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RESEARCH ARTICLE

Long-term feasibility of reduced tillage in organic farming

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Abstract Agricultural practices such as soil tillage emit greenhouse gases such as CO_2 and N_2O. As a consequence, reducing the tillage could both reduce greenhouse emissions and improve soil quality. In Europe about 25 % of arable land is managed under reduced tillage and no tillage, mainly using herbicides to get rid of weeds. Therefore, a major drawback for organic farmers is that the lack of herbicide and soil inversion could increase weed infestation. Here, we compared reduced tillage and conventional tillage in a 2002–2011 field experiment under organic management in Switzerland. We analyzed crop production and weed flora, with a focus on perennials and grasses. Data on yield, cover, richness, and composition of the weed flora were collected for wheat in 2003 and 2009, sunflower in 2004 and 2010, and spelt in 2005 and 2011, through two complete rotations. We found that weed abundance was 2.3 times higher under reduced tillage, though we did not observe a systematic increase with time. The average abundance of perennials almost doubled over time under reduced tillage, thus changing the community composition between tillage systems. Despite the weed increase, yields were similar for reduced tillage and conventional tillage. As a consequence, this study represents the first long-term trial under organic management showing that reduced tillage improves the environmental performance of this cropping system.

Keywords Perennial species · Weed species richness and composition · Chisel and moldboard plow · Crop yields

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1 Introduction

Agricultural activities contribute up to 29 % of the global greenhouse gas emissions (Vermulen et al. 2012). Soil tillage is one of the main factors contributing to CO_2 emissions, but it also may increase the N_2O emissions from the soil (Stavi and Lal 2013). Reducing tillage decreases energy consumption and CO_2 emissions and increases carbon sequestration but it has also been proven to be useful in reducing soil erosion, improving soil fertility and biodiversity, and increasing water retention (Holland 2004; Berner et al. 2008). Thus, conservation tillage techniques such as no till and reduced tillage which imply a lack of deep soil inversion have been widely adopted worldwide (Kassam et al. 2010) and are strongly encouraged by international institutions such as the Food and Agriculture Organization of the United Nations and by the Common Agricultural Policy in the European Union (Hobbs et al. 2008; Basch et al. 2011).

However, conservation tillage techniques are primarily applied in conventional cropping systems and are hardly accepted by organic farmers because of the potential of increased weed infestation. In fact, the use of herbicides and the adoption of herbicide-tolerant crops have been regarded as the main reasons for the success of the widespread adoption of conservation tillage among conventional farmers (Légère et al. 2013). Moldboard plowing is traditionally considered a key preventive weed control method for arable crops, especially in organic farming, where the lower efficiency of the mechanical weed control compared with herbicides usually leads to higher weed infestations (Armengot et al. 2013). In contrast, with non-inversion tillage (Fig. 1), weed infestations are likely to increase due to the higher seedling recruitment in the upper soil layers. Thus, the tillage system influences weed populations by changing the vertical distribution of the seeds, by mechanically destroying the seedlings, and, in an indirect way, by modifying soil conditions, which affect seed dormancy, germination, and growth (Peigné et al. 2007). In conservation tillage systems, weed abundance and density may

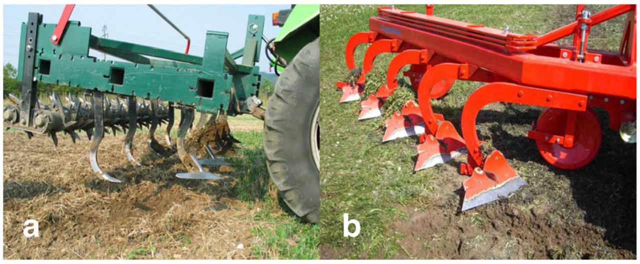

Fig. 1 Different farm tillage equipment used under reduced tillage. **a** A chisel with wide sweeps that undercuts weeds at 5 cm below the soil surface and with narrow sweeps that loosen the soil at 15-cm depth. **b** A stubble cleaner used for undercutting and turning the first 5 cm of soil

be higher, as well as the presence of perennial and grass species, which are more difficult to control (Gruber and Claupein 2009; Peigné et al. 2007; Santín-Montanyá et al. 2013). However, this trend is not always constant over time, and it is usually crop specific (Légère et al. 2013; Sans et al. 2011; Vakali et al. 2011). In a similar way, there are no clear results on the role of the tillage system on weed diversity (Hernandez Plaza et al. 2011; Sans et al. 2011; Santín-Montanyá et al. 2013), which is especially relevant for weed conservation because of the general low diversity of agroecosystems and the ecological and cultural values of the weeds (Clergue et al. 2005).

Most of the studies on weed flora under different tillage systems are performed in conventionally managed fields (Hernandez Plaza et al. 2011; Santín-Montanyá et al. 2013). Until now, studies on organic farming only covered the first years after the conversion to reduced tillage or to organic farming, including moldboard plowing at some point of the experiment or only reporting data on a few years of a longer experiment (Gruber and Claupein 2009; Légère et al. 2013; Sans et al. 2011; Vakali et al. 2011). Studies monitoring and dealing with the management of weed flora under reduced tillage in organic systems in the long term are, therefore, crucial to evaluate the feasibility of the reduced tillage practices over time.

Here, we present data evaluating the feasibility of reduced tillage with chisel plow compared with conventional tillage using a moldboard plow for organic farming through the analysis of crop yields and weed flora in a long-term field experiment. We hypothesized that (1) crop yield will be lower under reduced tillage in relation to higher weed infestation and that the weed community composition and diversity will differ between tillage systems, (2) there are a higher presence and abundance of grass and perennial species, and (3) there is higher weed diversity under reduced tillage.

2 Material and methods

2.1 Study site

The field experiment commenced in autumn 2002 in Frick, Switzerland, 47° 30′ N, 8°01′ E, 350 m above sea level. The climate is temperate, and the mean annual temperature and precipitation are 8.9 °C and 1,000 mm, respectively. The field was converted to organic standards according to the Economic European Community regulation 834/2007 in 1995, and it was managed using conventional tillage at 15-cm plowing depth until the beginning of the experiment. The soil type is Stagnic Eutric Cambisol. On average, the mineral fraction consists of 22 % sand, 33 % silt, and 45 % clay, and the soil organic carbon is between 2.2 and 2.6 % by weight. During the winter and springtime, the soil can be temporally waterlogged.

2.2 Experimental design

The experiment involved three factors, each with two levels: tillage system comparing conventional versus reduced tillage, fertilization, where the application of slurry alone was compared to the use of composted farmyard manure with a reduced quantity of slurry, and biodynamic preparations, which tested the application of biodynamic compost and field preparations in relation to the lack of application. The three factors were arranged in a strip plot design, with tillage being the main factor. In total, 32 12 m×12 m plots were established. Conventional tillage used a moldboard plow operating at 15-cm depth. In the reduced tillage system, a chisel plow with wide sweeps ("WEco-Dyn System", EcoDyn Company, Schwanau, Germany) or a stubble cleaner ("Stoppelhobel", Zobel Company, Rot am See, Germany) was used, operating at 5-cm depth, and only three times in nine years, a chisel was applied at a 15-cm depth. Seedbed preparation was performed using a horizontal rotary harrow in both tillage systems. Fertilization was applied at a yearly average input, N_{total}/P/K, of 85/18/156 kg ha^{-1} in the slurry-fertilized plots and 90/22/159 kg ha^{-1} in the plots with composted farmyard manure and a reduced quantity of slurry. A detailed description of the experiment is given by Berner et al. (2008).

The field was sowed uniformly with silage maize in 2002 before the establishment of the experiment. The crop rotation of the experiment consisted of winter wheat (*Triticum aestivum* L. 'Titlis', 2003), an oat–clover intercrop (*Trifolium alexandrinum* L. and *Avena sativa* L., 2003/2004), sunflower (*Helianthus annuus* L. 'Sanluca', 2004), spelt (*Triticum spelta* L. 'Ostro', 2005), a 2-year grass–clover ley (mixture of *Trifolium campestre* L., *Trifolium repens* L., *Dactylis glomerata* L., *Festuca pratensis* Huds., *Phleum pratense* L., and *Lolium perenne* L., 2006 and 2007), silage maize (*Zea mays* L. 'Amadeo', 2008), winter wheat (*T. aestivum* L. 'Titlis', 2009), sunflower (*H. annuus* L. 'Sanluca', 2010), spelt (*T. spelta* L. 'Ostro', 2011), and 2-years of grass–clover ley (2012 and 2013). Weeds were controlled mechanically by a tractor-driven flex-tine weeder in cereals once a year and by a rolling cultivator with sweeps and spiders of 35 cm of diameter without shields twice a year and also by hand within the sunflower and maize rows according to local practices.

2.3 Sampling procedures and statistical analyses

The percentage of cover of weed species was estimated visually using figures ranging from 0 to 100 % per each wheat, sunflower, spelt, and maize crop within the inner 8 m×8 m of each plot before harvest. The percentage of cover was scored by vertically projecting all of the leaf surfaces on the ground and was integrated over all of the weeds and the crop, reaching a maximum of 100 % according Sans et al. (2011). Data on maize were not analyzed in this study because only 1-year data were available. The crop yield was evaluated by harvesting the grain in a 1.5 m×8 m plot. The cereals were harvested in this area by a plot-sized combined harvester. The sunflowers were cut manually, and the heads were processed with a thresher machine. We performed an overall analysis to test the effect of the tillage system, using the crop type and its interaction with tillage system as confounding variables, on the percentage of the total weed cover and on the cover of perennial and grass species and on the weed species richness and the crop yield through linear mixed-effect models. The plot and the tillage block were introduced as random factors. Previous statistical analysis revealed no significant effects or interactions related to fertilization type and biodynamic preparations. Therefore, the data were consequently pooled across fertilization and biodynamic preparation levels. Orthogonal contrasts were fixed a priori to compare the different levels of the factor crop type. Winter cereal crops, i.e., wheat and spelt, were compared with a summer crop, i.e., sunflower, and the wheat was compared with the spelt. Orthogonal contrasts were also fixed to compare the different levels of the factor tillage, which compared the conventional with the reduced tillage. For each crop, we evaluated the effect of the tillage system, the year, and their interaction on the abundance of weeds to check for any trend of the tillage system over the years. Orthogonal contrasts were fixed for year; the first year of the crop in the rotation was compared with the second year. Data were transformed when necessary to meet the normality and homoscedasticity requirements. All of the analyses were performed in R 2.7.1 (R Development Core Team 2008), with the "lme4" package (Bates et al. 2008) for mixed models and "languageR" to evaluate the significance of effects (Baayen 2008).

To evaluate the effects of the treatments on weed community composition, we performed a multivariate analysis based on weed abundance. Weed species occurring just once were removed. The resulting data were analyzed by means of a distance-based multivariate analysis of variance to analyze the effect of the tillage system and of the crop on weed community composition. This analysis allows partitioning a distance matrix among sources of variation. The Bray–Curtis metric was used to compute the distances between plots according to their weed community. The partial R^2 obtained indicates the percentage of variance that is explained by each factor. The significance of the explanatory variable was obtained from an F test based on the sequential sums of squares from permutations of the raw data. The permutations were restricted within each strip to incorporate the experimental design. To ease the visualization of changes in community composition, we performed a non-metric multidimensional scaling, a dimension reduction method that maps the distance in community composition between samples into a reduced set of axes. We

Table 1 Coefficients and their standard errors of the linear mixed models and levels of significance of the effect of tillage, crops, and their interaction on the percentage of total weed cover and the cover of perennial and grass species and on the species richness and crop yield

	Total weed cover (%)[a] Estimate±SE	Cover of perennials (%)[b] Estimate±SE	Cover of grasses (%)[c] Estimate±SE	Species richness[c] Estimate±SE	Crop yield (kg ha^{-1})[c] Estimate±SE
Intercept	3.992±0.211	0.226±0.032	−0.185±0.133	1.741±0.035	1.573±0.016
Tillage	−0.492±0.211*	−0.061±0.026*	−0.124±0.114	−0.081±0.035	0.015±0.016
Crop (cereals versus sunflower)	−0.739±0.041#	−0.025±0.006#	0.506±0.061#	0.085±0.018#	−0.138±0.012#
Crop (wheat versus spelt)	0.075±0.063	−0.025±0.010***	0.225±0.104**	0.135±0.031#	0.207±0.020#
Tillage×crop (cereals versus sunflower)	0.048±0.041	−0.022±0.006#	−0.187±0.061***	0.018±0.018	−0.012±0.012
Tillage×crop (wheat versus spelt)	0.304±0.063#	0.014±0.010	0.202±0.104**	0.011±0.031	−0.024±0.200

Orthogonal contrasts compare conventional tillage with reduced tillage for the factor tillage and the cereal crops (wheat and spelt) with the sunflower and the wheat with the spelt for the factor crop. Reduced tillage increased total weed cover and the cover of perennials, but it neither affected the crop yields nor the weed diversity. The sunflower crop harbored higher weed cover and cover of perennials but less weed diversity compared with the cereal crops

SE standard error

*P<0.09; **P<0.05; ***P<0.01; #P<0.001

[a] Squared-root-transformed

[b] Arcsine (squared root)-transformed

[c] Log-transformed

Table 2 Coefficients and their standard errors from the linear mixed models and levels of significance of the effect of the tillage system and year on the percentage of total weed cover and the cover of perennial and grass species

	Total weed cover (%) Estimate±SE	Cover of perennials (%) Estimate±SE	Cover of grasses (%) Estimate±SE
Wheat			
Intercept	2.476±0.071[a]	0.705±0.278[a]	2.013±0.428
Tillage	−0.113±0.071	−0.890±0.278*	−0.150±0.428
Year	−0.130±0.035***	−0.551±0.133***	−0.566±0.137***
Tillage×year	−0.022±0.035	−0.093±0.133	−0.291±0.137*
Sunflower			
Intercept	26.438±4.861	1.926±0.257[a]	−0.844±0.420[a]
Tillage	−14.406±4.861*	−0.611±0.257*	0.237±0.420
Year	6.875±1.309***	−0.117±0.064	0.794±0.107***
Tillage×year	0.781±1.309	0.382±0.064***	0.342±0.107*
Spelt			
Intercept	2.321±0.129	0.226±0.036[b]	0.836±0.420[a]
Tillage	−0.440±0.129*	−0.097±0.036**	−0.261±0.420
Year	0.104±0.052*	−0.006±0.007	−0.317±0.107***
Tillage×year	0.098±0.052	0.042±0.007***	−0.211±0.107***

Orthogonal contrasts compare conventional tillage with reduced tillage for the factor tillage and the first year of the crop in the rotation with the second year for the factor year

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

[a] Log-transformed

[b] Arcsine (square-root)-transformed

restricted the number of dimensions to two, as it maximizes the variability of the original data that can be shown on a flat display. Analyses were also carried out under R 2.7.1 using the "vegan" package (Oksanen et al. 2013).

3 Results and discussion

3.1 Effects of tillage and crop type on weed abundance and crop yields

Overall, the mean percentage of the total weed cover over the years was 17 %; the perennial species had an average of 7 % of the cover, whereas the cover of the grasses was 2 %. In general, total weed cover was higher under reduced tillage (Table 1), which concurs with previous studies (Peigné et al. 2007; Santín-Montanyá et al. 2013). However, it was not consistent for all of the crops; for the wheat crop, no significant differences were observed between both tillage systems in the 2 years included in the rotation (Table 2). More interestingly, we did not observe any increase in the tendency of the weed infestation over the years under reduced tillage (Table 2 and Fig. 2). Significant differences of the factor year indicated higher values of weed cover for the first year of sunflower and spelt and for the second year for the wheat, and no significant interactions between the tillage system and the year were found. These indicate fluctuating rather than directional changes in weed cover, which is probably more related to varying weather conditions than to the tillage factor itself.

In contrast, the cover of perennial species was clearly higher under reduced tillage compared with conventional tillage for all of the crops and coverage increased over the years, whereas perennial species cover decreased under conventional tillage, as it is shown by the interaction between tillage and year. The growth of perennial weeds with creeping roots or rhizomes is favored with the reduction of the tillage intensity, but the discs or tines can also promote growth by dispersing the perennial weed's rhizomes (Peigné et al. 2007). Growing perennial grass–clover is a common way to control perennial weeds under organic farming, although their beneficial effects may be very short-lived (Gruber and Claupein 2009). In our study, the 2 years of grass–clover included in the rotation was not enough to lower the cover of perennials under reduced tillage. Up to now, inversion tillage and/or intensive within-crop cultivation are the only known solutions for managing severe perennial weed infestations in organic systems (Melander et al. 2012). In the long term, the steady increase of perennials under reduced tillage could pose a serious threat to the crop yields, and thus, alternative management strategies should be considered. For instance, occasional plowing could offer some benefits for the control of perennial weeds. However, even shallow plough may adversely affect the soil quality (Stavi et al. 2011), thus reducing the overall performance of the reduced tillage system.

Fig. 2 Mean±standard error of total weed cover and the cover of perennials and grass species, species richness, and crop yields under conventional (*blue bars*) and reduced (*red bars*) tillage for the wheat, sunflower, and spelt crops for each year included in the rotation. Overall, total weed cover was higher under reduced tillage, but it did not increase over the years. However, the cover of perennials increased under reduced tillage over time. No clear pattern was observed for grass species. Weed cover was higher in cereal crops compared with the sunflower. Species richness was also higher in cereal crops, but it was not affected by the tillage system. Overall, the tillage system did not affect the crop yields ▶

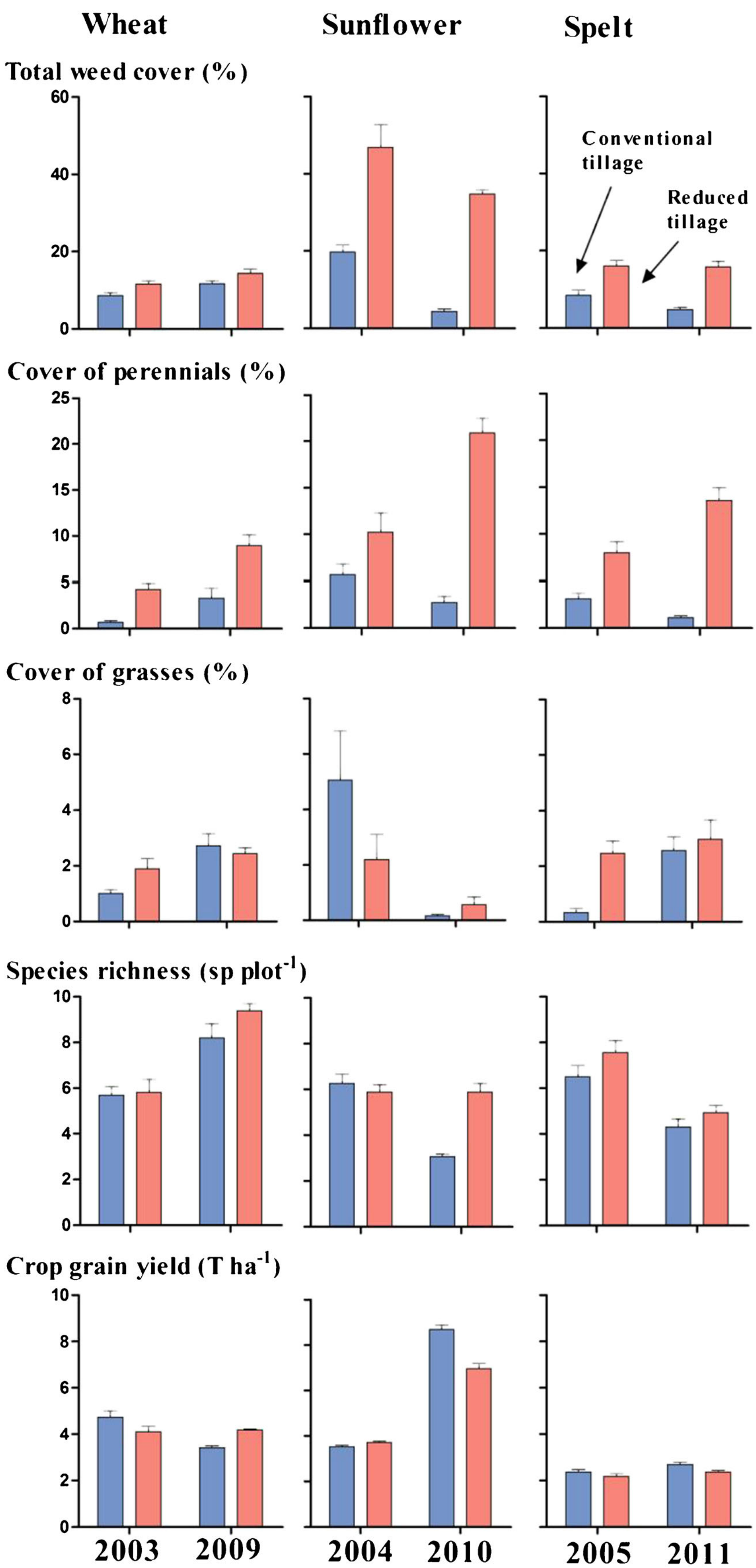
Wheat
Sunflower
Spelt
Total weed cover (%)
Conventional tillage
Reduced tillage
Cover of perennials (%)
Cover of grasses (%)
Species richness (sp plot-1)
Crop grain yield (T ha-1)
2003
2009
2004
2010
2005
2011

Table 3 Results from the distance-based analysis of variance based on 1,000 permutations, testing the effect of the tillage system (reduced or conventional tillage), the crop type (wheat, sunflower, and spelt), and their interaction on weed species composition

	Sum of squares	Partial R^2
Tillage	6.762	0.111*
Crop type	9.725	0.159*
Tillage×crop type	4.048	0.066*
Total	61.074	

The weed community composition was affected by both the tillage system and the type of the crop. However, whereas the tillage system did not modify weed species richness, it was affected by the type of the crop

*$P<0.001$

Conversely to perennial species, our results did not show any clear tendency of the tillage system on the cover of grass species (Tables 1 and 2, Fig. 2). These results, which contrast with previous studies claiming higher values of grasses under reduced tillage (Melander et al. 2013), may be a consequence of the very low cover of grasses in our experimental field. As previously mentioned, most of the studies testing the effects of reduced tillage on the weed flora are conducted under conventional farming, which are commonly more infested by grasses than organic fields (Romero et al. 2008). This is mainly explained by the extended use of herbicides to control broad-leaved weeds and the appearance of resistance to herbicides in several major grass species (Heap 2013). Conventional farmers rely more heavily on herbicides and show a lower adoption of cultural and preventive methods of weed control than organic farmers. These facts may also explain the increase of the cover of grasses in conventional fields under reduced tillage, which is not observed in our experiment under organic farming.

Nevertheless, interestingly, the crop yields did not differ significantly between tillage systems (Table 1, Fig. 2) in spite of the higher cover of weeds, which were mainly perennial species, under reduced tillage. Previous studies on organic management have reported that the performance of the yields under conventional and reduced tillage is highly dependent on the crop grown (Légère et al. 2013; Sans et al. 2011; Vakali et al. 2011; Zikeli et al. 2013), although in most of these cases, the effect of the year, i.e., the environmental effects, is confounded with the crop because each crop is included only once in the rotation. Lower yields under reduced tillage have been mainly reported in crops such as corn, soybean, or fava bean, and reduced tillage concurs with higher weed infestation. These crops are sown in widely spaced rows, leaving a great amount of bare soil between and within rows, which provide much less shading conditions compared with other crops such as cereals, thus not hampering but promoting the growth of the weeds.

We also found clear differences between crop types in weed infestation, both the total weed cover and the cover of perennials. Weed infestation was higher in the sunflower compared with the cereals, and it was especially higher under reduced tillage (Table 1 and Fig. 2). Consequently, improving the weed management in these types of crops is critical for the feasibility of the reduced tillage systems in organic farming. Mechanical methods are crucial in organic cropping systems, but they have been mainly developed under conventional tillage. Thus, the weeding devices have to be modified to work in more compacted soil and with more crop residues (van der Weide et al. 2011).

The differences in weed infestation between crops also highlight the importance of a proper selection of the crop rotation. The crop choice and the planned sequence in the rotation could be even more relevant than the tillage for weed infestation (Cardina et al. 2002). A diverse crop rotation, which introduces different crop growth periods or management practices, could prevent the occurrence or reduce the abundance of some species (Peigné et al. 2007). However, special attention must be paid to those crops that are not very competitive or are sown in widely spaced rows. Direct and specific weed control such as interrow hoeing should be

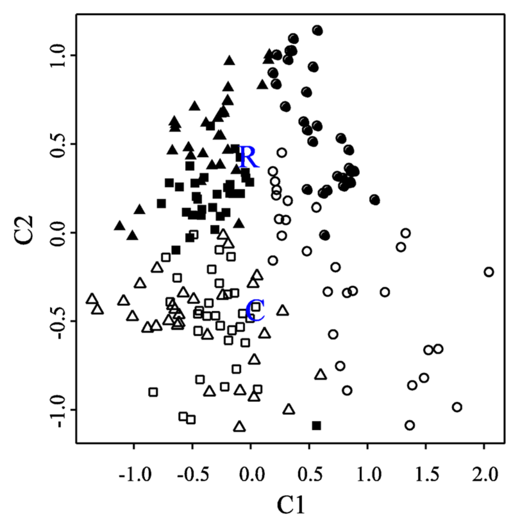

Fig. 3 Non-metric multidimensional scaling (NMDS) ordination plot. Each point represents a single weed community sample. The NMDS fits as much as possible the floristic dissimilarity between weed community samples in a two-dimensional plot to ease its visualization. Plotting symbols enable the visualization of the tillage system, i.e., reduced and conventional tillage, and the type of crop, i.e., wheat, spelt, and sunflower. The greater the dissimilarity between two weed communities, the more distant the respective symbols are in the plot. *Filled symbols* represent reduced tillage plots, and *empty symbols* represent conventional tillage plots. The labels *R* and *C* represent the centroids of reduced and conventional tillage, respectively. *Circles*, *squares*, and *triangles* represent sunflower, wheat, and spelt crops, respectively. The results show that weed communities surveyed under reduced tillage differ from those surveyed under conventional tillage. Moreover, weed communities found in the wheat and spelt crops are similar and both differ from those surveyed in the sunflower crop

accurately applied to them. Otherwise, these crops, which are more vulnerable to weed infestation, may increase the risk of higher infestation in succeeding crops and increase yield losses, thus affecting the overall feasibility of this type of tillage system.

3.2 Effects of tillage and crop type on weed diversity and community composition

In total, 38 species were found; the mean per year was 18.1. Thirty-one, 24, and 29 weed species were found in the wheat, sunflower, and spelt crops, respectively. Fourteen species were perennials, and five were grasses, of which *Convolvulus arvensis* L. and *Taraxacum officinale* Weber were the most abundant perennial species, and *Alopecurus myosuroides* Hudson was the most abundant grass.

The reduction in the intensity of the soil tillage did not promote higher weed diversity (Table 1, Fig. 2; Sans et al. 2011; Santín-Montanyá et al. 2013), but it had a strong effect on the weed community composition (Table 3, Fig. 3). This reflects the changes on the perennial weed species between tillage systems. This contrasts with the results found in long-term experiments under conventional farming (Hernandez Plaza et al. 2011), where the use of herbicides may hamper the expression of differences in weed composition between tillage systems. The different management regimes associated with each crop, such as the date and pattern of sowing, the weed control strategies, or the time of tillage operations also led to a different composition of the weed community (Fried et al. 2008), mainly between the cereal crops and the sunflower (Table 3, Fig. 3), as well as differences in weed diversity (Table 1).

4 Conclusions

The new European Union and national regulations on herbicides strongly encourage limiting herbicide applications, which could hamper the adoption of the reduced tillage techniques among conventional farmers. In this study, we show that reduced tillage is a viable cropping system for organic farming that totally excludes herbicides. In this long-term trial, crop yields were similar between conventional and reduced tillage systems in organic farming. Weed infestation remained within acceptable levels for reduced tillage, but a substantial increase of perennial species was found over the years. Thus, improvements in the weed management strategies are needed to minimize the risk of weed infestations associated with reduced tillage and to ensure the feasibility of this system over time.

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