



Effects of no-tillage and non-inversion tillage on weed community diversity and crop yield over nine years in a Mediterranean cereal-legume cropland

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ABSTRACT

Both no-tillage and non-inversion tillage systems have been proposed within the context of 'conservation agriculture' as alternatives to conventional tillage for weed management and soil conservation. However, little information is available regarding their influence on weed community diversity and crop yield in Mediterranean cereal steppelands. Type of tillage represents a crop abiotic factor that largely influences the environmental conditions at the field scale to which weed communities may respond. The present paper examines the effect of no-tillage, subsoil tillage and minimum tillage (the latter two being non-inversion systems), on arable weed community diversity and composition in a cereal-legume crop rotation over 9 years. Their effects on crop yield are also explored. Inter-annual environmental variability was found to be more important than the tillage system in determining weed species diversity and assembly. None of the studied tillage systems exerted consistent effects, neither on weed community diversity nor on crop yields. In addition, the effect of tillage system on weed community diversity was crop-type dependent. The main effects of tillage systems were related to the composition of weed communities. Less common species resulted particularly affected while core species were consistent across tillage systems.

1. Introduction

Agricultural practices strongly influence plant and animal diversity (Stoate et al., 2001) and impact ecosystem functioning and services (Power, 2010). Unfortunately, efforts to increase crop yields have often resulted in these services becoming difficult to maintain. For instance, arable weeds have traditionally been identified as one of the main factors behind declining crops yields, so ways to remove them, including tillage, have long been sought (Hobbs et al., 2008). Weed communities, however, may provide important ecosystem regulation services in arable steppe cropland. Weeds are known to serve as forage and refuge for pollinators and other beneficial arthropods (Isaacs et al., 2009); whereas granivorous bird species, ants and rodents also feed on weed seeds (Marshall et al., 2003). These services among others may be lost if weed diversity declines. Once the importance of well conserved weed communities was recognised (Seifert et al., 2015), a new priority

of agricultural management emerged: ensuring crop productivity while maintaining weed diversity.

In the Mediterranean Basin, weed communities came to adapt to the traditional tillage systems that had been employed for centuries (Murphy and Lemerle, 2006; Neve et al., 2009). The development of more modern equipment, however, such as the mouldboard plough, allowed the mechanization of traditional practices, and the deep inversion of the soil profile. This type of soil management, now known as conventional tillage, affects the vertical distribution of weed seeds in the soil (Forcella et al., 2000; Colbach et al., 2014), and this has a profound influence on plant emergence, recruitment (Légère et al., 2011; Nichols et al., 2015; Singh et al., 2015), abundance, richness (Hernández-Plaza et al., 2011), other diversity indices, and on the composition of weed communities (Hyvönen and Salonen, 2002; Légère et al., 2005; Dorado and López-Fando, 2006; Légère et al., 2011; Sans et al., 2011; Hernández-Plaza et al., 2015).

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Within the context of 'conservation agriculture' (Morris et al., 2010; González-Sánchez et al., 2015), new tillage practices have been proposed, including no-tillage (NT), which is based on the use of herbicides prior to sowing (Eslami, 2014), and non-inversion tillage. The latter includes subsoil tillage (ST), which entails ploughing with a vertical (non-soil-turning) blade to a depth of 30 cm before sowing, and minimum tillage (MT), which involves the same but only to a depth of 15 cm. Neither of these techniques invert the vertical soil profile, thus helping to avoid pernicious effects on the soil biota (Palm et al., 2014; Gronle et al., 2015; Henneron et al., 2015). The effects of non-inversion tillage systems on arable weed communities, however, remain unclear, with contradictory results being returned by studies performed in different geographical contexts (Fried et al., 2008; Hernández-Plaza et al., 2015). Most of the discrepancies regarding their effects on weed diversity are probably the consequence of the short duration of the field experiments. Thus, it is especially important to distinguish between short-term responses (evaluated with short-term experiments) and long-term directional changes (evaluated with long-term experiments). This concept may be particularly important when climatic inter-annual variability is high, as in the case of the Mediterranean Basin. In this and other climatically variable contexts only long term studies allow to characterise tillage practices in terms of their value to the conservation of arable weed communities (Moonen and Bàrberi, 2008). Furthermore, only results emerging from long term studies will allow recommendations to balancing crop yields with weed diversity-related ecosystem services (Storkey and Westbury, 2007).

In the Mediterranean Basin, this lack of information is especially notable with respect to extensive cereal-legume rotation croplands where biodiversity has been shaped by a long evolutionary and cultural history. In Spain, such croplands once represented the largest agricultural use of land, accounting for some 6,586,909 ha or about 50% of the country's arable landscape (FAOstat, 2014). The weed diversity of these agroecosystems was traditionally supported, at least in part, by the rotation of the crops (Ulber et al., 2009). Indeed, it is thought that extensive crop management could play a crucial role in the conservation of the threatened weed species. This in turn can have an effect on different consumer groups, such as birds, ants, rodents (Storkey et al., 2012). Unfortunately, the recent intensification of cropland management has led to a reduction in the area given over to legumes, which are now grown in rotation on just 5% of the above-mentioned area based on ESYRCE (2015). Recovering this type of rotation is important if agriculture is to become more sustainable, and knowing the best tillage techniques to use in this setting is important if the ecosystem services provided by weed communities are to be preserved.

The aim of the present work was to examine the effect of ST, MT and NT tillage systems on the arable weed communities of a cereal-legume cropland in Central Spain. The period examined was nine years - long enough to ensure that the results would be representative of the inter-annual variability. Particular emphasis was placed on determining whether the type of tillage practiced can explain differences in: (1) weed abundance and diversity (weed density, taxonomic richness (S), the inverse of the Simpson diversity index (D), and the Simpson evenness index (eD)) (Magurran, 2004); (2) weed community composition; and (3) crop yield.

Since tillage systems were developed in order to reduce the presence of weeds and enhance crop yields, it was hypothesized that 1) tillage depth would be inversely related to weed abundance and diversity (weed density, S, D and eD) in the pattern $ST < MT < NT$ and positively related to crop yield in the manner $ST > MT > NT$; (2) that weed community composition would differ accordingly across the three tillage systems; and (3) that the strength of the effects of tillage on

weeds might be more noticeable when the cereal, rather than the legume crop, was present because legumes compete less with arable weeds than do cereals, allowing for greater weed development (Lutman et al., 1994; Blackshaw et al., 2002). The long term observation of tillage system effects on weed communities and crop yields should allow to identify the system that better maintains weed diversity than other systems without compromising crop yields.

2. Materials and methods

2.1. Experimental site

The fieldwork for the present study was conducted at the El Encín Experimental Station (40°57.31'N; 3°17'W, altitude 610 m) in Alcalá de Henares, Madrid, Spain. This study was started in 2002, within the context of a 2-year cereal-legume rotation system. Before the beginning of the experiment the whole field was cultivated with the same crop rotation (cereal-legume) using a conventional tillage system. The soil at the study site is an Alfisol Xeralf with a loam texture (pH 7.8, 1.2% organic matter). The mean annual temperature during the nine year study period (October 2002–June 2011) was 13.4 °C, and the mean annual precipitation 444 ± 116 mm with large inter-annual fluctuations among the October to June growing seasons (Appendix A Fig. A1).

2.2. Tillage systems

The legumes sowed were pea (*Pisum sativum* L.) in 2002, 2004 and 2006 and vetch (*Vicia sativa* L.) in 2008 and 2010. Winter wheat (*Triticum aestivum* L.) was sown in 2003, 2005, 2007, 2009 and 2011. The crops were sown using a multi-purpose direct-drill with 17 cm row spacing. The time of sowing for the legume crop ranged from November 6th to January 19th. Fertilizers were applied at sowing (14 kg N, 14 kg P, 14 kg K ha⁻¹). Post emergence herbicide (diclofop-methyl 36%, 3 L active ingredient [a.i.] ha⁻¹) was applied during vegetative growth. The time of sowing for the cereal ranged from October 30th to December 19th. Fertilizers were applied at sowing (30 kg N, 30 kg P, 30 kg K ha⁻¹) and mid-tillering (53 kg N ha⁻¹). Post emergence herbicide (0.2 kg a.i. ha⁻¹ ioxynil + 0.2 kg a.i. ha⁻¹ bromoxynil + 1.012 kg a.i. ha⁻¹ mecoprop) was applied at the tillering stage.

Three tillage systems were used, randomly assigned to 10 m × 40 m plots (24 plots in total, 8 plots per treatment): subsoil tillage (ST), minimum tillage (MT) and no-tillage (NT). ST involved at least one subsoil ploughing operation with a paraplow with slant shanks (it lifts and fractures the soil similar to the mouldboard plow but without soil inversion) to a depth of 30 cm; MT involved a primary cultivation with a chisel plough to a depth of 15 cm. Both MT and ST were followed by a secondary, superficial tillage with a field cultivator. NT involved the application of glyphosate[®] (0.9 L a.i. ha⁻¹) 4–6 days prior to crop planting.

2.3. Weed community survey and crop harvest

The number of weed species and their abundance (number of individuals per species) was recorded in 10 quadrats (30 cm × 33 cm) per plot every year—at stem elongation for the legume crop and at early tillering for the cereal crop. Weed surveys were always carried out before the application of the post-emergence herbicide. Sampling quadrats were located along an M-shaped itinerary, always at least 3 m away from the plot borders and at least 7 m away from each other. Data from the 10 quadrats were used to obtain weed density (as the total number of weed individuals found in the ten quadrats) and to compute

three measures of weed diversity (S, D, eD) independently for each plot. The crop yield for each plot was determined by harvesting two 1.40 m × 30 m strips with a combine harvester.

2.4. Statistical analysis

All analyses were made separately for each type of crop. The effects of year, tillage system and their interaction on plant density, S, D, eD and crop yield were analysed using lmer and glmer functions from the lme4 package (Bates et al., 2015) in R (R Development Core Team, 2015). We used a Gaussian distribution of errors with identity link function for weed density, D, eD and crop yield. A Poisson distribution was employed when analysing weed richness. 'Plot' was included in all models as a random factor. In all models, assumptions of equal variances and normal distribution of residuals were evaluated graphically. Spearman correlation coefficients were calculated to examine the relationship between crop yield and weed density, S and D independently for each crop and tillage system.

To analyze the effects of 'year', tillage system and their interaction on weed community composition, type III permutational multivariate analysis of variance (PERMANOVA) was performed on the large scale data. Species abundance was square-root transformed and a resemblance matrix constructed based on the Bray Curtis dissimilarity index. PERMANOVA is a semiparametric test directly analogous to multivariate ANOVA but with pseudo-F ratios and P values generated by resampling (1000 permutation) the resemblance measures of the actual data; it is therefore less sensitive to the assumptions made in parametric tests, which are frequently violated by community datasets (Anderson, 2001; Anderson et al., 2008). Pairwise comparisons were then made between the levels of each significant factor using PRIMER 6 software v.6.1.13 (Clarke and Gorley, 2006). Where group differences in community structure were found ($p < .05$ in PERMANOVA tests), similarity percentages analysis (SIMPER) was used to identify the species most responsible for them. SIMPER calculates the percentage contribution that each species makes to the total effect recorded.

3. Results

A total of 42 weed species were recorded over the study period (2002–2011), 30 of which appeared alongside both the legume and

Table 1
Effects of year and tillage system on crop yield (kg ha^{-1}), plant density, weed richness, Simpson diversity index and Simpson evenness for the legume and cereal crops. Chi-squared values and degrees of freedom (df) were derived via generalized linear mixed models, with a Poisson distribution of errors when analyzing richness, and a Gaussian distribution for the rest of the variables. (* $P < .05$, ** $P < .01$, *** $P < 0$).

| | df | Crop yield (kg ha^{-1}) | Weed density (Plants m^{-2}) | Richness | Simpson diversity | Simpson evenness |
|--------------------------|----|---------------------------------------|--|----------|----------------------|---------------------|
| a) LEGUME CROP | | | | | | |
| Year | 4 | 179.7*** | 36.47*** | 16.81** | 19.12*** | 7.84 |
| Tillage System | 2 | 3.77 | 6.71* | 0.08 | 2.32 | 3.17 |
| Year × tillage system | 8 | 8.84 | 16.84* | 5.49 | 9.11 | 10.95 |
| Residuals | 89 | | | | | |
| b) CEREAL CROP | | | | | | |
| Year | 3 | 247.02*** | 48.25*** | 4.19 | 24.29*** | 17.32*** |
| Tillage System | 2 | 14.94*** | 17.79*** | 1.89 | 8.46* | 5.03 |
| Year × tillage system | 6 | 15.19* | 18.66** | 3.63 | 13.91* | 10.63 |
| Residuals | 76 | | | | | |

cereal crop. For the legume crop, 36 species were recorded. For the cereal crop, the total number of recorded species was 34 (Appendix B Table B1).

3.1. Effects of year and tillage system on weed density and diversity metrics

Weed density was significantly affected by the interaction $\text{year} \times \text{tillage system}$ (Table 1). The highest and lowest weed density values were recorded for the MT system in 2004 and 2005 respectively.

The S value associated with the legume crop was affected by year (Table 1). The highest S value was recorded in 2007 for the ST system (Fig. 1).

The D value associated with the cereal crop was affected by the interaction $\text{year} \times \text{tillage system}$. However, the tillage system used did not affect the D value associated with the legume crop (Table 1, Fig. 2).

The factor 'year' was found to be more important than the tillage system in determining S and D in legume crops and D and eD in the cereal crop (Table 1).

3.2. Effects of year and tillage system on weed community composition

The weed community composition associated with the legume and cereal crops was significantly affected by year, tillage system and their interaction (Table 2). SIMPER showed *Papaver rhoeas*, *Descurainia sophia*, *Polygonum aviculare* and *Chenopodium album* to be responsible for > 10% each of the difference in the effect of the tillage system on weed species composition (Table 3).

3.3. Effects of year and tillage system on crop yield

The effect of tillage system on yield was crop dependent (Table 1). The legume yield was not affected by the tillage system, but the cereal yield was affected by the interaction $\text{year} \times \text{tillage system}$, with the highest and lowest yields both recorded for the NT system (Fig. 3).

The correlations between plant density, D, S and crop yield for each tillage system were also crop dependent (Appendix C Table C1). Plant density was positively related to cereal yield under ST and MT systems. S and D were negatively related to legume yield. For the cereal crop, yield showed no correlation with S under any tillage system, but higher D values were related to lower yields under the MT and NT systems. The same tendency was observed under the ST system.

4. Discussion

None of the studied tillage systems was consistently associated with a greater weed density, weed Richness (S), Simpson diversity (D), Simpson evenness (eD) or crop yield. Inter-annual variation (factor 'year') was the factor most significantly related to crop yield, weed abundance and diversity. However, the tillage system and its interaction with year did account for some variability. Tillage effects were greater in the cereal crop than in grain legumes. Weed community composition was significantly affected by the interaction $\text{year} \times \text{tillage system}$ in both crops, but no weed composition could be unequivocally associated with any tillage system on its own. In cereals, NT registered the lowest richness values while diversity (D) was higher in ST.

4.1. Tillage and inter-annual variation explain arable weed community diversity and crop yield

Inter-annual variability interacts with the tillage system, shaping the weed community structure and determining crop growth and yield. 'Year', however, would appear to be more important than the tillage

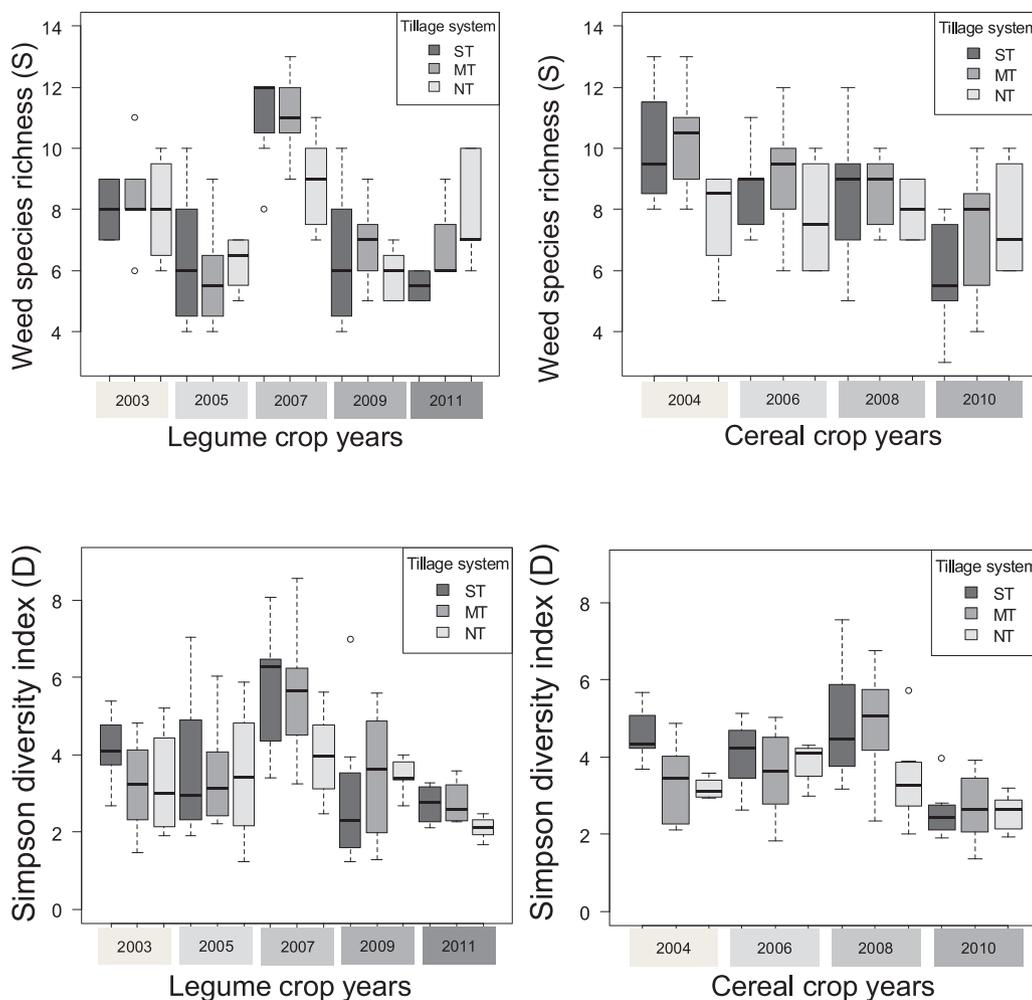


Fig. 1. Weed species richness (S) by year and tillage system (subsoil tillage (ST), minimum tillage (MT) and no tillage (NT)) observed along in a legume-cereal crop rotation over 9 years. Central lines in boxes represent the median; top and bottom lines of boxes represent the interquartile range. Whisker lines represent the full range of the data within 1.5 × the interquartile range.

Fig. 2. Simpson diversity index (D) observed for weed communities by year and tillage system (subsoil tillage (ST), minimum tillage (MT) and no tillage (NT)) observed along in a legume-cereal crop rotation over 9 years. Central lines in boxes represent the median; top and bottom lines of boxes represent the interquartile range. Whisker lines represent the full range of the data within 1.5 × the interquartile range.

Table 2
PERMANOVA results for the effect of year and tillage system and their interaction, on weed community composition.

| | Year | Tillage system | Year × tillage system |
|----------------|----------|----------------|-----------------------|
| a) LEGUME CROP | | | |
| df | 4 | 2 | 8 |
| Pseudo-F | 17.67*** | 4.19*** | 1.84*** |
| b) CEREAL CROP | | | |
| df | 3 | 2 | 6 |
| Pseudo-F | 11.25*** | 3.86*** | 1.72*** |

df = degrees of freedom (*P < .05, **P < .01, ***P < .001).

system used (Table 1). This might reflect differences in environmental conditions over the study period. Mean annual rainfall varied widely over the nine years (Appendix A Fig. A1). The amount of rain, plus its distribution over time, strongly influence seed germination (Blackshaw et al., 2001; Sánchez et al., 2014) and could explain differences both in weed abundance and in weed diversity due to (different) specific germination requirements. Similar results with respect to weed diversity were previously reported by other authors working in the same setting

Table 3
Results of SIMPER analysis identifying the weed species primarily responsible for observed differences in community composition among the tillage systems (subsoil tillage (ST), minimum tillage (MT) and no tillage (NT)). The total contribution explained by the species listed is 99%.

| Species Code | % Contribution in Legume crop | | | % Contribution in Cereal crop | | |
|-------------------------------|-------------------------------|-------|-------|-------------------------------|-------|-------|
| | ST | MT | NT | ST | MT | NT |
| <i>Amaranthus blitoides</i> | 8.98 | 8.71 | 2.5 | 4.78 | 3.59 | 1.36 |
| <i>Anacyclus clavatus</i> | 5.24 | 6.18 | 4.52 | 5.82 | 6.85 | 3.42 |
| <i>Atriplex patula</i> | 1.89 | 1.61 | 0.35 | 1.22 | 1.45 | |
| <i>Avena sterilis</i> | 1.46 | 2.96 | 5.28 | | | 2.7 |
| <i>Chenopodium album</i> | 15.24 | 18.38 | 10.82 | 14.95 | 17 | 10.91 |
| <i>Coryza canadensis</i> | | | 2.08 | | | |
| <i>Descurainia sophia</i> | 15.36 | 11.35 | 23.06 | 15.16 | 14.31 | 22.27 |
| <i>Epilobium brachycarpum</i> | | | 0.53 | | | |
| <i>Galium tricornutum</i> | | 0.51 | 2.03 | 0.94 | | 4.08 |
| <i>Lactuca serriola</i> | 1.9 | 1.54 | 1.37 | 2.86 | 1.66 | 0.92 |
| <i>Lamium amplexicaule</i> | 1.31 | 0.96 | | 1.1 | 1.36 | |
| <i>Lolium rigidum</i> | 7.77 | 9.89 | | 5.15 | 3.88 | |
| <i>Papaver hybridum</i> | | | | | 0.56 | 1.36 |
| <i>Papaver rhoeas</i> | 17.87 | 15.73 | 31.86 | 24.62 | 22.37 | 32.6 |
| <i>Polygonum aviculare</i> | 21.25 | 20.96 | 14.16 | 20.78 | 23.73 | 16.16 |
| <i>Veronica hederifolia</i> | 0.88 | 0.3 | 0.59 | 1.74 | 2.55 | 3.77 |

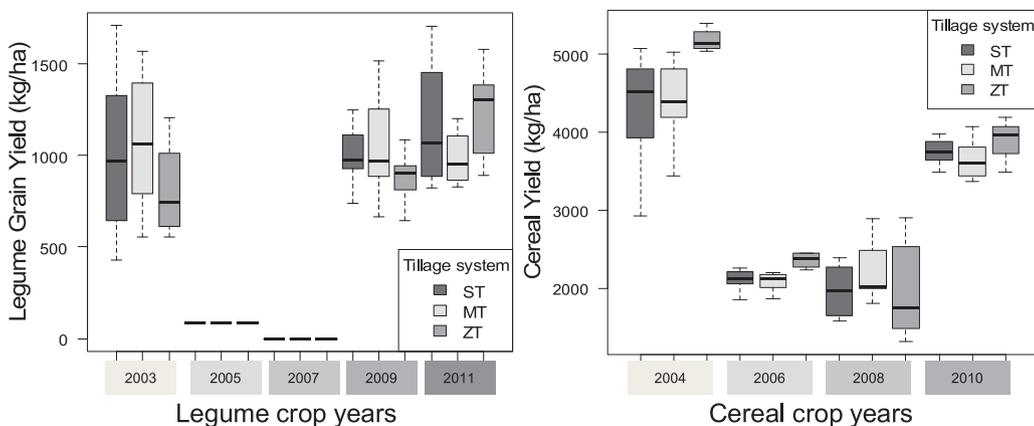


Fig. 3. Effect of the interaction year \times tillage system on crop yield (kg ha^{-1}) observed along in a legume-cereal crop rotation over 9 years. Central lines in boxes represent the median; top and bottom lines of boxes represent the interquartile range. Whisker lines represent the full range of the data within $1.5 \times$ the interquartile range.

(Hernández-Plaza et al., 2011), and may perhaps be explained in the same way, i.e., the widely varying mean annual rainfall of Mediterranean steppeland (Sternberg et al., 2000; Luzuriaga et al., 2012; Pérez-Camacho et al., 2012; Carmona et al., 2015). The characteristic temporal heterogeneity of Mediterranean environmental conditions might therefore explain the differences between the results of short and long term studies (Dorado and López-Fando, 2006; Hernández-Plaza et al., 2011).

Independent of the tillage system, higher legume and cereal yields were associated with a negative impact on weed diversity (D) and, in the case of the legume crop, weed richness (S). Increasing crop yields which reflect the intensification of crop production (Pretty and Bharucha, 2014) have been related to a reduction in the number of rare weed species across Europe (Storkey et al., 2012). Although, in other studies no-tillage has appeared as the most beneficial system in terms of yield increase and environmental conservation, the present results identify no tillage system that consistently enhanced the yield of the study crops or better preserved potential weed-delivered ecosystems services.

4.2. Importance of tillage system in arable weed community assembly

The influence of the tillage system on weed community composition was greater than that which it exerted over weed abundance (density) and species diversity (S and D). However, weed community composition was also affected by the interaction year \times tillage system, once again suggesting the importance of environmental inter-annual variation for weed community assembly.

Irrespective of the tillage system used, and in all years, the weed communities always contained the four species *Papaver rhoeas*, *Polygonum aviculare*, *Descurainia sophia* and *Chenopodium album*. These may therefore be considered “core” species in the present setting (Magurran and Henderson, 2003). All are characterized by their high colonization ability, a consequence of their copious seed production and their capacity to persist and grow alongside crop plants (Mohler and Mohler, 2004). However, slight differences in the abundance of these core species were detected. For example, *P. aviculare* was consistently less abundant under the NT system. Similarly, Dorado and López-Fando (2006) reported *P. aviculare* to be less abundant under NT than conventional tillage or MT management. This species has relatively large seeds, conferring upon it a higher risk of seed predation (Albrecht and Auerwald, 2009); if no ploughing of any kind is

performed, the number of surviving seeds might be reduced.

Weed richness, however, was found to rely on the relative presence of the less abundant species in each system. For example, *Epilobium brachycarpum* and *Conyza canadensis* were only found under NT conditions. Both species have a high dispersion ability so they were probably present as seeds in all plots. However, only in the absence of any soil movement (as happening in NT system) did they germinate and become established, indicating a filter against them by the other two systems. It may be that germination is hindered if they become slightly soil-covered by the non-inversion tillage systems (Nandula et al., 2006; Dauer et al., 2007).

The present results suggest that the filtering pressures exerted by each tillage system favour certain weed species over others, depending on their functional traits. They provide no evidence, however, to support the idea of Trichard et al. (2013) that monocotyledons and perennial species grow better under no-tillage condition. In the present work, the grass species *Avena sterilis* was associated with the NT system, whereas *Lolium rigidum* was linked to the MT and ST systems. The different soil physical conditions induced by each tillage system might affect the speed at which seeds become incorporated into the soil matrix. Seed functional attributes, such as self-burial in the case of *A. sterilis*, seed dormancy, and seed persistence in the soil (e.g., *L. rigidum* shows little seed persistence) may also play their part (Thompson et al., 1998; Albrecht and Auerwald, 2009). The slightly different effects of tillage system on weed communities might, however, translate into larger shifts in community composition in the long term (Marshall et al., 2003; Cirujeda et al., 2011).

4.3. Importance of crop type in arable weed community dynamics

As hypothesized, the effect of tillage on the weed community dynamics was greater when the cereal crop was present. From a functional viewpoint, legumes and cereals are completely different, and they will interact differently with the weed community (Hyvönen and Salonen, 2002). Cereals are more competitive and may act as a stronger biotic filter on weed community than do legume crops (Lutman et al., 1994; Blackshaw et al., 2002). In the present work, this was reflected in the reduced weed emergence observed in the legume crop years - the effect of the control exerted by the cereal crop in the previous season. Subsequently, legumes might permit an increase in seed production by less abundant weed species, which might contribute towards a refilling of the soil seed bank. Like fallow periods, the presence of legumes in

rotation could play an important role in preventing the simplification of weed communities (Castro et al., 2016; Poggio, 2005). The present results suggest that the election of one or the other tillage system may only have a minor effect on weed taxonomic diversity. Nevertheless a complete evaluation of the effects of tillage systems on weed diversity needs to take into account species growing in the intercropping period.

5. Concluding remarks

The present work shows that inter-annual environmental variability is the main driver behind changes in winter weed communities, with the tillage system and crop rotation modulating weed diversity to a lesser extent. Cereal-legume traditional rotation could enhance weed diversity in Mediterranean steppelands, helping to ensure the provision of ecosystems services.

The maintenance of arable plant diversity in crop fields is of particular importance in steppes where semi-natural areas (e.g., field boundaries) are scarce. In such agroecosystems, biodiversity con-

Appendix A

servation at the landscape scale becomes closely related to the crop rotation and to the associated arable weed community.

None of the studied tillage systems appeared consistently associated with higher weed community diversity values or higher crop yields in the medium term. Consequently none can be recommended over any other in terms of weed conservation or yield improvement.

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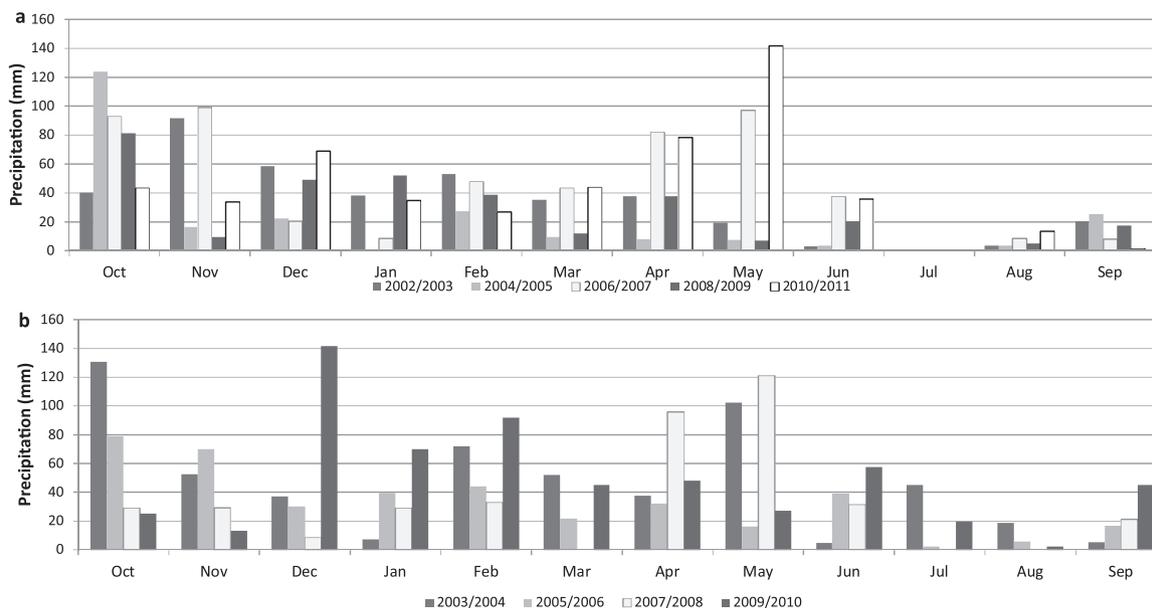


Fig. A1. Mean monthly precipitation over the study period: a) years with the legume crop, b) years with the cereal crop.

Appendix B

Table B1
Densities of arable weed species over the nine-year study period, with respect to tillage system.

| Species | Tillage System (Plant m ⁻² ± SD) | | |
|---|---|-----------------|---------------|
| | Subsoil tillage | Minimum tillage | No-tillage |
| <i>Adonis flammea</i> Jacq. | 0.00 ± 0.00 | 0.01 ± 0.12 | 0.00 ± 0.00 |
| <i>Amaranthus blitoides</i> S.Watson | 6.51 ± 15.83 | 11.25 ± 32.34 | 4.48 ± 16.58 |
| <i>Anacyclus clavatus</i> (Desf.) Pers. | 2.82 ± 4.12 | 3.53 ± 5.39 | 2.25 ± 3.30 |
| <i>Asperugo procumbens</i> L. | 0.10 ± 0.35 | 0.07 ± 0.50 | 0.02 ± 0.13 |
| <i>Atriplex patula</i> L. | 0.79 ± 1.55 | 0.91 ± 1.66 | 1.27 ± 5.13 |
| <i>Avena sterilis</i> L. | 0.44 ± 1.01 | 0.57 ± 1.19 | 4.52 ± 13.09 |
| <i>Bromus diandrus</i> Roth | 0.04 ± 0.21 | 0.07 ± 0.31 | 0.00 ± 0.00 |
| <i>Buglossoides arvensis</i> (L.) I.M. Johnst. | 0.00 ± 0.00 | 0.00 ± 0.00 | 0.02 ± 0.13 |
| <i>Capsella bursa-pastoris</i> (L.) Medik. | 0.04 ± 0.21 | 0.25 ± 0.92 | 0.23 ± 1.16 |
| <i>Cardaria draba</i> (L.) Desv. | 0.13 ± 0.54 | 0.37 ± 1.42 | 0.29 ± 1.51 |
| <i>Cardus</i> sp. | 0.01 ± 0.12 | 0.00 ± 0.00 | 0.00 ± 0.00 |
| <i>Convolvulus arvensis</i> L. | 0.03 ± 0.17 | 0.01 ± 0.12 | 0.07 ± 0.42 |
| <i>Conyza canadensis</i> (L.) Cronq. | 0.03 ± 0.24 | 0.04 ± 0.21 | 0.30 ± 0.83 |
| <i>Chenopodium album</i> L. | 9.18 ± 12.98 | 15.00 ± 21.87 | 11.07 ± 19.80 |
| <i>Descurainia sophia</i> (L.) Webb. ex Prantl | 7.51 ± 8.41 | 6.21 ± 6.07 | 13.39 ± 14.34 |
| <i>Dittrichia viscosa</i> (L.) Greuter | 0.00 ± 0.00 | 0.01 ± 0.12 | 0.00 ± 0.00 |
| <i>Epilobium brachycarpum</i> C. Presl, | 0.04 ± 0.36 | 0.01 ± 0.12 | 0.11 ± 0.41 |
| <i>Fallopia convolvulus</i> (L.) Á. Löve | 0.03 ± 0.24 | 0.01 ± 0.12 | 0.00 ± 0.00 |
| <i>Fumaria officinalis</i> L. | 0.06 ± 0.24 | 0.16 ± 0.59 | 0.02 ± 0.13 |
| <i>Galium tricorutum</i> Dandy | 0.85 ± 3.57 | 0.13 ± 0.38 | 4.61 ± 10.67 |
| <i>Heliotropium europaeum</i> L. | 0.01 ± 0.12 | 0.00 ± 0.00 | 0.00 ± 0.00 |
| <i>Helminthotheca echioides</i> (L.) Holub | 0.01 ± 0.12 | 0.01 ± 0.12 | 0.00 ± 0.00 |
| <i>Hordeum murinum</i> L. | 0.16 ± 0.78 | 0.37 ± 1.88 | 0.02 ± 0.13 |
| <i>Hypochaeris glabra</i> Sm. | 0.24 ± 0.95 | 0.04 ± 0.21 | 0.02 ± 0.13 |
| <i>Lactuca serriola</i> L. | 0.84 ± 1.44 | 0.85 ± 1.40 | 0.55 ± 0.97 |
| <i>Lamium amplexicaule</i> L. | 0.56 ± 0.92 | 0.60 ± 1.12 | 0.27 ± 0.80 |
| <i>Lolium rigidum</i> Gaudin | 2.90 ± 5.47 | 4.66 ± 12.54 | 0.16 ± 0.42 |
| <i>Malva sylvestris</i> L. | 0.01 ± 0.12 | 0.00 ± 0.00 | 0.00 ± 0.00 |
| <i>Papaver hybridum</i> L. | 0.06 ± 0.24 | 0.22 ± 0.77 | 0.79 ± 2.56 |
| <i>Papaver rhoeas</i> L. | 9.60 ± 7.55 | 12.41 ± 10.44 | 28.88 ± 22.17 |
| <i>Phalaris minor</i> Retz. | 1.79 ± 6.84 | 0.40 ± 1.19 | 0.00 ± 0.00 |
| <i>Polygonum aviculare</i> L. | 15.90 ± 27.89 | 20.71 ± 25.47 | 11.54 ± 15.73 |
| <i>Salsola kali</i> L. | 0.01 ± 0.12 | 0.00 ± 0.00 | 0.00 ± 0.00 |
| <i>Scorzonera laciniata</i> L. | 0.03 ± 0.17 | 0.01 ± 0.12 | 0.00 ± 0.00 |
| <i>Senecio vulgaris</i> L. | 0.04 ± 0.21 | 0.03 ± 0.17 | 0.00 ± 0.00 |
| <i>Sisymbrium irio</i> L. | 0.03 ± 0.17 | 0.00 ± 0.00 | 0.02 ± 0.13 |
| <i>Sonchus asper</i> (L.) Hill | 0.01 ± 0.12 | 0.00 ± 0.00 | 0.00 ± 0.00 |
| <i>Sonchus oleraceus</i> L. | 0.07 ± 0.31 | 0.13 ± 0.52 | 0.02 ± 0.13 |
| <i>Trigonella polyceratia</i> L. | 0.00 ± 0.00 | 0.06 ± 0.24 | 0.00 ± 0.00 |
| <i>Urtica urens</i> L. | 0.00 ± 0.00 | 0.00 ± 0.00 | 0.07 ± 0.32 |
| <i>Vaccaria hispanica</i> (Mill.) Rauschert. | 0.00 ± 0.00 | 0.00 ± 0.00 | 0.02 ± 0.13 |
| <i>Veronica hederifolia</i> L. | 0.71 ± 1.72 | 0.68 ± 1.38 | 0.89 ± 1.37 |
| Total | 61.7 ± 44.2 | 79.8 ± 57.2 | 85.9 ± 41.6 |

Appendix C

Table C1
Relationship between crop yield, and weed density, richness (S), and Simpson diversity index (D) in each tillage system.

| | ST | | MT | | NT | |
|----------------------------------|-------|---------|-------|---------|-------|----------|
| | r | P value | r | P value | r | P value |
| Legume crop relationships | | | | | | |
| Yield/Weed density | 0.11 | 0.513 | −0.09 | 0.600 | −0.24 | 0.188 |
| Yield/S | −0.37 | 0.026* | −0.37 | 0.026* | −0.26 | 0.151 |
| Yield/D | −0.38 | 0.023* | −0.39 | 0.020* | −0.61 | 0.000*** |
| Cereal crop relationships | | | | | | |
| Yield/Weed density | 0.37 | 0.033* | 0.43 | 0.012* | 0.03 | 0.887 |
| Yield/S | −0.03 | 0.834 | 0.05 | 0.762 | 0.02 | 0.932 |
| Yield/D | −0.25 | 0.155 | −0.47 | 0.006** | −0.45 | 0.021* |

r = Spearman's correlation coefficient and P value (*P < .05, **P < .01, ***P < .001).

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