher than the 8 species found in English conditions in set-aside fields 13 years after abandonment (Smith et al. 2010) or the 10 species found in the Czech Republic 20 years after abandonment (Knappova and Muenzbergova, 2015). However, these figures are lower than the 25 species recorded in recently abandoned fields in the arid Australian environment (Scott and Morgan, 2012). Surprisingly, in a German study, the mean number of plant species remained stable in one- to four-year-old set-aside fields (Dewenter and Tscharntke 2001) and even decreased in set-aside land in England (Smith et al. 2010).

Proportion of forbs and annual plants

In the FBs the most frequent species were forbs, regardless of the year and the FB, the mean percentages ranging between 71 and 92% with quite stable values comparing within years (data not shown). The proportion of forbs also tended to stabilize, except FB 4 and FB 6 in 2011 and 2013, which had lower forb richness than the other FBs, as already observed for the plant cover. In a study on set-aside land, Critchley and Fowbert (2000) found that sites located in an arable region remained at an earlier successional stage for longer; this effect could be what occurred in FB 4, where more water and probably more nutrients were available. In contrast, Boatman et al. (2011) and Critchley and Fowbert (2000) found mainly perennial monocotyledons in set-aside fields in England, demonstrating that successional processes may vary substantially from one region to another, and confirming the importance of conducting regional studies.

Annuals dominated but not in all years and FBs exceeding 50% of the total species found in the years 2006–2008 and 2013, but in 2011 in 2012 in only six out of the 10 FBs (data not shown).

Annual plants dominated in the FBs in years 2006–08 and in 2013, exceeding 50%; however, in 2011 and 2012 they accounted more than 50% only in six out of 10 FBs (data not shown). Overall, there was a decreasing tendency in the proportion of annuals, and thus an increase in the proportion of perennials, for all FBs, especially the younger ones, confirming the second part of hypothesis 4 of this work. This data is in accordance with results found in Germany, where a significant shift from annual to perennial vegetation was observed from the third year onwards (reviewed by Tscharntke et al. 2011). In England, in a survey conducted on set-aside fields, annuals decreased in the first two years of abandonment but then remained stable until 15 years of age (Boatman et al. 2011). In contrast, in a 13-year study also conducted in England, a much faster decline in annual species and a dramatically rapid increase in perennials was observed (Smith et al. 2010).


(a)
Total plant ground cover (%)
0
10
20
30
40
50
60
70
80
90
100
0 1 2 3 4 5 6 7 8 9 10
Boundary age (years)
FB1 FB2 FB3 FB4 FB5 FB6 FB7 FB8 FB9 FB10
(b)
Total plant ground cover (%)
0
10
20
30
40
50
60
70
80
90
100
0,5 1,5 2,5 3,5 4,5 5,5 6,5 7,5 8,5 9,5 10,5
Boundary age (years)
FB1 FB2 FB3 FB4 FB5 FB6 FB7 FB8 FB9 FB10

◂**Fig. 2** **A** Mean values of the total plant ground cover (%) in the different field boundaries (FBs) left set-aside from 2003 to 2007 in the winter samplings. Different letters within each FB refer to statistically significant differences according to SNK at $P<0.05$. Data from FB7 and 8 was back-transformed from arcsin($\sqrt{x/100}$)). Solid lines: winters 2006–08, scattered lines: winters 2011–13. **B** Mean values of the total plant ground cover (%) in the different field boundaries (FBs) left set-aside from 2003 to 2007 in the spring samplings. Different letters within each FB refer to statistically significant differences according to SNK at $P<0.05$. No data in FB6 in spring 2008 is due to uncontrolled grazing. Solid lines: springs 2006–08, scattered lines: springs 2011–13

Abundance and frequency of dominating arable weeds and their changes

Annual arable weed species abundance tended to decrease with increasing FB age (Table 5), confirming the first part of hypothesis 3. The number of these species exceeding 10% cover declined with time, showing how weediness decreased over the years; nevertheless, there was a sudden increase in this parameter in 2013 due to abundant rainfall, especially in younger FBs (Fig. 3). However, when calculating the regression between the appearance of these species and the age of the FBs, the decrease in the outcome of weeds at high densities is even more constant despite the exceptional rainfall in 2013, demonstrating that weed cover decreases with increasing FB age (Fig. 4), confirming again hypothesis 4.

Concerning frequency, very few weed species were found at > 10% plant ground cover in all 4 quadrats of each FB, only *Eruca vesicaria* (L.) Cav. in FB 5 in year 2006, *Diplotaxis erucoides* in FBs 7 and 8 in year 2007 and *Rapistrum rugosum* (L.) All. in FB 9 in year 2007. These FBs were 1 year old or recently established, showing how frequency of highly-abundant weed species decreased with increasing FB age. An exception was *Anacyclus clavatus* (Desf.) Pers., found in all 4 quadrats of FB in year 2013, which had been established 8 years before.

Abundance of *Brassicaceae* species in particular tended to decrease rapidly. For example, mean cover of *E. vesicaria* stood at 29% in the first year of FB 5 but decreased to 5.8% in year 2 and remained at 0% in the following years. Also *R. rugosum*, which was very abundant at a high frequency (in six of the eight sampling quadrats) in FB 9 and FB 10 in the first year of establishment with a mean ground cover of 23 and 16%, respectively, showed no cover at all in the following year (2008) and less than 2% in 2011. In contrast, *A. clavatus* was one of the most long-lasting arable weed species (high abundance and frequency) in most FBs, being found in 46 of the sampled quadrats at ≥ 10% ground cover in FBs aged 1–10 years (Table 5).

However, annual meteorological conditions had an important effect and the rainy spring of 2013 caused the reappearance of some weed species with much higher ground cover than in previous years (Table 5, Fig. 2 A, B). *A. clavatus* and *Lolium rigidum* Gaud. and, in some margins, *Papaver rhoeas* L. as well as the *Brassicaceae R. rugosum* and *Sisymbrium crassifolium* Cav. appeared again with ≥ 10% abundance, whereas *Diplotaxis erucoides* (L.) DC. was less persistent, as it did not re-emerge that year with outstanding frequency or abundance. During the previous year, 2012, which was very dry, only *Bromus madritensis* L. and *B. diandrus* grew at ≥ 10% in some of the sampling quadrats (Table 5).

Biennial and perennial arable weeds were not common in any of the three environments and these species moreover appeared irregularly over time (Table 6). When found in the FBs, ground cover was ≥ 10% in only one out of four sampling quadrats and a maximum of two species were detected per FB. *E. serrata, Cirsium arvense* L. and *Silene vulgaris* (Moench) Garcke were the most frequent species of this group. The FBs thus contained biennial or perennial arable weeds only sporadically, and stands did not increase over time, confirming Smith et al. (2010), who stated that weeds are a short-lived problem in newly established FBs.

Changes in dominating non-weed species

Annual non-weed species exceeding 10% ground cover first appeared as of the second or third year of FB establishment (Supplementary Table 1). The wind-dispersed species *Crepis capillaris* (L.) Wallr. and *C. vesicaria* L. were very frequent and abundant especially in the first years after margin establishment, decreasing afterwards. Neither species was frequent in the FCs and generally neither of them is typical within cereal fields in the area. Later in the succession, the *Poaceae Hordeum murinum* L. and several *Bromus* species other than *B. diandrus* or *B. rigidum*, which are weed species, were other very common non-weed species and are typical of ruderal

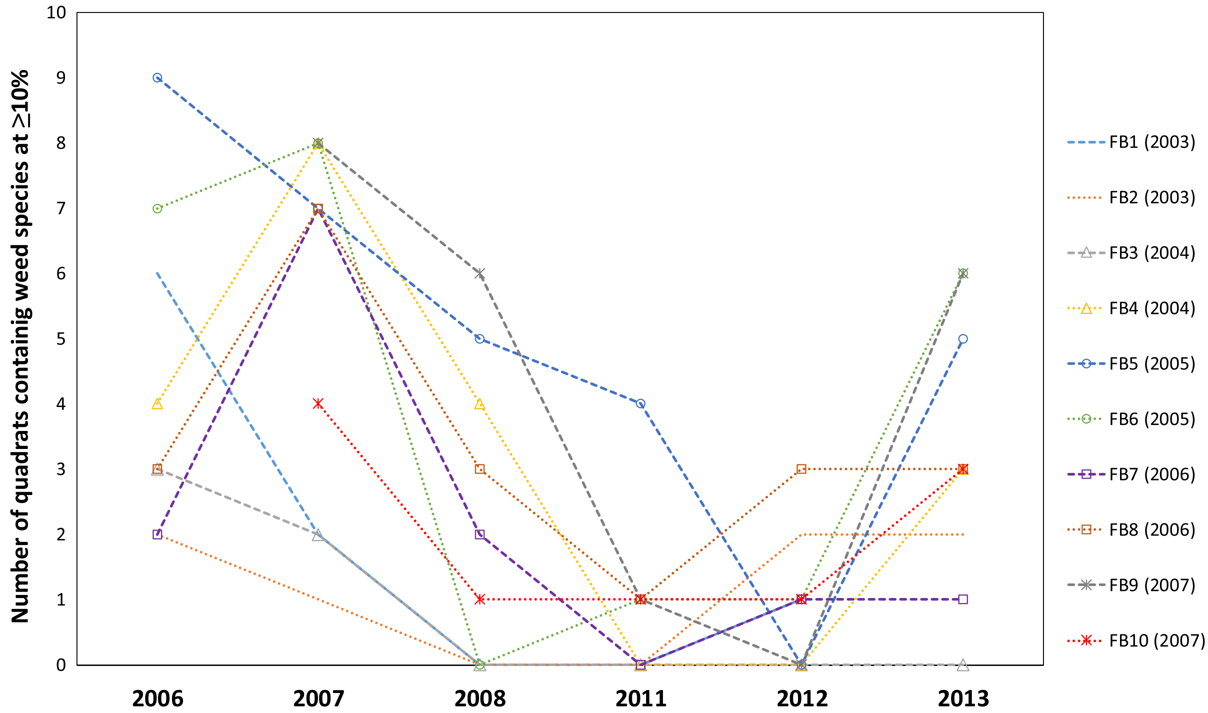


Fig. 3 Number of sampling quadrats containing weed species exceeding 10% plant ground cover related to the sampling year. Years 2003–2007 refer to the establishment date of the different boundaries

habitats (Puente, 2004). Also several small-sized species grew in importance in the FBs from year to year (Supplementary Table 1): *Alyssum simplex* Rudolphi, *Astragalus sesameus* L., *Bombycilaena erecta* (L.) Smolj., *Filago pyramidata* L., *Trigonella monspeliaca* L. and *T. polyceratia* L., which are typical of pseudo-steppe with grasses and annuals of the Thero-Brachypodietea (habitat number 6220, considered as a priority) (EU 1992). No relevant species of this group was found in the CFBs or the FCs.

Concerning perennials, many of the dominating species in the FBs were representative of ruderal habitats. Other species were typical of nitrophilous and subnitrophilous shrubland (Puente, 2004): *Artemisia herba-alba* Asso, *Melica ciliata* L. subsp. *magnolia* (Gren. & Godr.) Husnot, *Retama sphaerocarpa* (L.) Boiss., and *Salsola vermiculata* L. Some other abundant species were *Xeranthemum inapertum* (L.) Mill., which is typical of pseudo-steppe with grasses and annuals of the Thero-Brachypodietea (habitat number 6220, considered as a priority) (EU 1992), and *Plantago albicans* L. and *Reseda alba* L. subsp. *gayana* (Boiss.) Maire, which are typical of endemic oro-Mediterranean heaths with gorse (habitat number 4090) (EU 1992).

Plant ground cover, species richness, proportion of annuals and forbs in the CFBs and FCs

Plant ground cover in the CFBs was 86 ± 18.9 (standard error) in 2013 and 96 ± 8.0 in 2014, similar to the cover found in the 6- to 10-year-old FBs, suggesting that both boundary types had probably reached their maximum coverage capacity. Weed ground cover in the FCs ranged between 3 and 34% (mean: 14 ± 2.8) (Table 3); these relatively high weed infestations were not surprising because no herbicides were used in the

Table 3 Total plant species richness (lsmeans) found in spring 2006 to spring2013 in the different field boundaries (FBs) created in 2003–2007

Sampling year	Age	FB1	FB2	Age	FB3	FB4	Age	FB5	FB6	Age	FB7	FB8	Age	FB9	FB10
2006	3	17.5 w	17.3 w	2	17.3 w	10.5 x	1	9.8 c, x	10.3 x	0	7.0 c, x	8.3 d, x	–	–	–
2007	4	22.0 w	17.5 wx	3	22.3 w	10.0 yz	2	15.3 ab, xy	10.0 yz	1	14.0 b, xy	11.5 c, xyz	0	6.0 b, z	9.3 b, yz
2008	5	15.2 w	16.8 w	4	16.8 w	10.9 wx	3	14.0 abc, w	–	2	13.5 b, w	16.8 ab, w	1	7.0 b, x	9.0 b, wx
2011	8	24.5 w	22.3 wx	7	23.3 w	11.8 y	6	14.3 abc, xy	13.3 y	5	19.8 a, wxy	20.0 a, wxy	4	16.0 a, wxy	16.5 a, wxy
2012	9	19.8	18.0	8	20.0	12.3	7	12.8 bc	11.3	6	17.0 ab	14.5 bc	5	15.8 a	14.5 ab
2013	10	22.5 w	22.5 w	9	21.0 w	11.5 y	8	18.5 a, wxy	12.0 xy	7	20.5 a, wx	18.8 a, wxy	6	16.0 a, wxy	19.5 a, wxy

Different letters within each column (a-c) refer to statistically significant differences for each FB separately; different letters within each row (w-z) refer to statistically significant differences for each sampling moment comparing margins, according to SNK-test at $P<0.05$; no letters indicate no significant differences

fields. Unexpectedly, weed cover in the rainy spring of 2013 was low, probably due to higher cereal competition. However, cover was even lower in 2008, in that case due to the drought.

Overall, total species richness was lower in the FCs than in the FBs and CFBs (Tables 3, 4). Herbicide use and tillage as the main weed control methods prior to FB establishment, combined with crop competition, are probably responsible for this low diversity (Roschewitz et al. 2005).

FBs harboured a higher species richness than CFBs (Tables 3, 4). The reasons for this might be that i) some species adapted to agricultural environments (to tillage, fertilization) still remained in the new FBs but had disappeared from the CFBs after decades of establishment. ii) CFBs separate field portions while the FBs were located next to roadways. Moreover, the CFBs had a mean height of 1.5 ± 0.19 m, whereas the FBs were flat. iii) No herbicide was used in the newly established FBs but CFBs might receive some fertilizer and herbicide drift (Gove et al. 2007), so probably more species were able to grow and reproduce in the FBs. iv) The mean width of the CFBs was only 2.2 ± 0.2 m compared to the 8 m of the FBs, even though only 2×2 m were surveyed. Schippers and Joenje (2002) suggest that wider field margins have richer plant diversity than narrow field margins because they provide an opportunity for plant species to escape from large nutrient loads and because species number rises with increasing area.

The proportion of annuals was similar in the CFBs and was lowest in the FCs, taking into account arable weeds only (Table 4). The only exception was one FC sampled in 2011 where no annuals were found at all, but three perennial dicotyledonous weeds dominated (Table 4).

Concerning dominating weed species, in each CFB, one or two different arable weed species exceeded 10% abundance; curiously, the same particular species did not appear at high abundance repeatedly in several CFBs. Thus, the sampled CFBs were revealed not to be an important weed seed source for the nearby fields, as often feared by farmers (Table 5).

Only three species surpassed 10% ground cover in the FCs: *R. rugosum*, *L. rigidum* and *P. rhoeas*, the latter two appearing in two different years and also in younger FBs as well as in the rainy spring

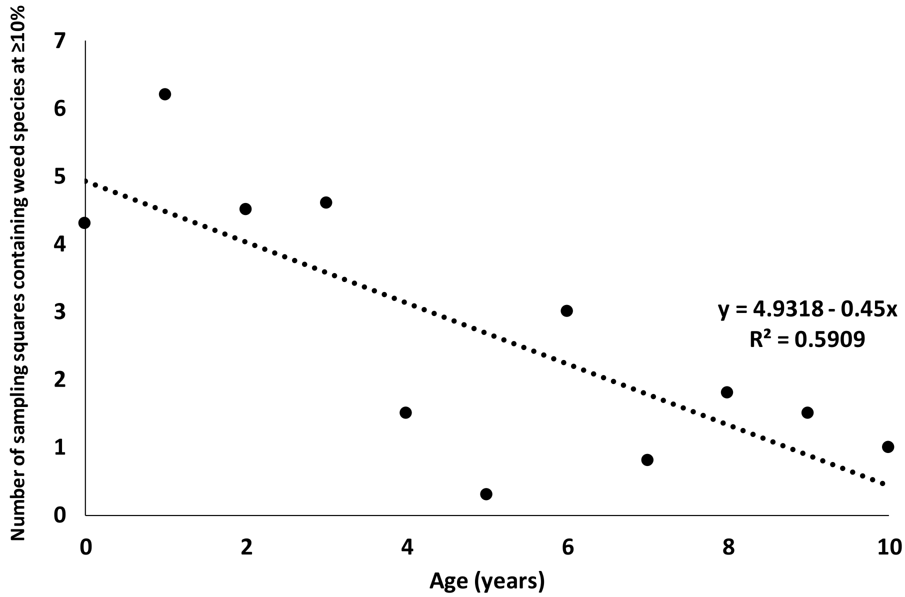


Fig. 4 Points and regression line relating the number of sampling squares containing weed species exceeding > 10% plant ground cover and the age of each boundary at sampling. Number of squares containing weeds > 10% = 4.9318 – 0.45 the age of the boundary, $R.^2 = 0.5909$, $P > 0.001$

of 2013 (Table 5). These results are not surprising, because both species are among the three most frequent species in winter cereals in Aragon (Cirujeda et al. 2011). Curiously, *R. rugosum* was not especially abundant in the FCs during the rainy spring of 2013, in contrast to what occurred in the FBs, probably because the ploughing regime in the field changed the species' dormancy cycle.

In the present study, only *C. arvensis* was quite abundant in the FCs, exceeding 10% ground cover in five quadrats in three different years; *C. juncea* was the second most abundant non-annual weed found at ≥ 10% in two sampling quadrats in two different years. Both species are well adapted to minimum tillage practices and to semi-arid rainfall conditions.

Concerning dominating non-weed species, in the CFBs several forb shrubs dominated, covering the soil considerably: *Atriplex halimus* L., *S. vermiculata*, *Santolina chamaecyparissus* L., *A. herba-alba*, *Lygeum spartum* L. and *Gypsophila tomentosa* L. None of these species was found in the FCs, probably as a consequence of the annual tillage and fertilization.

In the FBs perennial non-weeds needed more than four years to become established and were smaller than in the CFBs; the FBs can thus be considered to be at an earlier successional stage than the CFBs (Supplementary Table 2). Few changes were observed in perennial non-weed species in the 8- to 10-year-old FBs, showing very constant dominant species in frequency and abundance after the fourth or fifth year of establishment (as of 2008 for FBs 1–4). These results are in the range of the data collected in England, where the fifth year was chosen as the cut-off point between the age classes of the set-aside vegetation, as a rapid decline in annual species was observed in the first 2–3 years, with replacement by perennial grasses by the fifth year (Critchley and Fowbert 2000). Also Bartha (1990) found a sharp transition from primary colonizers to ruderal annuals and biennials in 3–4 years and afterwards a more gradual change to perennial domination within 10 years on set-aside land. Focusing on field margins, in Netherlands species richness increased in the first four years after establishment and the cover of agriculturally harmful weeds decreased in the years following initial

Table 4 Weed ground cover (C), total plant species richness (T) (lsmeans), percentage of forbs (F) and annuals (A) found in spring 2006–2013 in the centre of adjacent winter cereal fields (FCs) and in the commercial field boundaries (CFBs) in the same area (means ± standard error)

Sampling year		FC1	FC2
2006	C	26 ± 0.71	25 ± 1.1
	T	4.0 ± 0.71	5.3 ± 1.11
	F	83	81
	A	88	93
2007	C	19 ± 0.7	15 ± 1.0
	T	7.0 ± 0.71	3.8 ± 1.03
	F	100	100
	A	64	61
2008	C	5 ± 0.3	3 ± 0.3
	T	3.5 ± 0.29	2.5 ± 0.29
	F	71	72
	A	66	52
2011	C	10 ± 0.4	9 ± 1.0
	T	2.0 ± 0.41	3.0 ± 1.00
	F	100	60
	A	0	60
2012	C	11 ± 1.1	34 ± 1.5
	T	3.0 ± 1.08	8.0 ± 1.47
	F	60	81
	A	50	54
2013	C	8 ± 1.0	6 ± 0.9
	T	9.3 ± 0.95	2.8 ± 0.85
	F	81	89
	A	57	64
Sampling year		CFBs	
2013	C	86 ± 18.9	
	T	10.4 ± 0.83	
	F	75	
	A	79	
2014	C	96 ± 8.0	
	T	13.3 ± 1.93	
	F	64	
	A	48	

establishment (Musters et al. 2009), similarly to the observations of the present work.

Vegetation distribution in the three environments

As expected, few coincident species were found between the three environments (20), followed by environments CFBs and FCs (21) while the most coincident species appeared between CFBs and FBs (43) (Fig. 5). Despite this, many species were present in the FBs and not in the CFBs (74) and the other way round (26). Notable differences in the plant species were thus detected in the vegetation of the three surveyed environments. It should be expected that some of the species most abundant in the CFBs will gradually increase in importance in the FBs while others, still present in the FBs and absent in the CFBs, will probably gradually disappear after decades of no-till.

The explanatory variables accounted for only 7.8% of the total variation in the CCA but the analysis was significant. The vegetation of the three environments was clearly separated into different groups (Fig. 6). Most arable weeds were related to the FCs, except the annual weeds *Descurainia sophia* (L.) Webb ex Prantl, *Lamium amplexicaule* L. and *Malcolmia africana* (L.) R. Br. (Fig. 6), which were only found in the CFBs. However, none of these three species causes severe competition in cereals in the area, so their presence in the CFBs does not represent a threat for nearby fields. Several biennial or perennial non-weed species were related to FBs and a lot of species were characteristic of CFBs. Although the number of perennial non-weed species tended to increase with age in the FBs, the species were not the same as in the nearby CFBs (hypothesis 5). For example, the woody perennials *A. halimus* or *S. chamaecyparissus* were not found in the FBs, which is in accordance with the observations of Saatkamp et al. (2018), who did not find any woody plants colonizing their experiments even 23 years after grazing abandonment.

The results of the multivariate analysis are supported by the relatively low number of coincident species in the different environments (Fig. 5) and by the different species found at ≥ 10% (Tables 5, 6 and Supplementary Tables 1–2). All three analysis approaches confirm the assumption that vegetation in the FBs is different from that found in the FCs (hypothesis 4) but contradict the presumption that the FBs would show a similar vegetation 8–10 years after establishment to that in the CFBs (hypothesis 5). Thus, although the FBs seem to reach a certain stability in species richness, type of species and ground cover after the fourth year, still many species are different from those found in the nearby CFBs. These results confirm that the renaturalization process in the FBs will probably take much longer, as supported by other studies; for example, Helm et al. (2019) found

Table 5 Annual arable weed species found at a plant ground cover ≥ 10%

FC	Field boundary (FB) age (years)											CFBs
< 1	0	1	2	3	4	5	6	7	8	9	10	> 20
Pr (17.5, 17.5)	De (40)	Ac (20,30,37)	Ac (30)	Ac (10,15,18)	Ac (10)	–	Ac (11,14,34)	–	–	Bm (13)	–	–
Sk (17.5)	Gc (10)	Ev (20,30, 30,37)	Bd (53)	Bs (20)	De (12)		Lr (18)					
		De (10)	De (18)	De (10,18)								
		Lr (10)										
		FB5-2006		FB1-2006			FB5-2011	FB3-2011	FB1-2011	FB1-2012	FB1-2013	13-Jun
2006	FB7-2006		FB3-2006		FB1-2007	FB1-2008						
Rr (15)	De (30,30)	Ac (10,18,40)	De (20)	Ev (10)	Ac (23)	-	Bd (50)	–	–	Bm (10,28)	Ac (10)	Bd (15)
	Pr (15)	De (12)	Lr (20,30,53)	Lr (15)							Lr (19)	Fo (15,15)
		Ev (12)										
		Lr (10,12)	FB4-2006							FB1-2012		
2007	FB8-2006	FB5-2006		FB2-2006	FB2-2007	FB2-2008	FB6-2011	FB4-2011	FB2-2011		FB2-2013	13-Jul
–	Ev (14,15,67)	Ac (34)	Ac (17,25)	Ac (16)	–	–		–	–	–		Lr (10,30)
	Lr (12)	De (11,14,31, 34)	Ev (16,23,25)	Bs (10)			Bm (52)					Bm (10)
	Rr (12,23,28, 30)	Lr (16)	Lr (10)									
	FB9-2007	Pr (13)	Ec (21)									
2008												
		FB7-2007	FB5-2007		FB3-2008	FB7-2011		FB5-2012	FB3-2012	FB3-2013		
				FB3-2007			FB7-2012					13-Aug

Table 5 (continued)

FC	Field boundary (FB) age (years)										CFBs
Lr (12)	De (16,20)	De (12,12,14, 33)	Ac (14,27)	Ac (14,24,27)	Ac (11,29, 29)	Lr (26)	Bm (14,18,36)	Bd (35)	–	Ac (19,19)	Bd (36)
	Rr (13,45)	Lr (14,17)	De (14)	De (17)	Lr (14)					Lr (19)	Ga (35)
		Pr (13)	Ev (14,30)	Lr (14,20,37)							
			Lr (13,14,14)	So (25)	FB4-2008						
2011				FB4-2007						FB4-2013	
	FB10-2007	FB8-2007	FB6-2007			FB8-2011	FB8-2012	FB6-2012	FB4-2012		
											13-Sep
Lr (10.5, 15)		Ac (12, 34)	Ac (43)	Ac (23)	Ac (16, 29)	–	Lr (28)	Ac (10)	Ac (10, 18, 19, 40)		Si (28,17)
Pr (10, 12)		Ev (11, 17)	Lr (34)	Bs (14)			Pr (15, 32)		Lr (19)		13-Oct
		Lr (10, 16)		De (14)			Rr (10, 13, 24)				
				Ev (15)					FB5-2013		
				Lr (12)	FB9-2011		FB9-2013				
2012		FB9-2008	FB7-2008	FB5-2008		FB9-2012		FB7-2013			
–		Lr (12, 35)	De (12, 15)	No data	Ac (14)	Bm (15)	Ac (14)	Ac (10)	Ac (19, 19)		Bm (30)
2013			Lr (13)	(grazing)			Ph (12, 30)	Lr (15)	Bd (19)		
								Pr (17)	Sc (10)		
									Lr (14)		
									Pr (19)		
		FB10-2008	FB8-2008	FB6-2008	FB10-2011	FB10-2012	FB10-2013	FB8-2013	FB6-2013		
											14-Oct
											Bst (14,25)
											Bs (15)
											14-Dec

In parentheses: soil cover in those sampling quadrats. *CFB* commercial field boundary, *FC* field centre

Ac Anacyclus clavatus; Bd: *Bromus diandrus;* Bm*: Bromus madritensis;* Bs: *Bromus spp.;* Bst: *Bromus sterilis*, De: *Diplotaxis erucoides;* Ec: *Erodium ciconium*; Ev: *Eruca vesicaria;* Fo: *Fumaria officinalis;* Ga: *Galium aparine*; Gc: *Glaucium corniculatum;* Lr: *Lolium rigidum*¸ Ph*: Papaver hybridum;* Pr*: Papaver rhoeas;* Rr: *Rapistrum rugosum,* Sc: *Sisymbrium crassifolium;*, Si: *Sisymbrium irio*; Sk: *Salsola kali*; So: *Sonchus oleraceus*

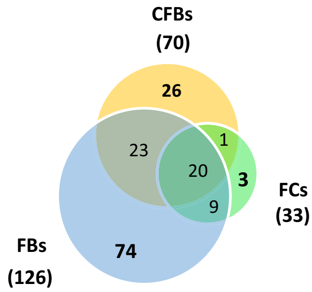


Fig. 5 Number of coincident species in the three environments. *FB* field boundary, *CFB* commercial field boundary, *FC* field centres. In parentheses: total species number in each environment

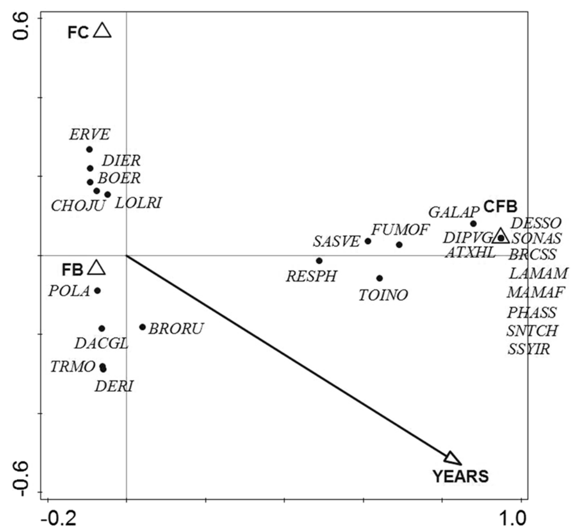


Fig. 6 Biplot of the CCA-analysis considering sampling sites (FB, CFB and FC) and age of establishment (year) showing the 25 best fitting species. *FB* field boundaries, *CFB* commercial field boundaries, *FC* field centres, *ATXHL Atriplex halimus*, *BOER Bombycilanea erecta*, *BRCSS Brachypodium* sp., *BRORU Bromus rubens*, *CHOJU Chondrilla juncea*, *DACGL Dactylis glomerata*, *DESSO Descurainia sophia*, *DERI Desmazeria rigida*, *DIER Diplotaxis erucoides*, *DIPVG Diplotaxis virgata*, *ERVE Eruca vesicaria*, *FUMOF Fumaria officinalis*, *GALAP Galium aparine*, *LAMAM Lamium amplexicaule*, *MAMAF Malcolmia africana*, *PHASS Phalaris* sp., *POLA Podospermum laciniatum*, *RESPH Reseda phyteuma*, *SASVE Salsola vermiculata*, *SONAS Sonchus asper*, *SNTCH Santolina chamaecyparissus*, *SSYIR Sisymbrium irio*. *TRMO Trigonella monspeliaca*

35 years of abandonment in a Mediterranean environment insufficient to form a steppe with similar vegetation composition to natural ones.

It is important to highlight that in the present study area no evident source of non-weed species is available, except a small pine plantation, and that the soil now devoted to the FBs had been tilled and used as agricultural soil for decades, so a small seed bank is expected. However, the bird census conducted in 2004 on the Vedado farm showed that 31% of the 71 bird species sighted were granivorous (J. Lucientes, pers. comm.), so they are potential seed suppliers. In other study areas, granivorous birds and ant-borne seeds have been considered to be the most important seed sources (Buisson et al. 2006). But even in conditions of proximity to a mature forest with high seed availability, 18 years was not sufficient time for abandoned agricultural land to achieve the same species richness (Souza et al. 2014). However, following Zimmermann et al. (2000), animals do not necessarily make frequent visits to habitats modified by humans, so other factors such as self-dispersal and wind dispersal should be taken into account as possible seed sources for the recently established FBs. The strong and constant NW winds in the area could potentially disseminate anemochorous species, and in fact some wind-dispersed species were found (Tables 5, 6 and Supplementary Tables 1–2).

Conclusions

The results of the present study show how vegetation in the newly established FBs was different from the weeds found in the FCs and that the proportion of weeds in the FBs decreased with time. Plant ground cover and percentage of perennials were similar in the FBs and CFBs already after the first four years, regardless of the year of establishment. Differences in species composition in FBs and CFBs might be due to several reasons. From the weed point of view, the present results show that in the study site a rapid decline in weed abundance would probably occur when establishing new FBs in a similar semi-arid environment, but in a non-typical year with abundant rainfall certain species may reappear in young FBs at appreciable abundance. Establishing new boundaries in the study area thus increased plant biodiversity, which can consequently attract arthropods, birds, reptiles and small mammals without causing damage in the surrounding fields.

Table 6 Biennial and perennial arable weed species found at a plant ground cover ≥ 10%

FC	Field boundary (FB) age (years)											CFBs
< 1	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**> 20**
Coa (17.5) 2006	– FB7–2006	Ca (10) Cj (10) FB5-2006	Cd (18) FB3-2006	– FB1-2006	– FB1–2007	– FB7–2011	– FB5–2011	– FB3–2011	– FB1–2011	– FB1–2012	– FB1–2013	– 06/13
Coa (19,19) Ch (16) 2007	– FB8–2006	– FB6–2006	– FB4–2006	Sv (10,15) FB2-2006	– FB2–2007	– FB8–2011	– FB6–2011	– FB4–2011	Es (12) FB2-2011	– FB2–2012	– FB2–2013	– 07/13
– 2008	Es (15) FB9-2007	- FB7-2007	– FB5-2007	Ch (12) FB3-2007	– FB3–2008	– FB9–2012	– FB7–2012	– FB5–2012	– FB3–2012	– FB3–2013		– 08/13
Es (18) 2011	– FB10–2007	Cj (10) Sv (10) FB8–2007	– FB6–2007	Ca (28) FB4–2007	– FB4-2008	Es (14) FB10–2012	Es (12) Sv (17) FB8-2012	– FB6–2012	– FB4–2012	Ca (19) FB4–2013		– 09/13
Coa (12,12) Ch (10) 2012		– FB9-2008	– FB7–2008	– FB5-2008	Msy (18) FB9-2011		Mas (24) FB9-2013	– FB7-2013	– FB5-2013			– 10/13
– 2013		– FB10–2008	– FB8–2008	No data (grazing) FB6-2008	– FB10–2011		Mas (24) FB10-2013	Sv (17) FB8-2013	– FB6-2013			Cd (20) 10/14
												– 12/14

In parentheses: soil cover in those sampling quadrats. *CFB* commercial field boundary, *FC* field centre

Ca Cirsium arvense, Cd Cardaria draba, Coa Convolvulus arvensis, Ch Chondrilla juncea, Es Euphorbia serrata, Mas Mantisalca salmantica, Msy Malva sylvestris, Sv Silene vulgaris

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Author contribution Study conception and design were performed by Alicia Cirujeda and Sonia Murillo. All authors contributed to the data collection. Data analysis was conducted by Alicia Cirujeda, Gabriel Pardo and Ana Isabel Marí. The first draft of the manuscript were conducted by Alicia Cirujeda and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

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