Weed harrowing in organically grown cereal crops avoids yield losses without reducing weed diversity

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RESEARCH ARTICLE

Weed harrowing in organically grown cereal crops avoids yield losses without reducing weed diversity

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Abstract This report shows that weed harrowing in organic cereal fields is an efficient alternative to herbicides since weed harrowing does not reduce yields compared to weed-free plots. Arable weeds provide resources and habitat to many organisms. However, weeds are the most important constraint to crop production. Indeed, the potential crop losses of the eight major crops due to weed–crop competition amount to about 30 %. New ways of food production are needed due to the current severe biodiversity decline, about 1,000 times higher than the natural rate of species loss, and the growing food demands. Herbicides are highly efficient at reducing crop losses due to weed–crop competition, but at the expense of declining biodiversity. Studies have shown a poor efficiency of weed harrows in terms of weed reduction in organic farming systems. Here, we evaluated the feasibility of weed harrows in organic fields to reduce weeds to a threshold that does not limit crop production, while maintaining a rich flora. The results were compared to results obtained using herbicides in conventionally managed fields. Eleven organic and conventional cereal field pairs in Catalonia, Spain, were evaluated for one season in 2006–2007. Three different weed control treatments were applied: weed-free plots; weed-controlled plots, using herbicide in conventional fields and weed harrowing in organic ones and non-weeded plots. Crop yield and the abundance, richness and composition of the weed flora, which was dominated by ryegrass and poppies, were evaluated. Our results show that weed harrowing prevents weeds from being a limiting factor of crop productivity in organic cereal fields, since weed-controlled plots did not reduce yields compared to weed-free plots. A similar trend was observed in herbicide-controlled plots. However, herbicides diminished weed species richness in approximately 47 % and changed the species composition whereas harrowing allowed the maintenance of high levels of weed diversity in the organic fields.

Keywords Crop-weed competition · Herbicide applications · Mediterranean climate · Weed control · Weed species richness and composition

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1 Introduction

The role of weeds in agroecosystems has been largely debated because of both their potential delivery of ecosystem goods and services and the competition between weeds and crops. Weeds are at the basis of the food web of agroecosystems. This notion implies numerous interactions with other organisms such as earthworms, arthropods, farmland birds and mammals (Petit et al. 2011). In addition, arable weeds not only offer ecological and agronomical services, but they also have conservational and aesthetic values (Clergue et al. 2005). However, recent research has shown a severe decline in weed abundance and diversity as well as changes in weed species composition due to the intensification of agricultural practices of the last decades (Cirujeda et al. 2011). These intensified practices might negatively affect the food web interactions and, in turn, the ecosystem services.

However, weeds are often recognised as a major constraint for crop production (Milberg and Hallgren 2004) because they use part of the resources that are essential for crop growth. In many situations, they lead to higher economical losses when compared to other pests, such as insects or fungi (Oerke and Dehne 2004). Therefore, weed control is considered as one of the crucial requisites for a successful production (Gerowitt 2003). Chemical weed control, i.e. the application of herbicides, has been effective for reducing yield loss and minimising weed infestations. However, the generalised and continuous application of herbicides is being seriously questioned because it has prompted the appearance of herbicide resistance (Heap 2010) and the extension of the potential negative side effects on the environment (Boutin et al. 2004). Moreover, the use of herbicides has been identified as one of the main drivers of the current weed diversity decline in agroecosystems (Marshall et al. 2003).

The farmers' interest in alternative methods, such as mechanical and cultural weed control, has partially increased due to concerns about herbicide use and to the growing demand of organic products. Weed harrowing with flex-tine harrows is one the most widely used mechanical methods for weed control in organically grown cereals (Fig. 1). They till the soil surface, uprooting and/or covering weed seedlings with soil. However, weed control remains a major concern for organic farmers and a perceived obstacle for the conversion towards organic farming (Sumption et al. 2004). Organic fields usually harbour higher levels of weed infestation than conventional ones (Romero et al. 2008), probably because mechanical weed control commonly achieves lower control effects than herbicides (Lundkvist 2009). Indeed, some studies have reported a poor efficiency of weed harrowing in terms of weed reduction (Ryan et al. 2010; Ulber et al. 2009). Weed harrows could therefore favour the maintenance of weed diversity and, in turn, of the ecosystem services, but they will not be a feasible method for organic producers unless they minimises crop losses to an economically acceptable level.

Fig. 1 Organic farmer using a weed harrow. Most organic farmers use weed harrows as a direct physical method to control weeds. Weed harrows till the soil surface, uprooting and/or covering the weed seedlings with soil

Accordingly, one of the current challenges that farmers face is the reduction of crop yield loss due to the weed–crop competition while preserving the weed flora. Here, we aimed to assess the effects of weed control on weed flora and on prevention of yield losses and compare the effects of weed harrowing in organic fields to that obtained through chemical weed control, i.e. herbicide applications, in conventionally managed cropping systems. With this purpose, three different weed control treatments: non-weeded, weed-controlled and weed-free plots were applied for one season to 11 organic and conventional winter cereal field pairs in central Catalonia, i.e. northeastern Spain. The abundance, richness and composition of weed flora, as well as crop production, were evaluated. We hypothesised that: (1) weed harrowing in organic farming systems can reduce weed–crop competition to a threshold level where crop production is not compromised, and (2) in contrast to herbicides, weed harrowing enables to maintain a rich weed flora.

2 Material and methods

2.1 Study site

The study was conducted in 2006–2007 at 11 localities in Central Catalonia, northeastern Spain. The criterion for selecting the localities was the presence of farms that have been organically managed, at least since 2002. These organic farms were managed according to the European Union regulation 2092/91/EEC, which prohibits the use of synthetic fertilisers and pesticides. The studied area covered approximately 100×50 km, extending from 1°05′ to 2°05′E and from 41°24′ to 42°05′N. The mean altitude is 537±55 m a.s.l. (mean±standard error). The climate is Mediterranean, with an annual average precipitation from September 2006 to August 2007 of 513±15 mm, which is within the average 500–600-mm annual rainfall range; the mean annual temperature for the abovementioned period was 12.7±0.2 °C.

In each locality, we selected two proximate cereal fields, one organic and one conventional. The fields had a similar area: conventional, 1.68±0.22 ha; organic, 1.39±0.20 ha; Wilcoxon's paired tests within locality, P=0.31; and perimeter: conventional, 558.2±24.8 m; organic, 512.16±37.32 m; P=0.51. All the fields had soils with a loamy-clay texture. Both conventional and organic farmers sowed the cereal, winter wheat or barley, between October and November. The seed density did not differ between farming systems: conventional, 177.7±6.3 kg ha^{-1}; organic, 189.5±6.3 kg ha^{-1}; P=0.31; and the row spacing was 12.5 cm in all the fields.

2.2 Experimental design

After sowing the cereal, we randomly placed four 7×7-m blocks in the centre of each field, i.e. at least 10 m away from the field edge. In each block, we delimited three 2×2-m plots, 3 m apart. In one plot, weeds were not controlled, hereafter the non-weeded plot. In the other two plots, weeds were controlled by means of herbicides in the conventional fields and by harrowing with long-flex spring tines in the organic ones. Moreover, one of the weeded plots was hand-weeded twice after the weed control to minimise weed growth, hereafter the weed-free plot. The non-weeded plots involved placing a plastic sheet over each plot to intercept the herbicide spray in the conventional fields; the plastic sheet was removed immediately after the herbicide application. In the organic system, the cultivation equipment was lifted while passing through the plot.

The weed control was applied according to the farmers' regular practices. All of the conventional farmers applied herbicides once a year in February or March, with the exception of one farmer, who also applied herbicide before sowing. Six farmers applied broad leaf herbicides, and five farmers applied both broad leaf and grass herbicides. The active ingredients used were diflufenicon, 2,4-dichlorophenoxyacetic acid, isoproturon, *N*-(phosphonomethyl)glycine, tralkoxydim, tribenuron, thifensulfuron and triasulfuron. The organic farmers harrowed once between January and March.

2.3 Sampling procedures

The weed sampling was conducted in May 2007 by weed species scouting in non-weeded plots and in plots with weed control, but not in plots that had been hand-weeded. The presence of every weed species in each 2×2-m plot, i.e. four weeded and four non-weeded plots per field, was recorded. The total weed cover and the cover of each species were visually estimated using figures ranging from 1 to 100 %. Tree seedlings and volunteer crop species were not considered. All the surveys were conducted by the same two people to standardise the sampling method as much as possible. The contribution of each species to the community structure was analysed by means of Shannon's diversity index (Shannon and Weaver 1949), calculated as follows:

$$H' = -\sum_{i=1}^{S} p_i \log 2p_i$$

where S is the number of species, and p_i is the relative cover of each species in a sample. This index is sensitive to species richness and maximised for a certain number of species when their abundances are even.

Before the cereal harvest, we randomly selected four 25×25-cm squares in each non-weeded, weeded and weed-free plot to assess the aboveground dry weight of cereal and weeds. Squares which were not representative of the entire plot, e.g. due to sowing failure, were avoided. The harvested biomass was oven-dried at 60 °C for 48 h. The number of weed individuals was counted, and the cereal biomass was separated into spikes and straw. However, the total cereal biomass was highly correlated with the spike biomass: Spearman's correlation coefficient ρ=0.95, P<0.0001; hereafter, we only present and discuss the results regarding the total aboveground cereal biomass, which can be interpreted as a surrogate of crop yield.

2.4 Statistical analyses

The effect of the farming system, the weed control treatment and their interaction on cereal biomass and on weed community, i.e. species richness, Shannon diversity index, weed biomass, weed density and weed cover, was analysed using mixed models. Mixed models account for random effects and nested sampling designs. Locality, field and block were introduced as random factors when all the fields were analysed together, and field and block were introduced as random factors when the organic and the conventional fields were analysed separately.

Orthogonal contrasts to compare the different levels of the factor weed control treatment were fixed a priori. For the analysis of cereal yield, non-weeded plots were compared with weed-controlled and weed-free plots. Plots with weed control were also compared with weed-free plots. For the analysis of weed community, non-weeded plots were compared to plots with weed control. Orthogonal contrasts were also fixed to compare the different levels of farming system, conventional versus organic. The adequacy of each model was assessed through the normality and unbiased nature of the residuals and through the predictive power of each model. Weed biomass and density variables were log-transformed, and weed cover was square-root transformed to meet the requirements of the residuals. The analyses were carried out using R 2.7.1 (R Development Core Team 2008), with the “lme4” package for R (Bates et al. 2008) for mixed models and “languageR” (Baayen 2008) to evaluate the P values.

The species composition was analysed using multivariate analysis based on presence/absence data. Species present in only one locality were not considered. We performed a permutational multivariate analysis of variance using distance matrices to analyse how the farming systems and weed control treatments affected the weed species composition. The Jaccard dissimilarity index was applied. This analysis allows partitioning a distance matrix among sources of variation and fitting a linear model to it. The obtained partial R squared indicates the percentage of variance that is explained by the analysed factor. The significance of each explanatory variable was obtained by means of F tests based on sequential sums of squares from permutations of the raw data, which restrict permutations within each locality to take into account the hierarchical sampling. Compositional analyses were performed using the "vegan" package for R (Oksanen et al. 2009).

3 Results and discussion

3.1 Efficacy of weed control on preventing yield losses

Weed harrowing efficiently avoided yield reduction due to weed–crop competition, since our results showed no significant differences in cereal biomass between plots with weed control and plots where the weed growth had been minimised, i.e. weed-free plots (estimate±standard error=−12.86±24.52, P=0.65; Fig. 2). Likewise, in the conventional fields, weed-free plots neither achieved greater yields than plots where herbicide applications were applied (estimate±standard error=0.31±21.49, P=0.99). Therefore, in this study, weeds under the standard weed control management of the study area did not constrain the crop production in organic fields nor in conventional ones. Despite this fact, we found lower crop yields in the organic fields, approximate 23 % mean reduction compared to conventional yields (estimate±standard error= 105.15±44.30, P=0.002; Fig. 2). This outcome revealed that in the absence of weeds, organic yields do not equal or exceed conventional ones. The lower yields of organic fields were probably related to other causes such as fertilisation rates (Seufert et al. 2012). For instance, in the study fields, the amount of nitrogen fertilisation was, on average, three times higher in the conventional than in the organic fields (Armengot et al. 2011a).

The weed control resulted in an improved yield compared to non-weeded plots in both farming systems (Fig. 2; organic fields: estimate±standard error=−53.94±14.16, P<0.001; conventional fields: estimate±standard error=−50.71± 12.48, P<0.001). But notably, the cereal yield loss in our study is relatively low in both farming systems, which is in agreement with other studies (Milberg and Hallgren 2004). The yield reduction in non-weeded plots compared to plots with weed control was 11.4 % on average in conventional fields, with a minimum of 0 % and a maximum of 21.1 %, and 15.2 % with a minimum of 0 % and a maximum of 43.5 % in organic fields. Therefore, the use of weed control methods should be case-specific to balance the crop loss with the cost of the treatment as well as with the potential damage to the crop due to the phytotoxicity of herbicides (Pannell 1990) and the mechanical damage by harrows (Rasmussen et al. 2004). For instance, Nazarko et al. (2003) reported manageable weed densities after 1 year without herbicide application. Moreover, since rainfall in Mediterranean dryland cereal fields is often identified as one of the main factors affecting crop yield, as

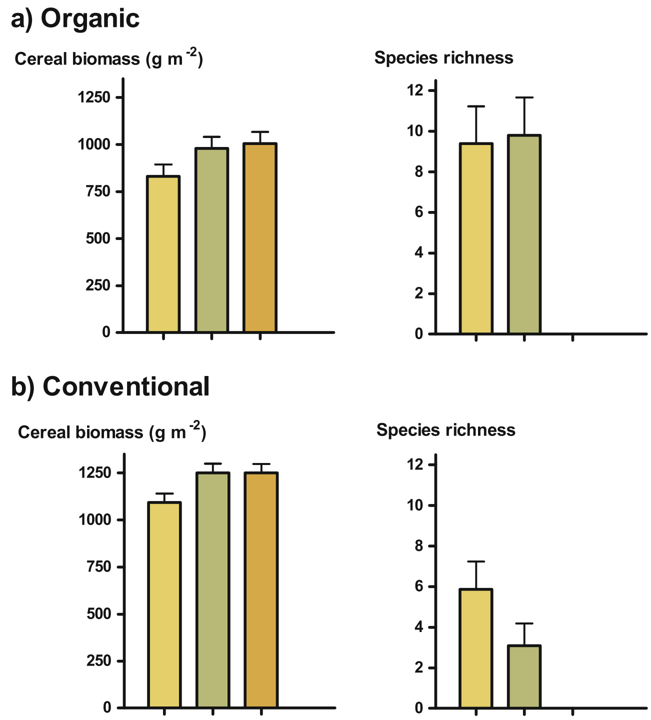

Fig. 2 Mean±standard error of cereal biomass and species richness in the organic and conventional fields under different weed control treatments: weed-free plots, *red colour*; weed-controlled plots, *green colour* and non-weeded plots, *yellow colour*. Weed control was performed by means of weed harrowing in the organic fields and herbicide applications in the conventional ones. No differences in cereal biomass were found between weed-free and weed-controlled plots. Thus, both weed control methods avoid cereal yield losses from weed–crop competition. Contrary to weed harrowing, herbicide applications reduced weed species richness

well as the growth of weeds, further research is required to evaluate the necessity of each weed control method in different rainfall conditions.

3.2 Effects of weed control on weed community

Our results revealed that weed harrowing reduced the cover, biomass and density of the weed flora, thus allowing higher crop yields compared to non-weeded plots (Table 1); however, it did not affect the weed species richness nor Shannon's diversity index (Table 1; Fig. 2). This advantage is of special interest due to the current decline of species diversity in agroecosystems and the growing concern for weed species conservation. Herbicide applications also reduced the cover, density and biomass of weeds, but contrary to weed harrowing, they diminished the weed species richness and diversity (Table 1; Fig. 2). Indeed, both species richness and diversity were reduced under conventional farming even in the absence of weed control. Therefore, the 1-year abandonment of chemical control in conventional fields was not sufficient to equal them to the values found in the organic

Table 1 Coefficients and their standard errors of the linear mixed models performed for all fields and for the conventional and the organic fields separately, and levels of significance of the effect of farming system and weed treatment on weed cover, weed biomass, weed density, species richness and Shannon's diversity index

	Weed cover[a] (%) Estimate±SE	Weed biomass (g m^{-2})[b] Estimate±SE	Weed density (individuals m^{-2})[b] Estimate±SE	Species richness Estimate±SE	Shannon's diversity index Estimate±SE
All fields					
(Intercept)	3.83±0.49	2.92±0.40	4.11±0.23	7.02±0.59	2.02±0.12
Farming system	−1.36±0.27***	−0.59±0.08***	−0.55±0.07***	−0.58±0.12***	−0.19±0.04***
Weed treatment	−0.64±0.07***	−0.86±0.10***	−1.15±0.20***	−2.19±0.48***	−0.52±0.10***
Farming system× weed treatment	−0.22±0.07*	−0.14±0.08**	−0.01±0.01	−0.79±0.12***	−0.19±0.04***
Conventional fields					
(Intercept)	0.25±0.03	1.94±0.44	2.73±0.45	1.77±0.10[b]	1.50±0.16
Weed treatment	−0.09±0.01***	−0.74±0.12***	−0.69±0.09***	−0.23±0.03***	−0.38±0.06***
Organic fields					
(Intercept)	0.52±0.07	3.85±0.36	5.01±0.30	9.59±0.97	2.53±0.16
Weed treatment	−0.04±0.01***	−0.42±0.08***	−0.56±0.10***	0.20±0.16	0.01±0.03

Orthogonal contrasts compare non-weeded plots with weed-controlled plots for the factor weed treatment, and conventional with organic fields for the factor farming system. Weed control was performed by means of weed harrowing in the organic fields and herbicide applications in the conventional ones. Both weed control methods reduced the cover, biomass and density of weeds compared to non-weeded plots. However, weed species richness and diversity were not affected by weed harrowing whereas they were reduced by the herbicide applications

* $P<0.05$; ** $P<0.1$; *** $P<0.001$

[a] Square root transformed

[b] Log transformed

fields. This result therefore highlights the long-lasting negative effects of conventional farming practices on both weed species richness and diversity, especially the use of herbicides (José-María and Sans 2011; Ryan et al. 2010; Ulber et al. 2009).

Overall, weed cover, density and biomass were significantly higher under organic farming (Table 1). Although the weed control applied clearly led to their reduction, the use of herbicides in conventional fields was more effective in controlling weeds than weed harrowing in organic ones, as the interaction between farming system and weed treatment revealed. The average reduction of weed biomass in weed-controlled plots compared to non-weeded plots in the conventional and the organic fields, respectively, was 76.5 and 26.7 % for the weed cover, 64.7 and 54.0 % for the weed density and 72.1 and 51.8 % for the weed biomass. The lower efficiency of weed harrows in the organic fields could have negative consequences at the long term, since the soil seed bank could severely increase in comparison to that of the conventional fields (José-María and Sans 2011). As a consequence, weed management in organic fields should rely not only on direct weed control methods, but also on a system approach including preventive, cultural and weed control methods in order to optimize the whole cropping system rather than the weed control per se and keep the weeds under a manageable threshold (Bàrberi 2002). Actually, in studies showing poor efficiency of weed harrows, the weed cover and biomass largely exceeded the figures found here (Ryan et al. 2010; Teasdale et al. 2007), which resulted in a clear yield reduction.

Table 2 Results from the permutational analysis of variance and levels of significance in species composition performed for all fields and for conventional and organic fields separately

	Sums of squares	Partial R squared
All fields		
Farming system	0.53	0.009***
Weed treatment	2.23	0.037***
Farming system× weed treatment	1.06	0.006**
Conventional fields		
Weed treatment	0.69	0.023*
Organic fields		
Weed treatment	0.23	0.008

Non-weeded plots are compared with weed-controlled plots for the factor weed treatment and conventional with organic fields for the factor farming system. Weed control was performed by means of weed harrowing in the organic fields and herbicide applications in the conventional ones. Weed control changed weed species composition in the conventional fields but not in the organic ones.

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

3.3 Effects of weed control on weed species composition

A small number of species predominated the weed communities of both organic and conventional fields: *Lolium rigidum* Gaudin and *Papaver rhoeas* L. together accounted for 57 and 63 % cover of all weeds in the organic and conventional fields, respectively; these were followed by *Polygonum aviculare* L. (14 %) in the organic fields and *Medicago polymorpha* (6 %) in the conventional ones.

Herbicide applications were the main factor determining weed assemblages. Our results revealed that weed control was a more important factor driving weed species composition than farming system, i.e. the percentage of explained variance was higher for weed control than that of farming system (Table 2). Nevertheless, the interaction between farming system and weed control showed that the weed control treatment only affected weed assemblages under conventional farming; therefore, the species composition did not differ between weed-controlled and non-weeded plots in organic fields, but it did differ in conventional ones. These results reflect that the weed flora strongly responds to management events, but especially to chemical weed control, which is one of the most important factors in determining actual weed assemblages (Armengot et al. 2011b; Booth and Swanton 2002; Légère et al. 2005).

4 Conclusions

In order to preserve the ecosystem services and biodiversity, the final goal of weed control should not be the total elimination of weeds, but the reduction of crop losses to an economically acceptable level. This study demonstrates that weed harrowing is an effective weed control method in organic cereal fields, which prevents weeds from being a limiting factor of crop productivity while maintaining a rich flora. Likewise, herbicide applications in conventional cereal fields minimise yield loss. However, contrary to weed harrowing, they reduce weed species richness and diversity as well as change the species composition.

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