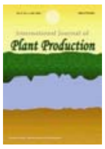

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Individual and interactive effects of crop type and management on weed and seed bank composition in an organic rotation

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Abstract

We investigated the effects of organic and conventional pest and fertility management on weed cover and the seed bank community in an organic rotation. The study was conducted during the 4th and 5th years of an organic rotation on part of a long term organic-conventional comparison trial. Results showed that although crop type (potato vs. cabbage) in a single year significantly affected weed functional group and cover of individual species, it did not change weed functional group and composition in the seed bank in the following year. Five years of organic crop protection management increased weed species that depend on regeneration from seed and increased Ellenberg light, reaction and nitrogen values and a seed bank persistence index in comparison with conventional crop protection management. Three species (*Chenopodium album* L., *Poa* spp. L. and *Stellaria media* (L.) Villars) that is important for biodiversity of arable fields were more prevalent in organic protection plots. Fertility management had no significant effects on weed seed bank composition and functional group. The additive effect of organic practices on perennial ratio and competitor radius value was an important finding. Organic fertility management and crop protection acted together to increase these two aspects of the soil seed bank in comparison with other treatment combinations and a similar effect was seen on *Poa* spp. L.

Keywords: Additive effect; Weed cover; Weed functional group; Crop protection; Fertilizer.

Introduction

Arable weeds provide an important resource for biodiversity, including many invertebrate taxa, farmland birds and other wildlife (Altieri, 1999; Storkey and Westbury, 2007). They increase the structural diversity, species richness and variation in ecological function within arable crops and intensively farmed landscapes (Hawes et al., 2003). The severe decline in arable weed populations in the 20th century has important implications for the diversity of associated herbivores, predators and parasitoids dependent on them (Siemann et al., 1998; Marshall et al., 2003; Hawes et al., 2003, 2009; Taylor et al., 2006).

A common observation in studies is that weed abundance and species richness increases when arable farming is converted from conventional to organic management (Moreby et al., 1994; Hald, 1999; Rydberg and Milberg, 2000; Van Elsen, 2000; Salonen et al., 2001; Albrecht, 2005). Maintenance of weed species richness and conservation of species important for biodiversity requires appropriate weed control practices and a diverse crop rotation (Ulber et al., 2009).

In order to apply effective integrated weed management programmes and to increase the success of agri-environment schemes, it is necessary to understand the many factors affecting weed seed bank community responses to cropping systems. Cropping systems can affect the weed seed bank density and diversity, with higher values associated with low-input systems than conventionally managed systems (Menalled et al., 2001; Davis et al., 2005; Sosnoskie et al., 2006). The change in management from conventional to organic farming particularly increases summer annual, perennial and dicotyledonous weeds (Albrecht, 2005). Arable farming practice also influences seed traits in the soil seed bank, for example a dense crop canopy selects for competitive, large-seeded weed species and seed longevity increases with tillage frequency, independent of the farming system (Albrecht and Auerswald, 2009). The method of tillage also affects the weed seed distribution in the soil profile (Mohler et al., 2006), seed survival and seedling emergence (Roberts and Feast, 1972; Benvenuti et al., 2001; Boyd and Van Acker, 2003; Grundy et al., 2003; Tuesca et al., 2004; Davis et al., 2005). Additionally, changes in weed emergence times, persistence, dormancy and over-winter survival can be affected by both crop rotation (Bellinder et al., 2004) and weed management strategies (Cardina et al., 2002).

The seed bank is the main source of arable weed propagules and can have severe and long-lasting effects on crop yields (Cardina et al., 2002; Tuesca et al., 2004; Murphy et al., 2006; Sosnoskie et al., 2006). Thus, assessing the relationship between the above-ground and underground weed communities could allow the design of predictive weed management programmes. However, past research has produced some conflicting results. Some studies have found strong relationships between the weed seed bank and aboveground communities (Dessaint et al., 1997; Zhang et al., 1998; Rahman et al., 2001; Tuesca et al., 2004; Rahman et al., 2006) but others have shown low correlation (Wilson et al., 1985; Forcella, 1992; Cardina and Sparrow, 1996; Webster et al., 2003). Both seed bank and emerged flora respond to farming practice but the seed bank is also buffered by the persistence of weed seeds in the soil and is more strongly influenced by soil properties, such as % organic carbon and % total nitrogen, than by management (Hawes et al., 2010). Yearly fluctuations in environmental factors can also have significant effects on the weed seed bank (Harbuck et al., 2009).

Although the effects of organic and conventional management on the soil seed bank are relatively well studied, there has been less focus on how the key components of organic management i.e. the crop protection and fertility management strategies, affect weed populations. In addition, the long-term effects of organic and conventional crop protection and fertility management practices on the species and functional composition of the seed bank are not well understood. In this study the effects of organic and conventional crop protection and fertility management practices on weed populations were investigated using: (a) weed cover measurements in both potato and cabbage crops (2008) and (b) seed bank assessments in a subsequent bean crop (2009).

Materials and Methods

Study site and experimental design

The study reported in this paper was part of the larger Nafferton Factorial Systems Comparison (NFSC) trial at the University of Newcastle's Nafferton Experimental Farm, Northumberland, UK (54:59:09 N; 1: 43:56 W). The NFSC trial was established in 2001 to investigate the effects of organic and conventional farming practices on food quality, crop disease and other agronomic characteristics. In this study, a subset of plots within an organic crop rotation (rich in legume and potato/vegetable crops as recommended by organic farming standards/principles) was used. The sequence of crops was grass/clover (2005 and 2006), winter wheat (2007), cabbages and potatoes (2008) and spring beans (2009). Within this subset of plots the experiment can be described as a 2×2 factorial in a split plot design, with crop protection at two levels (organic and conventional) as the main plot (12×48 m) and fertility management at two levels (organic based on composted manure inputs and conventional based on mineral NPK inputs) as the sub-plot (12×24 m) (Figure 1). Crop protection and fertility treatments are carried out according to either (a) organic standards (Soil Association organic farming standards; Soil Association 2005) or (b) conventional farming practice (Red Tractor Farm Assured Combinable Crops Standard; Red Tractor Farm Assurance 2010), with details for cropping in 2007-09 shown in Table 1. In one year out of the eight-year rotation, the fertility management sub-plots are split lengthwise and potatoes are grown on one half of each plot (6×24 m) while cabbages are grown on the other half. The whole experiment is replicated four times in the field and there are 10 m unplanted separation strips between crop protection plots and 5 m unplanted separation strips between fertilization sub-plots.

In this study weed cover was assessed in potato and cabbage plots grown within the organic crop rotation in 2008 and weed seed bank assessments were conducted in soils from the same plots that had been planted to spring beans in 2009.

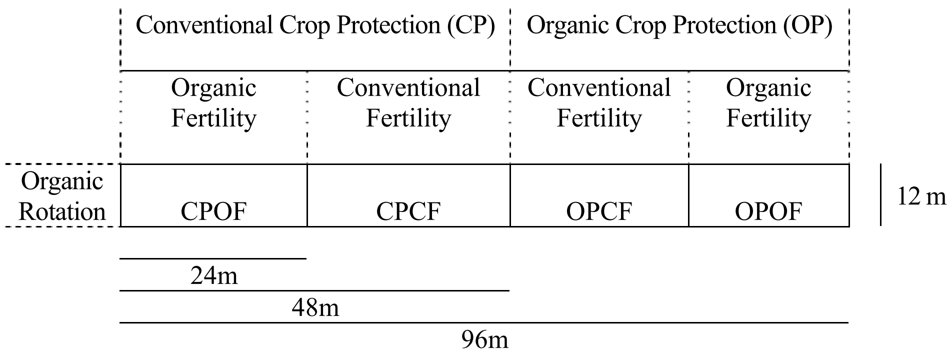

Figure 1. Diagram showing the composition of the four plots in the basic unit of the organic rotation.

Table 1. Crop management practices for wheat, cabbages, potatoes and beans grown in the NFSC trial in 2007, 2008 and 2009.

Treatment	Wheat (2007)	Potatoes (2008)	Cabbages (2008)	Beans (2009)
conventional protection				
Herbicides product (rate), date;	isoproturon (2.5 l ha^{-1}), mecoprop-P (0.5 l ha^{-1}) and pendimethalin (2.5 l ha^{-1}), 7 November 2006	Linuron (3.5 l ha^{-1}), 14 May 2008	Propachlor (9 l ha^{-1}), 4 June	pendimethalin (3 l ha^{-1}), 1 April 2009
Mechanical weed control/ridging		Ridging, 8 May, 12 May, 9 June	17 June	
Fungicides product (rate), date;	epoxiconazole (0.5 l ha^{-1}), chlorothalonil (1 l ha^{-1}), proquinazid (0.125 l ha^{-1}) and chlormequat (2.3 l ha^{-1}), 21 April 2007; epoxiconazole (0.5 l ha^{-1}), chlorothalonil (0.4 l ha^{-1}), fenpropidin (0.25 l ha^{-1}) and azoxystrobin (0.6 l ha^{-1}), 1 June 2007	Fluazinam (300 ml ha^{-1}), 24 June, 4 July, 31 July, 7 August, 26 August 2008; Mancozeb + metalaxyl-M (1.9 kg ha^{-1}), 17 July, 24 July, 15 August 2008	Azoxystrobin (1 l ha^{-1}), 24 June, 8 July, 21 July 2008; chlorothalonil (3 l ha^{-1}), 4 August 2008	Chlorothalonil (1.5 l ha^{-1}), 12 June 2009
Dessicant		Diquat, 25 August, 5 September 2008		
Insecticide			Chlorpyrifos (1 l ha^{-1}), 4 June 2008	
organic protection				
Fungicides product (rate), date;		Copper oxychloride (4.6 l ha^{-1}), 1 July, 17 July, 4 August, 15 August 2008	Capatex netting for insect control	
Mechanical weed control/ridging	Finger weeding with Einbock weeder, 14 March, 28 March 2007, 5 April 2007	Ridging, 8 May, 12 May, 30 May, 9 June 2008	19 June	Finger weeding with Einbock weeder, 8 May, 13 May 2009
conventional fertility				
N	50 kg N ha^{-1}, 28 March 2007; 130 kg N ha^{-1}, 17 April 2007	180 kg N ha^{-1}, 7 May 2008	100 kg N ha^{-1}, 4 June; 160 kg N ha^{-1}, 17 June 2008	
P		134 kg P_2O_5 ha^{-1}, 22 April 2008	100 kg P_2O_5 ha^{-1}, 22 May 2008	60 kg P_2O_5 ha^{-1}, 30 March 2009
K		200 kg K_2O ha^{-1}, 22 April 2008	150 kg K_2O ha^{-1}, 22 May 2008	90 kg K_2O ha^{-1}, 30 March 2008
organic fertility				
compost		170 kg total N ha^{-1}, 25 March 2008	250 kg total N ha^{-1}, 25 March 2008	

Study 1: Weed cover assessments

Weed cover assessments were carried out during August 2008 in the potato and cabbage crops. Percentage cover of all weed species was estimated by eye in each of five randomly located 0.5×0.5 m quadrats in each 24×6 m sub-plot. Weeds were then classified on the basis of these functional traits: life history (Grime et al., 2007), competitor radius (Thompson, 1994), mycorrhizal association, regenerative strategy (Grime et al., 2007), Ellenberg's light, reaction and nitrogen indicator values (Hill et al., 1999) and seed bank persistence index (Thompson et al., 1997) (Table 2). Cover ratios of summer annual, winter annual, perennial, mycorrhizal association (VA and + species) and regenerative strategy were calculated for each quadrat. The relative values of competitor radius, Ellenberg light, reaction and nitrogen and the seed bank persistence index were also calculated for each quadrat as follows:

Relative value=∑ (value × weed cover percentage)/ total cover percentage

Statistical analysis was carried out using Analysis of Variance derived from linear mixed-effects models (Pinheiro and Bates, 2000). Crop type, fertility management and crop protection management were fixed factors, whilst the trial blocks and crop protection management were random factors incorporated into the models where appropriate (Crawley, 2007), using the Nome library in the R statistical environment (R Development Core Team, 2011). Residual normality was assessed using the quorum function in R (Crawley, 2007), with no data showing violations from normality. Mean comparisons were carried out using the Tukey HSD test (Crawley, 2007).

Study 2: Weed seed bank assessments

Seed bank assessments were done from 20th October 2009 to 25th April 2010. Ten soil cores (0-30 cm depth) per 24×6 m sub-plot were collected from the bean crops using a soil auger (5 cm diameter) in an approximate 'W' pattern on 20th October. Cores were mixed to one bulked sample per sub-plot and stored in a shed at ambient temperature until processing. Each bulked sample was sieved twice, through 11 mm and 4.75 mm mesh respectively. To avoid cross-contamination the sieves were brushed and rinsed between sieving.

Table 2. Functional properties of species recorded in weed cover and seed bank assessment experiments.

Species name	Life history	Competitor radius	Mycorrhizal association	Seed regenerative strategy	Ellenberg light value	Ellenberg reaction value	Ellenberg nitrogen value	Seed bank persistence index
Atriplex patula L.	As	1	VA	S, Bs	7	7	7	0.833
*Capsella bursa-pastoris (*L.) Medikus	Asw	1	-	Bs	7	7	7	0.907
Chenopodium album L.	As	2	-	Bs	7	7	7	0.931
Fumaria officinalis L.	As	1	-	Bs	6	7	6	0.905
Lamium amplexicaule I.,	A	1	VA	Bs	7	7	6	0.571
Lamium purpureum L.	Aws	1	VA	Bs	6	7	7	0.769
Matricaria discoidea DC.	Asw	1	VA	Bs	7	7	7	0.9
Poa annua L.	A/P	1	VA	V, S, Bs	7	6	7	0.889
Poa trivialis L.	P	3	+	V, Bs	7	6	6	0.823
Polygonum aviculare L.	As	1	+	Bs	7	6	7	0.813
Persicaria maculosa Gray	As	1	+	Bs	7	6	7	0.879
Rumex crispus L.	P/A	2	+	(V), Bs	8	7	6	0.765
Rumex obtusifolius L.	P	3	-	Bs	7	7	9	0.789
Senecio vulgaris L.	Asw	1	+	W, Bs	7	7	7	0.75
Sinapis arvensis L.	Asw	1	nd	Bs	8	7	7	0.914
Stellaria media (L.) Villars	Aws	1	-	Bs	7	6	7	0.802
Taraxacum officinale agg. Weber	P	2	VA	W	7	7	6	0.472
Veronica persica Poiret	Aws	1	VA	Bs	6	7	7	0.772

A: annual; As: summer annual; Aw: winter annual; P: perennial; VA: normally mycorrhizal; +: intermediate mycorrhizal; - : non-mycorrhizal; Bs: seed bank; S: seasonal by seed; V: vegetative spread, attached to parent for long period; (V): attached for shorter period; W: widely-dispersed seeds or spores; nd: no data.

Three replicate sub-samples per sub-plot bulked sample were set up in 21×16×5.5 cm seed trays. Sterilized peat was first added to *c*. 1 cm depth and 550 g wet weight of sieved soil was then added over the peat layer and levelled. Measuring equipment was rinsed and dried between each tray preparation to avoid cross-contamination. Three blanks (controls) with sterilized peat only were also prepared.

The 96 seed trays were set out on 28 October 2009 in a randomized block design in a glasshouse, i.e. 3 blocks with 1 replicate from each plot per block in a random location within the block. One control seed tray (peat only) was added in a random location to each block. Light was set at 15 h per 24 h and temperature at 15 ^{o}C minimum (fluctuation maximum *c*. ±10 ^{o}C at any time/night). Water was added manually to field capacity as required. Maximum and minimum temperature was recorded during the duration of study.

The total number of seedlings per tray was counted weekly. Seedlings were identified, counted and removed monthly and soil in each tray stirred to stimulate germination and break down any solid lumps. Any seedlings that were too small were transferred to a separate pot with sterilized peat and grown on (watering manually) until identification could be confirmed. After three months about 150 g of soil from each tray was collected. Soil samples were dried at room temperature for 48 hours. Then 100 grams of dry soil from each sample was used for seed extraction. Seed extraction was done using the K_2C0_3-Centrifugation method (Buhler and Maxwell, 1993). Extracted seeds were identified on the basis of their physical characteristics. Seeds that were entire and undamaged and appeared to be hard were assumed to be viable. An index of seed density was then calculated as the sum of emerged seedlings plus viable extracted seed.

Functional groups were defined as in Study 1, based on counts of seedlings or seed:

Relative value=∑(value × (weed seedling + viable seed number))/(total weed seedling + viable seed number).

Statistical analysis was carried out using the same linear mixed-effects model as in Study 1, on total counts of the three replicate sub-samples of weed seedlings and/or seed.

Results

Study I: Weed cover assessments

In this study 19 weed taxa were recorded but 5 were too scarce to analyse individually (*Galium aparine, Cirsium vulgare, Convolvulus arvensis, Papaver rhoeas, Poa* spp.). The mixed model ANOVA indicated that the total weed percentage cover was higher for the cabbage crop (31%) compared with the potato crop (9%) ($P \leq 0.0001$; Table 3). Individual species that showed this response to crop type were *Taraxacum officinale*, *Stellaria media*, *Senecio vulgaris, Matricaria discoidea*, *Lamium purpureum*, *Veronica persica, Chenopodium album, Persicaria maculosa, Polygonum aviculare*, *Atriplex patula* and *Fumaria officinalis* (Table 3).

Crop type affected summer annual species (Table 4). The ratio of summer annuals was greater in cabbage crops compared to potato crops. Winter annuals had lower cover than summer annuals and collectively were not affected by crop type. Individual examples were *Fumaria officinalis* and *Stellaria media* (winter and summer annual species respectively), which were reduced by 78.4% and 98.4% respectively in potato crops compared with cabbage crops (Table 3). Perennial species were not affected by crop type (Table 4); however they comprised less than 10% of the total cover. It seems that the type of crop used in the rotation had less effect on perennial weed cover than the effect of annual cropping itself.

Species with mycorrhizal associations were also affected by crop type (Table 4). The cover ratio of these species was reduced by about 17.2% in potatoes compared to cabbages. The proportion of species dependent on regeneration from the seed bank was also affected by crop type and was about 26% lower in potatoes (Table 4).

Crop type had a significant effect on the relative cover values for Ellenberg light, reaction and nitrogen (Table 4). The values were all lower in potatoes compared to cabbages. The seed bank persistence index was also significantly affected by crop type, being about 24.4% lower in potatoes compared to cabbages (Table 4).

Table 3. Weed cover (%) means (± standard errors) in August 2008 for study 1, showing significant main effects of crop type, crop protection and fertility management.

Species name	*Atriplex patula*	*Capsella bursa-pastoris*	*Chenopodium album*	*Fumaria officinalis*	*Lamium purpureum*	*Matricaria discoidea*	*Persicaria maculosa*	*Polygonum aviculare*	*Rumex crispus*	*Senecio vulgaris*	*Sinapis arvensis*	*Stellaria media*	*Taraxacum officinale*	*Veronica persica*	Total
Crop															
Cabbage	1.06*** ±0.25	0.13 ±0.09	3.56*** ±0.36	5.19** ±0.79	0.81*** ±0.19	2.31*** ±0.45	3.19*** ±0.31	2.88*** ±0.4	1.06 ±0.38	2.94*** ±0.31	1 ±0.37	3.81*** ±0.51	1.25* ±0.43	0.81*** ±0.23	31*** ±2.07
Potato	0.38 ±0.15	0.44 ±0.13	1.5 ±0.37	1.12 ±0.22	0.12 ±0.09	0.44 ±0.18	1.25 ±0.31	0.69 ±0.24	0.38 ±0.18	1.37 ±0.26	0.69 ±0.27	0.06 ±0.06	0.44 ±0.2	0.12 ±0.09	9 ±1.36
Crop protection															
Organic	0.5 ±0.18	0.25 ±0.11	2.44 ±0.38	3.06 ±0.77	0.69 ±0.2	1.5 ±0.34	0.37 ±1.75	1.75 ±0.36	0.31 ±0.18	2.13 ±0.35	0.31 ±0.2	1.75 ±0.53	0.38 ±0.18	0.06* ±0.06	17.5 ±2.52
Conventional	0.94 ±0.25	0.31 ±0.12	2.63 ±0.52	3.25 ±0.79	0.25 ±0.11	1.25 ±0.48	0.41 ±1.81	1.81 ±0.49	1.13 ±0.38	2.19 ±0.34	1.38 ±0.36	2.13 ±0.67	1.31 ±0.41	0.88 ±0.22	22.5 ±3.89
Fertility management															
Organic	1.0* ±0.27	0.31 ±0.12	2.56 ±0.49	4 ±0.93	0.69* ±0.19	0.46 ±0.44	2.31 ±0.38	2.06* ±0.38	1 ±0.38	2.31 ±0.29	0.44 ±0.26	1.69 ±0.51	0.5 ±0.24	0.5 ±0.21	21.44 ±0.94
Conventional	0.44 ±0.13	0.25 ±0.11	2.5 ±0.41	2.32 ±0.50	0.25 ±0.11	0.36 ±1.25	2.13 ±0.41	1.5 0.47	0.44 ±0.18	2 ±0.4	1.25* ±0.35	2.19 ±0.68	1.19 ±0.29	0.44 ±0.18	18.56 ± 0.5

Significantly higher means are indicated by: $^{*}P \leq 0.05$, $^{**}P \leq 0.01$, $^{***}P \leq 0.001$.

Table 4. Means (± standard errors) of weed functional groups in Study 1 in August 2008 showing significant main effects of crop type, crop protection and fertility management.

Functional group	Summer annual ratio	Winter annual ratio	Annual ratio	Perennial ratio	Mycorrhizal ratio	Competitor radius value	Seed bank regeneration value	Ellenberg light value	Ellenberg reaction relative value	Ellenberg nitrogen relative value	Seed bank persistence value
Crop type											
Cabbage	0.95*** ±0.04	0.39 ±0.17	0.95 ±0.02	0.09 ±0.02	0.58* ±0.02	1.23 ±0.04	0.96*** ±0.01	6.81** ±0.09	6.5** ±0.11	6.66** ±0.07	0.82** ±0.01
Potato	0.71 ±0.06	0.37 ±0.05	0.97 ±0.01	0.05 ±0.02	0.48 ±0.05	1.03 ±0.09	0.71 ±0.06	5.13 ±0.46	5.04 ±0.43	5.03 ±0.44	0.62 ±0.06
Crop protection											
Organic	0.8 ±0.07	0.38 ±0.04	0.97 ±0.02	0.04 ±0.02	0.47 0.04	1.03 ±0.08	0.8 ±0.07	5.57 ±0.46	5.38 ±0.43	5.51 ±0.45	0.69 ±0.06
Conventional	0.87 ±0.04	0.38 ±0.03	0.95 ±0.02	0.11 0.02	0.6 ±0.03	1.22 ±0.07	0.87 ±0.04	6.36 ±0.29	6.17 ±0.25	6.18 ±0.26	0.76 ±0.03
Fertility management											
Organic	0.88 ±0.05	0.38 ±0.04	0.98* ±0.01	0.05 ±0.02	0.57 ±0.04	1.13 ±0.06	0.88 ±0.05	6.1 ±0.33	5.99 ±0.31	6.02 ±032	0.75 ±0.04
Conventional	0.79 ±0.06	0.39 ±0.04	0.94 ±0.02	0.09 ±0.02	0.49 ±0.05	1.13 ±0.09	0.79 ±0.06	5.84 ±0.45	5.55 ±041	5.67 ±0.43	0.7 ±0.05

Significantly higher means are indicated by: * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$.

Organic crop protection was generally as effective in controlling weeds as the conventional approach, with the exception of V*eronica persica,* which had significantly higher cover under conventional crop protection (Table 3). However, there was a significant interaction between crop type and crop protection treatment for the proportional cover of annuals (annual ratio; $P<0.05$). Individual species showing this significant interaction were the perennials *Taraxacum officinale* ($P<0.001$) and *Rumex crispus* ($P<0.05$) and the annual *Veronica persica* ($P<0.01$). In all three species cover was significantly higher in cabbages under conventional crop protection than the other three treatment combinations (Figure 2). However, in potatoes cover of *T. officinale* but not the other two species was greater under organic than conventional crop protection.

There was no significant effect of fertility management on total weed cover (Table 3). However, the proportional cover of annuals was significantly greater under organic than conventional fertility management (Table 4), being 98% and 94% respectively. An effect of fertility management was detected for four individual species (Table 3). Of these, only *Sinapis arvensis* had lower cover under organic fertility management, while conventional fertility management significantly increased the cover of *Atriplex patula*, *Lamium purpureum and Polygonum aviculare*.

Although no significant interactions were detected for total weed cover, they were detected for some individual species. There were significant interactions between crop protection and fertility management for *Sinapis arvensis* and *Lamium purpureum* ($P<0.05$). In the case of *Sinapis arvensis*, cover was higher ($P<0.05$) under conventional crop protection and fertility management than the other treatments (Figure 3). In contrast, *Lamium purpureum* had greatest cover under organic crop protection and fertility management (Figure 3).

Study 2

In this study 19 taxa were recorded but 7 were too scarce to analyse individually (*Aethusa cynapium, Artemisia vulgaris, Capsella bursa-pastoris, Epilobium* spp.*, Lolium perenne*, *Sonchus asper, Veronica persica*).

There was no significant effect of crop type on seed bank functional groups (Table 5) but there was a significant effect on seed numbers of two species (Table 6). Seed numbers of *Lamium purpureum* were higher following potato crops than cabbage but the opposite response was observed for *Senecio vulgaris* (Table 6).

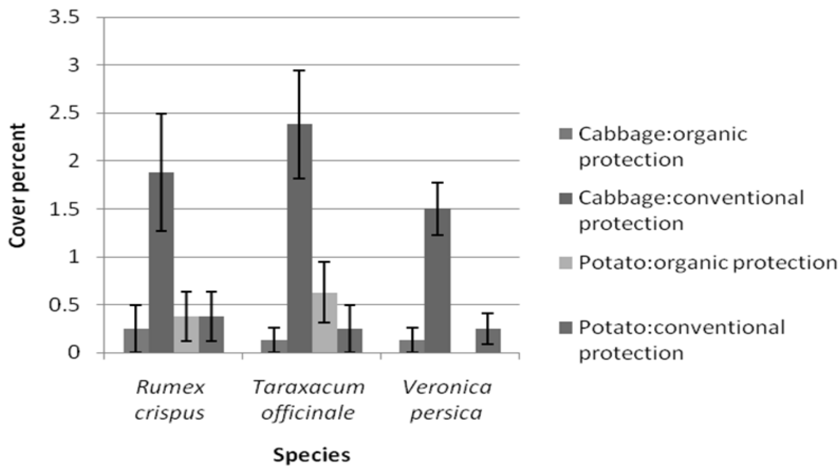

Figure 2. Interaction effect of crop type and crop protection management on cover of three species in study 1 in August 2008.

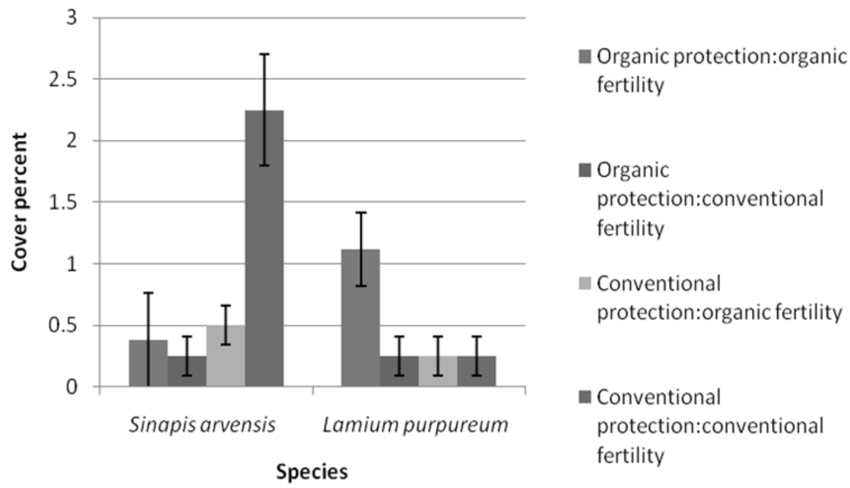

Figure 3. Interaction effect of crop protection and fertility management on cover of *Sinapis arvensis* and *Lamium purpureum* in study 1 in August 2008.

Table 5. Weed species functional groups in the soil seed bank in study 2 in 2009; means (± standard errors) showing significant effects of main effects of previous crop, crop protection and fertility management.

Functional group	Summer annual ratio	Winter annual ratio	Annual ratio	Perennial ratio	Mycorrhizal ratio	Competitor radius value	Seed bank regeneration value	Ellenberg light value	Ellenberg reaction relative value	Ellenberg nitrogen relative value	Seed bank persistence value
Previous crop											
Cabbage	0.49 ±0.04	0.24 ±0.05	0.49 ±0.04	0.37 ±0.04	0.51 ±0.05	1.6 ±0.12	0.83 ±0.05	5.94 ±0.36	5.32 ±0.31	5.61 ±0.34	0.7 ±0.43
Potato	0.45 ±0.04	0.18 ±0.03	0.47 ±0.05	0.41 ±0.03	0.5 ±0.05	1.64 ±0.1	0.81 ±0.05	5.84 ±0.37	5.32 ±0.34	5.51 ±0.36	0.7 ±0.44
Crop protection											
Organic	0.53 ±0.35	0.3 ±0.04	0.56 ±0.03	0.42 ±0.03	0.54 ±0.04	1.79 ±0.08	0.93* ±0.03	6.66* ±0.15	5.95* ±0.11	6.29* ±0.14	0.79* ±0.02
Conventional	0.4 ±0.4	0.12 ±0.02	0.41 ±0.05	0.37 ±0.04	0.5 ±0.05	1.45 ±0.12	0.71 ±0.06	5.13 ±0.41	4.69 ±0.39	4.83 ±0.38	0.61 ±0.05
Fertility management											
Organic	0.45 ±0.04	0.2 ±0.04	0.46 ±0.42	0.39 ±0.03	0.53 ±0.04	1.61 ±0.11	0.81 ±0.05	5.79 ±0.38	5.21 ±0.34	5.45 ±0.36	0.69 ±0.05
Conventional	0.49 ±0.04	0.22 ±0.05	0.5 ±0.05	0.39 ±0.04	0.51 ±0.05	1.64 ±0.1	0.82 ±0.05	5.99 ±0.35	5.44 0.31	5.66 ±0.32	0.71 ±0.04

Significantly higher means are indicated by: * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$.

Table 6. Weed seed bank species in study 2 in 2009; means (± standard errors) showing significant effects of main effects of previous crop, crop protection and fertility management.

Species name	*Chenopodium album*	*Lamium purpureum*	*Matricaria discoidea*	*Persicaria maculosa*	*Poa spp*	*Polygonum aviculare*	*Rumex crispus*	*Rumex obtusifolius*	*Senecio vulgaris*	*Sinapis arvensis*	*Stellaria media*	*Taraxacum officinale*	Total
Previous crop													
Cabbage	3.5 ±0.79	0.19* ±0.14	0.69 ±0.34	1.31 ±0.34	14.81 ±2.86	3.25 ±0.64	0.88 ±0.69	0.25 ±0.11	0.75* ±0.31	1.81 ±0.67	12.69 ±4.55	0.69 ±0.31	42.88 ±7.58
Potato	2.94 ±0.49	1 ±0.29	1.25 ±0.63	1.38 ±0.34	12.5 ±1.86	2.31 ±0.59	0.13 ±0.09	0.19 ±0.1	0.06 ±0.06	2.19 ±0.65	6.06 ±2.65	0.88 ±0.3	32.94 ±4.96
Crop protection													
Organic	3.44 ±0.57	0.81 ±0.29	0.62 ±0.24	1.69 ±0.38	19.2** ±2.02	4.0* ±0.62	0.19 ±0.1	0.25 ±0.11	0.19 ±0.1	3.13 ±0.82	17.1* ±4.61	0.88 ±0.33	53.1** ±6.02
Conventional	3 ±0.73	0.38 ±0.18	1.31 ±0.67	1 ±0.26	8.12 ±1.92	1.56 ±0.46	0.81 ±0.69	0.19 ±0.1	0.62 ±0.32	0.88 ±0.29	1.69 ±0.36	0.69 ±0.29	22.69 ±4.26
Fertility management													
Organic	2.31 ±0.42	0.56 ±0.24	1 ±0.58	1.44 ±0.32	14.13 ±2.72	2.63 ±0.52	0.19 ±0.14	0.25 ±0.11	0.38 ±0.2	2 ±0.75	7.75 ±2.29	0.5 ±0.22	35.25 ±5.15
Conventional	4.13 ±0.76	0.62 ±0.0.26	0.93 ±0.43	1.25 ±0.36	13.19 ±2.1	2.94 ±0.72	0.81 ±0.64	0.19 ±0.1	0.44 ±0.27	2 ±0.6	11 ±4.87	1.06 ±0.36	40.56 ±7.61

Significantly higher means are indicated by: * $P \le 0.05$, ** $P \le 0.01$, *** $P \le 0.001$.

Crop protection treatment affected functional groups of seed bank regeneration, Ellenberg light, reaction and nitrogen values and persistence index of the seed bank (Table 5). Relative values of all these groups were significantly higher under organic crop protection compared with conventional crop protection. Crop protection treatment also affected the total number of seeds (Table 6), with significantly greater numbers of *Poa* spp., *Polygonum aviculare* and *Stellaria media* seeds in organic compared with conventional crop protection.

There were no significant effects of fertilizer treatment on functional groups (Table 5), total seed number or seed number of individual species (Table 6). However, some interaction effects of treatments were detected. The interaction of previous crop and crop protection on winter annual ratio showed that winter annuals were more prevalent following a crop of cabbage under organic crop protection than the other three combinations ($P<0.05$, Figure 4). This was primarily attributable to the effects on the soil seed bank of *Stellaria media* ($P<0.01$), which was greater in cabbage: organic crop protection than the other treatments (Figure 5). However, for this species seed numbers were also higher in potato: organic protection than potato: conventional.

There were significant interactions between previous crop and fertility management for regeneration by seed, Ellenberg nitrogen values and total seed numbers ($P<0.05$). In cabbage: conventional fertility the values were all higher than in cabbage: organic fertility and potato: conventional fertility (Figure 6). There was also a significant interaction for *Rumex obtusifolius* ($P<0.05$), which was absent in the potato: conventional fertility treatment but present in other combinations (Figure 7).

There were significant interactions between crop protection and fertility management for the relative values of perennial and competitor radius ($P<0.05$). The highest values occurred under the combination of organic crop protection and fertility and the lowest values were recorded under conventional protection and organic fertility (Figure 8). This was partly attributable to *Poa* spp. which also showed this response ($P<0.001$, Figure 9).

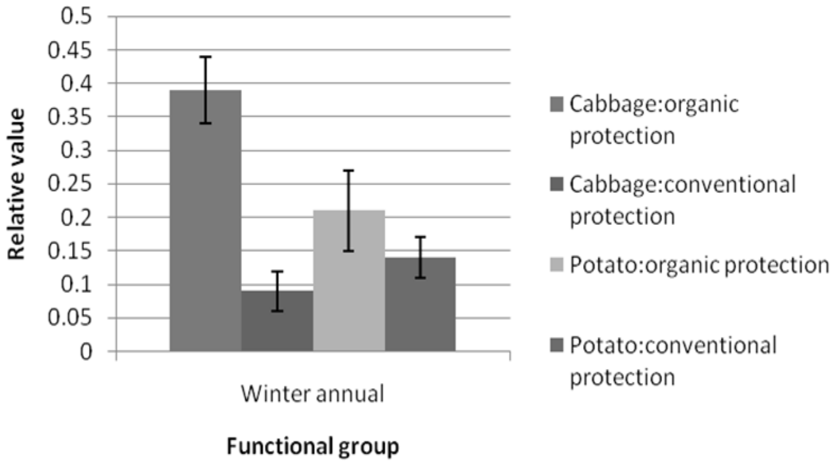

Figure 4. Interaction effect of previous crop and crop protection management on winter annual relative value in the soil seed bank in study 2 in 2009.

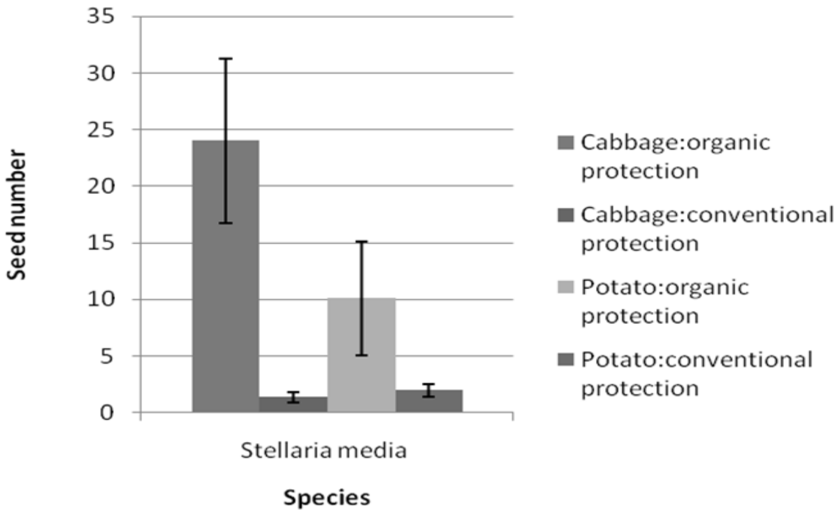

Figure 5. Interaction effect of previous crop and crop protection management on *Stellaria media* seed numbers in the soil seed bank in study 2 in 2009.

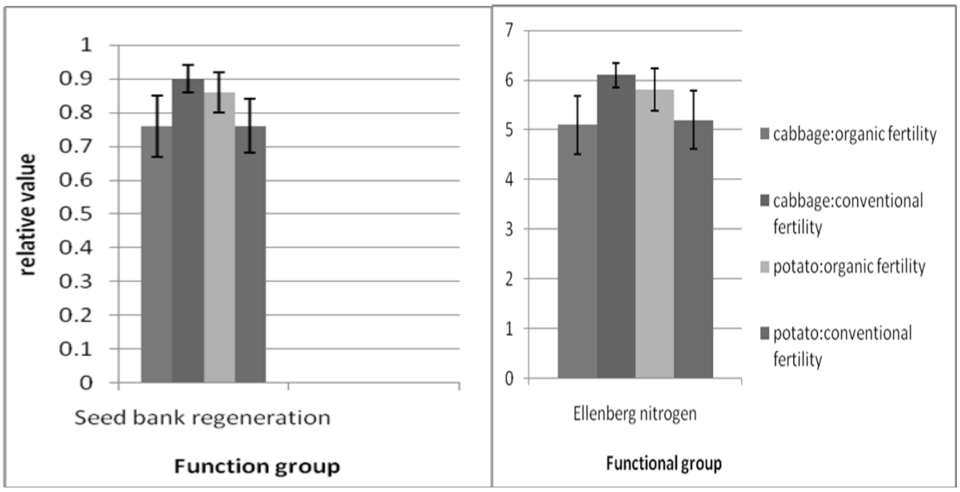

Figure 6. Interaction effects of previous crop and fertility management on regeneration by seed and Ellenberg N values in the soil seed bank in study 2 in 2009.

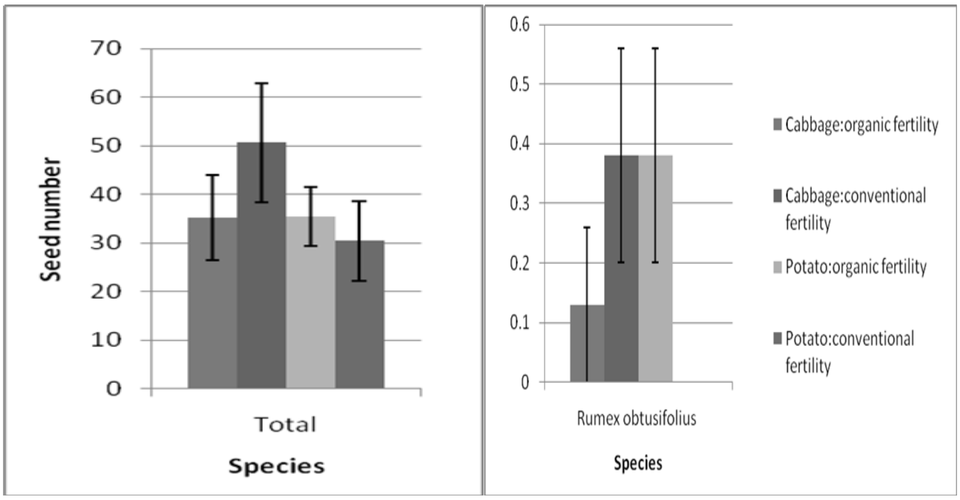

Figure 7. Interaction effects of previous crop and fertility management on total and *Rumex obtusifolius* seed numbers in the soil seed bank in study 2 in 2009.

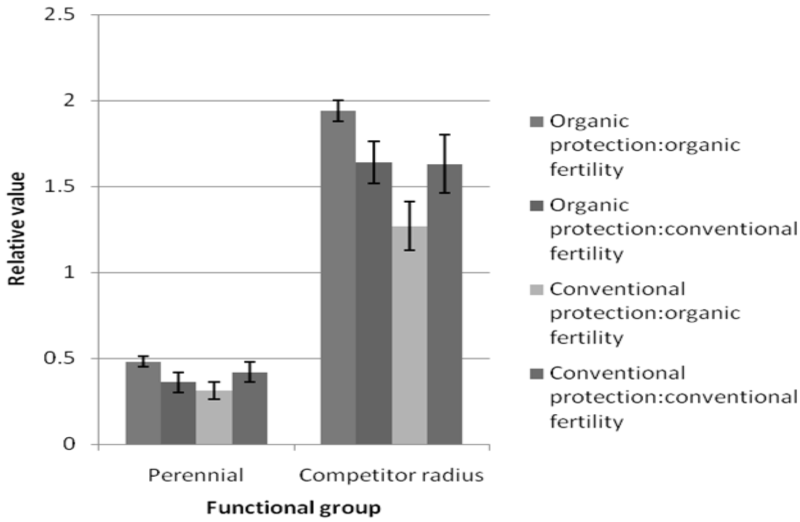

Figure 8. Interaction effects of crop protection and fertility management on perennial ratio and competitor radius in the soil seed bank in study 2 in 2009.

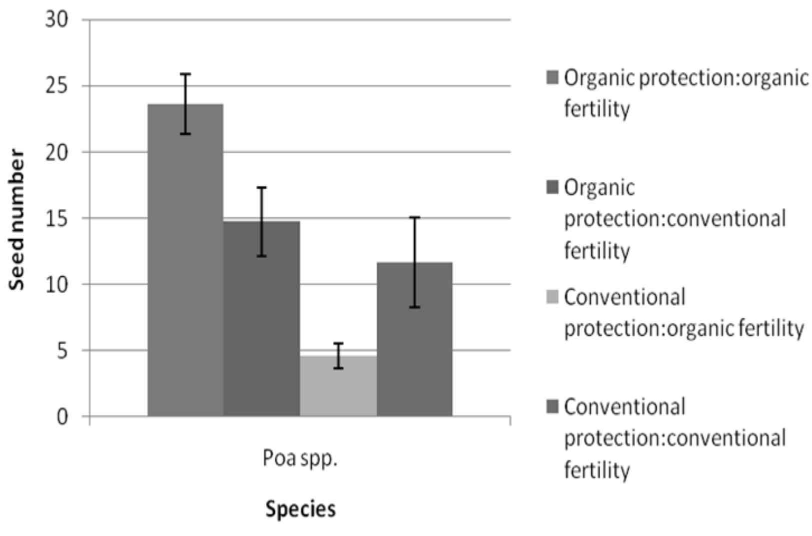

Figure 9. Interaction effects of crop protection and fertility management on *Poa* spp. seed numbers in the soil seed bank in study 2 in 2009.

Discussion

The level of weed cover in a given year was primarily affected by the crop grown. The higher levels of weed cover under the cabbages, regardless of the crop protection treatment, may reflect the intensive weed control under the potatoes, which were ridged three times under conventional crop protection and four times under organic crop protection (Table 1). In contrast, mechanical weed control in cabbages in 2008 was hindered by wet weather. The two studies showed that in spite of the effect of crop type on functional groups of weed species in 2008 (Table 4), this effect was not repeated in the soil seed bank in 2009 (Table 5). Similarly, the cover of many more species was affected by crop type in 2008 than of seed numbers in the seed bank in 2009. Differences in crop height, density and canopy architecture can favour some weed species over others (Leroux et al., 1996) but the weed seed bank is affected more by the crop rotation (Cardina et al., 2002) and the management system applied over a number of years (Davis et al., 2005).

Effects of crop protection treatment on functional group differed in the two studies. The type of crop protection had no significant effect on functional groups based on weed cover measurements taken in 2008 but did affect some functional groups in the seed bank study in 2009. It is possible that in 2008 the type of crop and related cultivations had a large effect which might have masked the effects of crop protection on weed cover. Crop protection treatments were applied for the previous 5 years and had a strong effect on seed bank properties. Repeated mechanical weeding operations under organic crop protection practices selected for species with a persistent seed bank and with seed bank regeneration strategy. This concurs with the findings of Albrecht and Auerswald (2009) who showed that more frequent disturbance favoured species with longer-lived seeds, although conversely, they also showed that organic systems in total selected for species with short-lived seeds. Organic crop protection in our study increased the proportion of species in the seed bank with Ellenberg values for light and fertility, indicating more open conditions under organic crop protection and the presence of more competitive weed species. In contrast, the use of herbicides under conventional protection could have lead to the selection of more herbicide tolerant species. Increases of weed species with high Ellenberg light, reaction and nitrogen values under organic management has been reported in other experiments. For example Hyvonen (2007) reported the species that showed the most rapid recovery after conversion to organic cropping were nitrophilous species that suffered previously from the application of herbicides or species that were tolerant of herbicides. Hyvonen also suggested that the recovery of perennials and non-nitrophilous species will take a longer time. Herbicide tolerant species encounter less competition when the abundance of herbicide-susceptible species has declined (Hume, 1987).

Although fertility management had been applied for 5 years in the experimental plots, these treatments in total had significant effects on cover of only four weed species in 2008. It is interesting to note that for three of these species, cover was higher under organic fertility management (i.e. following compost application). Although it has been suggested that farmyard manure that has not been well composted may contribute to the soil seed bank (Mt. Pleasant and Schlather, 1994), we did not detect any fertility management effects on the seed bank. Another possible explanation could be reduced N availability in the compost-amended plots. Nitrogen is the most important fertilizer that affects the dynamics of weed communities although other nutrients, particularly phosphorus, are also important (Banks et al., 1976; Hoveland et al., 1976; Goldberg and Miller, 1990). Under high nitrogen availability, the abundance or frequency of occurrence of nitrophilous species increases (Haas and Streibig, 1982; Mahn, 1988). However, most of the species present in our study had similar Ellenberg nitrogen values and there was no evidence of fertility management effects on nitrophilous species. The promotion of biomass production of both crops and weeds by increased nitrogen fertilization (e.g Mahn, 1988; Jørnsgård et al., 1996) creates greater competition for light (Haas and Streibig, 1982; Pyšek and Lepš, 1991; Van Delden et al., 2002; Wilson and Tilman, 1991) and favours species with a tall and erect growth form (Pyšek and Lepš, 1991) or physiological shade tolerance (Haas and Streibig, 1982). Again, we found no evidence of this, as the species favoured by organic fertility management did not have notably different canopy heights from the other species (Grime et al., 2007) and the species favoured by conventional fertility management (*Sinapis arvensis*) has a relatively high Ellenberg light value. It is likely, therefore, that the differences in species' responses to fertility management were the result of more subtle differences in the availability of nutrients and their interaction with other factors such as timing of tillage and weather. These effects would not be revealed by Ellenberg nitrogen values, which are a relatively crude indicator of species' associations with overall soil fertility.

However in our experiment fertility management in interaction with other treatments also had some small effects on the soil seed bank. The factorial design of this experiment allowed us to detect an additive effect of organic fertility management and crop protection practices on the perennial ratio and competitor radius value (Figure 8). Organic fertility management and crop protection acted together to increase these two functional groupings in the soil seed bank in comparison with other treatment combinations and a similar effect was seen on *Poa* spp. L. (Figure 9). The likely explanation for this is that many perennial species are able to regenerate vegetatively from root fragments that survive and are dispersed by, mechanical weed control. In addition, nutrients are released more gradually from organic compost than from inorganic fertilizer and become available over a longer period of time, which perennials are more able to exploit than annuals. Over a number of years, this would allow the seed bank of competitive perennial species to develop. Other studies have shown varying effects of organic management on seed bank properties. For example, Albrecht (2005) found that perennials increased but also summer annuals and dicotyledonous species. In contrast, other studies have shown that the seed bank in organic systems is dominated by annuals (Menalled et al., 2001; Davis et al., 2005) even although in one case perennial species were co-dominant in the weed community itself (Menalled et al., 2001). Our study suggests that under long-term organic management, perennial weeds might become a problem and to our knowledge, additive effects of organic practices have not been demonstrated previously.

Marshall et al. (2003) evaluated the role of common weeds in supporting the biodiversity of arable fields and listed nine weed species important for in-field biodiversity. Three of those species (*Chenopodium album*, *Poa* spp. and *Stellaria media*) had greater cover in our organic protection plots and the latter two also in the seed bank. This suggests that organic crop protection within farming systems may provide a useful ecosystem service in sustaining in-field biodiversity of arable plants.

Conclusions

These studies have shown that within an organic rotation, the crop grown in a particular year has the greatest effect on the weed community that establishes in that year; however, over the long-term, seed bank properties are predominantly affected by crop protection practices. Functional groups such as seedbank regeneration, Ellenberg light, reaction and nitrogen and seed bank persistence, were all enhanced by organic crop protection practices.

The use of organic fertility management practices also promoted certain weed species in the year of application. Organic systems therefore have both short-term and longer-term effects on the weed community, which are attributable primarily to the crop protection practices, with fertility management having much less influence. These will have immediate and longer-term consequences for both biodiversity and weed management strategies.

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