Crop Protection 98 (2017) 16–23

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

Control of perennial weeds in spring cereals through stubble cultivation and mouldboard ploughing during autumn or spring

L.O. Brandsæter [a, b, *], K. Mangerud [b], M. Helgheim [b], T.W. Berge [b]

[a] Norwegian University of Life Sciences (NMBU), Faculty of Biosciences, Department of Plant Sciences, P.O. Box 5003, NO-1432 Ås, Norway
[b] Norwegian Institute of Bioeconomy Research (NIBIO), Division of Biotechnology and Plant Health, P.O. Box 115, NO-1431 Ås, Norway

A R T I C L E I N F O

Article history:
Received 31 May 2016
Received in revised form
7 March 2017
Accepted 9 March 2017
Available online 18 March 2017

Keywords:
Weed control
Cirsium arvense
Elymus repens
Sonchus arvensis
Stachys palustris
Soil tillage

A B S T R A C T

Creeping perennial weeds are of major concern in organically grown cereals. In the present study, the effects of different timing of mouldboard ploughing with or without a preceding stubble cultivation period, on weeds and spring cereals were studied. The experiments were conducted at two sites in Norway during a two and three-year period, respectively, with the treatments repeated on the same plots. The soil cultivation treatments were a stubble disc-harrowing cultivation period followed by mouldboard ploughing and only mouldboard ploughing. The timing of the treatments were autumn or spring. The density and biomass of the aboveground shoots of *Cirsium arvense* (L.) Scop., *Elymus repens* (L.) Gould, *Sonchus arvensis* L. and *Stachys palustris* L. as well as the total aboveground biomass of the spring cereal crop (oats) were assessed. The control efficiency of *C. arvense* and *S. arvensis* was closely related to timing of the cultivation treatments. Cultivation in spring decreased the population of *C. arvense* and *S. arvensis* compared to autumn cultivation. For *E. repens*, timing of the treatments had no significant effect: the important factor was whether stubble cultivation was carried out (best control) or not. The overall best strategy for controlling the present perennial weed population was stubble cultivation followed by ploughing in spring. However, the associated relative late sowing of the spring cereal crop and lowered crop biomass, were important drawbacks.

1. Introduction

Cirsium arvense (L.) Scop. (Creeping thistle, Canada thistle) and other creeping perennial weeds such as *Elymus repens* (L.) Gould (Common coach-grass) are of major concern in organically grown cereals in the Nordic countries (Salonen et al., 2001) and elsewhere (e.g. Bacher et al., 1997; Cormack, 1999). In conventional farming in Norway, *E. repens* is normally controlled by glyphosate application pre-harvest in ripe barley or post-harvest in (all cereal species) stubble. Broad-leaved species such as *C. arvense* and *Sonchus arvensis* L. (Perennial sow-thistle), on the other hand, are typically controlled by post emergence application of phenoxy herbicides.

In a survey in Finland the total weed biomass in spring cereals was four times higher in organic versus conventional farming. Salonen et al. (2011) claimed that weed management in organic cropping calls for urgent measures such as direct mechanical weed control in crops stands. Although hardly used among farmers in the Finnish study, flex-tine weed harrowing is one the most widely used mechanical methods for control of weed seedlings in organically grown cereals (Armengot et al., 2013). Direct mechanical weed control against perennial weeds (in crop stands), as hoeing, are not so common in the Nordic countries, but provides promising results especially in combination with other cultural methods (Melander et al., 2005). The interest for this measure is growing. Both for preventing huge problems with creeping perennial weeds in organic farming, as well as decreasing the use of herbicides in conventional and integrated farming, there is a need for optimizing the soil tillage operations.

Numerous studies in conventional farming (e.g. Ekeberg et al., 1985; Håkansson et al., 1998) have shown that mouldboard ploughing gives a significant control of perennial weeds. Additionally, there is general agreement that effectiveness increases with the depth of mouldboard ploughing (e.g. Børresen and Njøs, 1994; Håkansson et al., 1998). The main consideration determining the minimum acceptable ploughing depth should be related to weed control, especially of perennials (Kouwenhoven

* Corresponding author. Norwegian Institute of Bioeconomy Research (NIBIO), Division of Biotechnology and Plant Health, P.O. Box 115, NO-1431 Ås, Norway.
E-mail address: lars.olav.brandsaeter@nibio.no (L.O. Brandsæter).

http://dx.doi.org/10.1016/j.cropro.2017.03.006

et al., 2002). To exemplify the effect of ploughing depth (conducted in spring), shoot numbers of *E. repens* and *S. arvensis,* as well as the total above-ground perennial weed biomass, were around 50% lower with deep (25 cm) compared to shallow (15 cm) ploughing (Brandsæter et al., 2011). The greatest advantage of deep ploughing was the control of *C. arvense*, which in some cases was reduced by more than 90% compared to shallow ploughing. This significant effect of ploughing depth on *C. arvense* may indicate that most shoots arise from the intact root system below the mouldboard plough depth, and not from root fragments. This may again indicate that spring ploughing is more detrimental than autumn ploughing for this species. If the most competitive shoots come from below the ploughing depth and deep ploughing is performed in spring, and the crop is sown shortly after ploughing, spring ploughing may significantly decrease the competitive ability of *C. arvense*.

In the studies of Permin (1961) and Brandsæter et al. (2012) stubble cultivation by shallow ploughing before harrowing in the autumn, gave generally the best control of perennial weeds. In the latter study, however, stubble cultivation by rotary tillage gave similar control as shallow ploughing plus harrowing. Shallow ploughing used for stubble treatment followed by another shallow treatment in late autumn has proven very effective in controlling *C. arvense* (Gruber and Claupein, 2009). Also Melander et al. (2012) concluded that intensive post-harvest cultivation followed by deep inverting tillage control perennial weeds effectively on sandy soils. The efficacy, however, may differ between weed species. Brandsæter et al. (2012) showed generally low effect of stubble treatment in autumn on *S. arvensis* compared to *E. repens*, because *S. arvensis* had probably developed bud dormancy at the time of cultivation (Brandsæter et al., 2010). *S. arvensis* may be better controlled by disturbance, as harrowing and ploughing, in spring because effective depletion is connected to seasons when regrowth is not restricted by physiological dormancy, temperature or drought (Håkansson, 2003). More recently, Ringselle et al. (2016) studied the effect of timing and repetitions of cultivation in autumn on *E. repens*. They concluded that a few days delay in tine cultivation did not reduce the control of *E. repens* compared to such cultivation immediately after crop harvest. A delay by 20 days, however, decreased control efficiency. Furthermore, their study showed that repeated tine cultivation did not improve weed control compared to one cultivation. Although most attention has been given to perennial weeds, stubble cultivation may also decrease annual weed populations (Pekrun and Claupein, 2006).

Very few studies have focused on the effects of timing of stubble cultivation and ploughing on weed growth. Njøs and Ekeberg (1980) found approximately equal effects of ploughing in autumn versus spring on *E. repens*. Agricultural advisers in the Nordic countries claim that spring ploughing gives better control of *C. arvense* and *S. arvensis* than autumn ploughing (Pedersen and Gustavsson, 2003).

Improved weed control from spring tillage will reduce both the need for herbicides in conventional farming and the requirement for mechanical weed control in organic and integrated cropping. Furthermore, methods like hoeing (inter-row cultivation) and frequently mowing of annual green manure lays for weed management may have unwanted effects regarding labour input, land use and energy consumption. For example, the use of green manure crops has under certain circumstances caused N losses, especially in systems that have large amounts of fresh plant material on the surface during winter (Korsæth and Eltun, 2008). Furthermore, spring tillage will give less soil erosion and nutrient leakage from fields than autumn tillage (Ulén et al., 2010). The following arguments against spring ploughing are often given by farmers (who traditionally plough in autumn) (i) ploughing in spring delays sowing as it entails more work at a busy time, (ii) ploughing heavy soils in spring results in a poor seedbed due to greater cloddiness, and (iii) ploughing in spring may hamper capillary rise, which can be a disadvantage under dry conditions.

The present study addresses the following hypotheses: (1) For the control of *C. arvense* the season – autumn vs. spring - of ploughing is more important than whether stubble cultivation is carried out or not, and spring ploughing gives the best control. (2) *S. arvensis* is better controlled by spring- than autumn ploughing, and stubble cultivation in spring will improve the control. (3) For the control of *E. repens*, stubble cultivation prior ploughing is the crucial aspect, while season – autumn vs. spring - of the cultivation is of no significance.

2. Material and methods

2.1. Study sites, experimental design and treatments

The study was located at two sites in SE Norway: (i) the Norwegian University of Life Sciences (NMBU), Ås (59°40′N, 10°46′E, 90 m above sea level) with a sandy loam soil (USDA Soil Survey classification), and (ii) Øsaker, Grålum (59°23′N, 11°02′E, 40 m above sea level) with imperfectly drained clay loam classified as Luvic Stagnosol (Clayic) (World Reference Base, 2006). Prior to the experiments, both fields had been farmed organically for a number of years, mainly with cereal crops.

The trials at Ås and Øsaker were initiated in autumn 2007 and 2008, respectively, and continued until August 2010 at both locations. Trials were designed as randomized block experiments. The four different weed control treatments were built up by two factors (i) soil cultivation and (ii) timing of the cultivation, both with two levels. The soil cultivation levels were (i) a stubble disc-harrowing cultivation period followed by mouldboard ploughing, and (ii) only mouldboard ploughing. Levels of timing of the cultivation was (i) autumn or (ii) spring. Crop was always sown in spring. The four weed control combinations were: stubble cultivation before ploughing in spring (SCPS) or autumn (SCPA) and only ploughing in spring (PS) or autumn (PA). Individual plot size was 5 by 9 m, and each treatment was replicated five (Ås) or four (Øsaker) times. Treatments were repeated on the same plots for 3 years at Ås (autumns 2007–2009 or springs 2008–2010) and 2 years at Øsaker (autumns 2008 and 2009 or springs 2009 and 2010) (Table 1).

The stubble cultivation period consisted of harrowing one pass at 8–10 cm depth, once or twice during autumn or spring, depending on date of cereal harvest (in autumn), weather conditions (Table 2) and whether the perennial weed species reached the growth stage of their compensation point (Håkansson, 2003: *E. repens* 3–4 leaf stage, *C. arvense* 4–7 leaf stage and *S. arvensis* 5-7 leaf stage; Korsmo et al., 2001: *S. palustris* ≈ 6 leaf stage). The compensation point may be defined as the stage where the sink-source dynamics of carbohydrate reserves shifts from the underground organs as the source and aboveground organs as the sink, to the opposite (Håkansson, 2003). Two disc harrow operations in autumn or spring were planned, but this had to be changed to one operation in some cases due to late harvesting and unfavourable weather conditions (Table 1). The harrowing was done when the soil was considered dry enough, by kneading the soil (to 10 cm depth) in the hand and evaluating whether the soil crumbled.

The stubble cultivation was carried out with a Väderstad "Carrier Disc harrow" (http://www.vaderstad.com/en/products/cultivation/carrier_carrierx, accessed 07.03.2017) with working width 5 m at Ås and with a Kverneland Disc harrow with 32 discs with working width 3 m at Øsaker. A Dyna Drive (http://www.bomford-turner.com/cultivation/_product/1/dyna-drive/, accessed 07.03.2017), a ground-driven rotary surface cultivator with working width 3 m, was used to 12–15 cm working depth prior to disc-

Table 1
Dates for management and assessment operations in the two experimental sites. Perennial weed control treatment were stubble cultivation period before ploughing in spring (SCPS), stubble cultivation period before ploughing in autumn (SCPA), only ploughing in spring (PS) or only ploughing in autumn (PA).

	2007	2008	2009	2010
Site Ås				
Disc harrowing #1 (SCPS)		26 April	6 May	
Ploughing (PS)		5 May	5 May	3 May
Seedbed preparation, fertilizing, sowing cereals (SCPA-PA-PS)		6 May	6 May	4–6 May
Disc harrowing #2, ploughing (SCPS)		15 May	25 May	31 May
Seed bed prep., fertiliz., sowing (SCPS)		15 May	25 May	1 June
Main weed assessment (all)		19–26 Aug	10–12 Aug	13–16 Aug
Grain harvesting (all)		15 Aug	3 Sep	9 Sep
Mowing, 5 cm (all)	3 Sep	18 Sep	16 Sep	
Disc harrowing #1 (SCPA)	7 Sep	26 Sep	23 Sep	
Disc harrowing #2 (SCPA)	10 Oct	–	–	
Ploughing (SCPA-PA)	23 Nov[a]	17 Nov	1 Nov	
Site Øsaker				
Disc harrowing #1 (SCPS)			27 April[b]	21 April[b]
Ploughing (PS)			22 April	19 April
Seed bed preparation, fertilizing, sowing cereals (SCPA-PA-PS)			23 April	21 April
Disc harrowing #2, ploughing (SCPS)			15 May	11 May
Seed bed prep., fertiliz., sowing (SCPS)			15 May	12 May
Main weed assessment (all)			18 Aug	11 Aug
Grain harvesting (all)			9 Sep	7 Sep
Disc harrowing #1 (SCPA)		24 Sep[b]	30 Sep	
Disc harrowing #2 (SCPA)		–	20 Oct	
Ploughing (SCPA-PA)		31 Oct	22 Oct	

[a] Late ploughing because of frozen soil earlier this autumn.
[b] Harrowed with DynaDrive before disc harrowing.

Table 2
Weather data for the two experimental sites. Mean air temperature (°C) and total precipitation (mm) per month in autumn and spring during the experimental period. The corresponding values for the normal period 1961–1990 in parentheses.

	Autumn 2007		Spring 2008		Autumn 2008		Spring 2009		Autumn 2009		Spring 2010	
	Sep	Oct	April	May	Sep	Oct	April	May	Sep	Oct	April	May
Temperature												
Site Ås	10.0 (10.6)	5.4 (6.2)	6.0 (4.1)	11.0 (10.3)	10.1 (10.6)	6.7 (6.2)	6.8 (4.1)	10.9 (10.3)	12.0 (10.6)	3.3 (6.2)	5.0 (4.1)	9.6 (10.3)
Site Øsaker					10.7 (11.4)	7.7 (7)	7.3 (4.6)	11.2 (10.4)	12.7 (11.4)	4.1 (7)	5.3 (4.6)	9.8 (10.4)
Precipitation												
Site Ås	77 (90)	33 (100)	67 (39)	30 (60)	60 (90)	161 (100)	41 (39)	56 (60)	28 (90)	56 (100)	31 (39)	96 (60)
Site Øsaker					66 (94)	147 (109)	27 (42)	61 (58)	68 (94)	80 (109)	40 (42)	47 (58)

harrowing at Øsaker.

All treatments ended by mouldboard ploughing (ploughing depth 23–25 cm) with a reversible mouldboard plough equipped with a disc coulter and skimmer. At Ås, a spring-tine cultivator equipped with an under-beam leveller, was used in spring. At Øsaker, the plots were levelled with a separate under-beam leveller, followed by harrowing before sowing. At Ås and Øsaker, respectively, plots were sown with organically certified oat cv. Hurdal (225 kg ha^{-1}, equivalent to 636 kernels m^{-2}) and cv. Belinda (225 kg ha^{-1}, equivalent to 545 kernels m^{-2}) all experimental years, with a row spacing of 12.5 cm, immediately after spring-tine harrowing in late April or early May, depending on the weather conditions (Table 1).

All plots were fertilized with 625 kg ha^{-1} dried chicken manure ("Marihøne Plus" 8 (% N) - 4 (% P) −5 (% K)), which corresponds to 50 kg N ha^{-1}, prior to harrowing with the spring tine cultivator for seedbed preparation. No weed control or other treatments were carried out between sowing and harvest. After the harvest and the main weed assessment in August (described below), the remaining aboveground vegetation in the field was removed by a combine harvester.

2.2. Weed and crop assessments

Weed shoot density and aboveground weed biomass per species and crop biomass were assessed before harvest (Table 1) in two randomly placed 1 m^2 quadrats per plot each year. Plants were cut 5 cm above the soil surface, simulating cutting at crop harvest. The biomass samples were dried at 70 °C for 72 h to determine the dry weight. All data were calculated to density (shoots m^{-2}) and aboveground dry matter (DM) (g m^{-2}) before statistical analysis.

2.3. Data analyses

The statistical data analysis was conducted with the MIXED procedure of SAS (SAS release 9.3). The initial analysis of variance indicated a significant site effect. Thus, datasets were analysed separately for each site. Since weed assessments were taken in successive years at the same plots, a repeated measurement mixed model was used to account for the serial correlations between weed observations at the successive times within each plot. Two serial structures for the correlations were considered, unstructured (un, in SAS) and first-order autoregressive [ar (1), in SAS] structure. The final model was chosen based upon the information criteria of Akaike (AIC) and Schwarz Bayesian (BIC). The data was analysed as if they were subjected to four independent weed control treatments because the time of ploughing and crop sowing differed between the two "levels" of the factor soil cultivation. Weed control treatments were treated as a fixed factor. Year was considered fixed because years were consecutive years. Hence, the measured responses - the perennial weeds in particular - were dependent across years. The initial perennial weed densities before onset of the experiments were taken into account in the statistical analysis using the initial density as covariates. At Ås, the initial weed density per species was taken from the final weed registration in a previous experiment on the same plots two years prior to the onset of the present study (August 2006). At Øsaker, the initial weed densities, except *E. repens*, were recorded just before the experiment started (5 September 2008). Because three perennial weed species co-occurred within the individual plots at site Ås and thus may have exerted interspecific competition, a second covariate, 'the present biomass of the two other weed species', was included in the statistical model (cf. Table 3). Specific contrasts were established to test differences between groupings of treatments using the CONTRAST statement of MIXED. The groupings tested were autumn vs. spring cultivation and with vs. without stubble cultivation. Assumptions for the statistical models used (normally distributed and independent experimental errors with homogeneity of variances and no outliers) were checked with visual inspection of standardized residuals plots; including normal probability plots and residuals versus fitted values of the response variables (y). Heterogeneous variances were removed through transformation of the response variables by square root or $\log_{10}$ (y+1) prior to the analysis when necessary. Tukey-Kramer multiple comparison tests, at 5% level of significance, were used to separate the least squares (LS) means or contrast of the response variables.

3. Results

3.1. Weeds

E. repens density was high before onset of the experiment at site Ås, on average 44.5 shoots m^{-2}. Weed control treatment, as well as the interaction between treatment and year, were significant for both dry matter (DM) and density at Ås (Table 3). Treatments including stubble cultivation (SCPA and SCPS) showed the lowest values for both DM and shoot density all years (Fig. 1) but significant differences of DM were only found between SCPS and PS the two last experimental years, and between SCPS and PA the last year (data not shown). The results for density were more or less the same (Fig. 1). Stubble cultivation in spring showed lower DM and density compared to both PS and PA (Table 5). Treatments including stubble cultivation gave lower DM and density than ploughing without stubble cultivation in spring. Grouping and comparing the two treatments with and without stubble cultivation showed that stubble cultivation decreased both DM and density of *E. repens*. Season of the weed control treatments did not influence DM or density of *E. repens* (Table 3, Contrasts). At Øsaker, where the *E. repens* infestation was low, no significant differences neither for DM or shoot density were found (results not shown).

C. arvense density was 5.2 *C. arvense* shoots m^{-2} before onset of the experiment at site Ås. There were significant effects of weed control treatment for both DM and density (Table 3; Fig. 1). The spring treatments decreased both DM and density compared to autumn treatments (Table 3, Contrasts). PS, but not SCPS, showed lower DM compared to both autumn treatments (Table 5). The number of thistle plants was highest after PA, but only significantly different from PS. At Øsaker, the mean field density was only 0.016 *C. arvense* shoots m^{-2} before the onset of the experiment. As with *E. repens* at this site, neither stubble cultivation nor timing influenced the shoot number or DM (results not shown).

S. arvensis density was 13.8 shoots m^{-2} before onset of the experiment at site Ås. The mean values of shoot density and DM were lowest for PS and SCPS (Fig. 1), but only significant for DM after SCPS compared to the two autumn treatments (Table 5). However, grouping and comparing the timing of treatments showed that weed control in spring gave significantly lower mean values of both *S. arvensis* DM and density compared to autumn treatments (Table 3, Contrasts; Table 5). At Øsaker, where the mean initial density was only 0.002 shoots m^{-2}, no differences were found between the different weed control strategies for *S. arvensis* (results not shown).

S. palustris was not present at Ås. At Øsaker, the mean initial density of *S. palustris* was low (0.207 shoots m^{-2}). Although stubble cultivation appeared to suppress the density of this weed species (Fig. 1), present data gave no statistically significant influence of either SCPS or SCPA in terms of DM or shoot density (Table 4).

For the total DM of perennial weeds at Ås, present results indicate that stubble cultivation prior to mouldboard ploughing in spring (SCPS) gave the best control, but no significant differences between the four weed control treatments were detected (Table 5). Grouping the treatments according to with and without stubble cultivation or by season, showed, however, that stubble cultivation and treatments done in spring decreased the total DM of the weeds

Table 3
ANOVA table with *P*-values for the four weed control treatments and their contrasting groupings for site Ås. Treatment to control perennial weeds were either stubble cultivation before ploughing in spring (SCPS), stubble cultivation before ploughing in autumn (SCPA), only ploughing in spring (PS) or only ploughing in autumn (PA).

Fixed factors	Response variable (y)							
	Elymus repens		*Cirsium arvense*		*Sonchus arvensis*		All weeds	Crop
	DM m^{-2}	shoots m^{-2}	DM m^{-2}	shoots m^{-2}	DM m^{-2}	shoots m^{-2}	DM m^{-2}	DM m^{-2}
Start[a], shoots m^{-2}	0.0127*	0.0057**	0.2510ns	0.3547ns	0.1576ns	0.0280*	0.0347*	0.05602ns
Other weeds[b], g m^{-2}	0.2958ns	0.5133ns	0.3014ns	0.6237ns	0.9812ns	0.4779ns	–	–
Year	0.3770ns	<0.0001***	0.0638ns	0.0685ns	0.0336*	0.0005***	0.0747ns	<0.0001***
Treatment	0.0024**	0.0032**	0.0410*	0.0331*	0.0314*	0.1780ns	0.0809ns	0.0073**
Year × Treatment	0.0006***	0.0367*	0.1464ns	0.1760ns	0.0959ns	0.1942ns	0.2091ns	0.0610ns
Transformation of y	square root		$\log_{10}$ (y+1)		$\log_{10}$ (y+1)		–	–
Type[c]	un		ar (1)		un		un	un
Contrasts								
Autumn vs. spring cultivation	0.6815ns	0.7428ns	0.0280*	0.0189*	0.0053**	0.0407*	0.0035**	–
With vs. without stubble cultivation	0.0005***	0.0008***	0.8769ns	0.1184ns	0.3852ns	0.4706ns	0.0392*	–

*significant at P < 0.05, **significant at P < 0.01, ***significant at P < 0.001, ns not significant.
[a] The density of the actual weed species before initiating the experiment was included as a covariate.
[b] To uncover possible inter-specific interactions, the total dry-matter of the shoots of the two other perennial weed species was included as a covariate.
[c] Two serial structures for the correlations were considered, unstructured (un, in SAS) and first-order autoregressive (ar (1), in SAS) structure. The final model chosen was based upon the information criteria of Akaike (AIC) and Schwarz Bayesian (BIC).

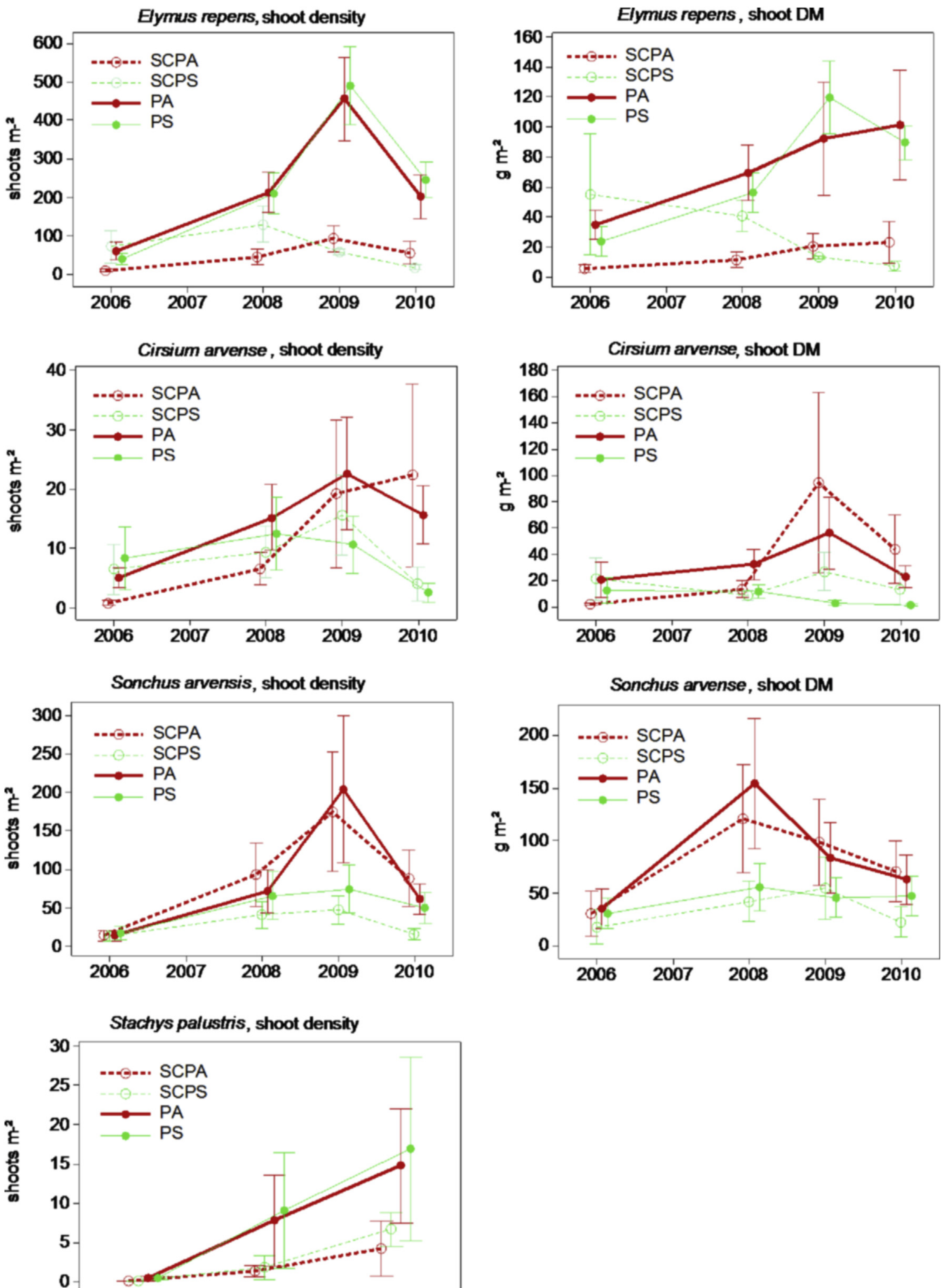

Fig. 1. Year to year changes in perennial weed populations. Mean number and dry-matter (DM) of shoots m^{-2} per year and weed control treatment of *E. repens*, *C. arvense*, *S. arvensis* at site Ås, and mean number of shoots m^{-2} of *Stachys palustris* at site Øsaker. Weed assessments were taken just prior cereal harvest. SCPA: stubble cultivation before mouldboard ploughing in autumn; SCPS: stubble cultivation before mouldboard ploughing in spring; PA: only mouldboard ploughing in autumn; PS: only mouldboard ploughing in spring; vertical interval bars: ± 1 SE.

Table 4
ANOVA table with *P*-values for site Øsaker. Treatment to control perennial weeds were either stubble cultivation before ploughing in spring (SCPS), stubble cultivation before ploughing in autumn (SCPA), only ploughing in spring (PS) or only ploughing in autumn (PA).

Fixed factors	Response variable (y)			
	Stachys palustris		All weeds	Crop
	DM m^{-2}	shoots m^{-2}	DM m^{-2}	DM m^{-2}
Start[a], shoots m^{-2}	0.001**	<0.0001***	0.0261*	0.5768ns
Year	0.0027**	0.0084**	0.0024**	<0.0001***
Treatment	0.5814ns	0.9466ns	0.8820ns	0.0536ns
Year × Treatment	0.4377ns	0.7629ns	0.7532ns	0.0348*
Type[b]	ar (1)	un	un	un

*significant at P < 0.05, **significant at P < 0.01, ***significant at P < 0.001, ns not significant.
[a] The density of *S. palustris* before initiating the experiment was included as a covariate.
[b] Two serial structures for the correlations were considered, unstructured (un, in SAS) and first-order autoregressive (ar (1), in SAS) structure. The final model chosen was based upon the information criteria of Akaike (AIC) and Schwarz Bayesian (BIC).

Table 5
Effect of the four weed control treatments on the perennial weeds and crop for site Ås. Mean dry-matter (DM) or number of shoots m^{-2} for weeds and crop averaged over all experimental years and four weed control treatments. Weed assessments were taken just prior cereal harvest. SCPA: stubble cultivation before ploughing in autumn; PA: ploughing in autumn; SCPS: stubble cultivation before ploughing in spring; PS: ploughing in spring.

Treatment	*Elymus repens*		*Cirsium arvense*		*Sonchus arvensis*		All weeds	Crop
	DM m^{-2}	shoots m^{-2}	DM m^{-2}	shoots m^{-2}	DM m^{-2}	shoots m^{-2}	DM m^{-2}	DM m^{-2}
SCPA	30.5 bc	101.6 bc	32.9 a	11.8 ab	97.7 a	119.8 a	176.7 a	5647.8 ab
PA	82.7 ab	274.5 ab	36.5 a	17.7 a	101.4 a	113.5 a	220.8 a	4719.3 a
SCPS	11.2 c	38.7 c	21.4 ab	11.0 ab	41.7 b	36.3 a	68.2 a	4255.8 a
PS	90.4 a	321.3 a	17.6 b	11.6 b	44.7 ab	57.7 a	143.1 a	6349.4 b

Values with the same letters are not significantly different at the 5%-level.

(Table 3, Contrasts; Table 5). At Øsaker, no significant effects of either stubble cultivation or timing on the total DM of perennial weeds (dominated by *S. palustris*) were detected (Table 4).

3.2. Crop

The factor treatment had a significant effect on crop DM at site Ås (Table 3), but not site Øsaker (Table 4). At Ås, PS gave significantly higher crop DM than SCPS and PA, but not SCPA (Table 5).

4. Discussion

The perennial weed species in our study, *C. arvense, S. arvensis, E. repens* and *S. palustris*, can be divided in two main groups regarding their response to tillage. The first wherein timing (season) of tillage is most important (*C. arvense; S. arvensis*) and the second in which inclusion of stubble cultivation (*E. repens*) seems to be the most crucial factor. Although not supported by the present data, it seems like *S. palustris* belongs to the same group as *E. repens*.

C. arvense and *S. arvensis* are representatives for the group in which season of tillage was of crucial importance. Soil cultivation in the spring gave significantly better control of *C. arvense* compared to similar soil cultivation treatments in autumn. For *C. arvense* there seemed clearly to be no advantage of a stubble cultivation period before mouldboard ploughing in spring. We can therefore conclude that our first hypothesis, "*For the control of C. arvense the season – autumn vs. spring - of ploughing is more important than whether stubble cultivation is carried out or not, and spring ploughing gives the best control*", was supported. Present result on the importance of mouldboard ploughing in spring on control of *C. arvense* is in agreement with previous findings (Brandsæter et al., 2011). The better control efficiency of spring mouldboard ploughing is likely explained by the results of Thomsen et al. (2013). They showed that *C. arvense* shoots emerging from the intact part of the root system, below the mouldboard ploughed layer, played a more crucial role than the shoots originating from shallower root fragments. Mouldboard ploughing in spring may decrease the competitive ability of *C. arvense* versus the crop in two ways: Shoots originating from 25 cm depth or deeper require a significant consumption of the root food reserves before reaching the soil surface. The second explanation may be even more important, namely delayed emerge of *C. arvense* compared to the spring crop, and hence the relatively stronger competitiveness of the cereal crop versus weeds. To improve the effect of spring mouldboard ploughing on control of thistles it is important to sow the crop as soon as possible after the ploughing. Few studies have focused on the effects of timing of stubble cultivation and ploughing on weed growth. Melander et al. (2012), however, compared mouldboard ploughing in spring and autumn but did not find any effect on *C. arvense*. They concluded that decisions on ploughing in spring vs. autumn should not be based on the need for perennial weed control. We suggest that the emerging thistle shoots encountered less resistance in the lighter and more sandy soil types in the study of Melander et al. (2012). Another explanation for the different results, could be that the actual ploughing time in spring hit the *C. arvense* plants at a more sensitive stage in our study.

For *S. arvensis*, soil cultivation in spring gave significantly better control compared to autumn treatment. For *S. arvensis*, however, stubble cultivation compared to only mouldboard ploughing in spring, generally tended to improve the control efficiency, but the difference was not significant. Our second hypothesis "*S. arvensis is better controlled by spring- than autumn ploughing, and stubble cultivation in spring will improve the control* " was therefore partly supported. Related to knowledge of the biological traits of *S. arvensis*, weaker effect of cultivation in autumn could be expected due to innate root bud dormancy (endodormancy) developed during autumn in Nordic countries (Brandsæter et al., 2010; Fykse, 1977). The general limited effect of stubble treatments in autumn on *S. arvensis*, in contrast to the effect on *E. repens*, was also found in a previous study (Brandsæter et al., 2012).

E. repens, and perhaps *S. palustris*, represent the second principal group, in which timing (season) of the soil cultivation does not seem to be of importance for control efficacy, whereas inclusion of stubble cultivation before ploughing showed a highly significant effect. The third hypothesis, "*For the control of E. repens, stubble cultivation prior ploughing is the crucial aspect, while season – autumn vs. spring - of the cultivation is of no significance* ", was clearly supported. Many studies (e.g. Håkansson, 1969, 1967; Thomsen et al., 2015) show that *E. repens* is efficiently controlled by repeated soil cultivation operations, followed by deep mouldboard ploughing. In present study, we were able to harrow two times only during the first autumn at Ås. The subsequent two years only one harrowing was conducted due to high precipitation and low temperature (cf. Table 2). If we had been able to conduct two harrowings each season, that might have improved the weed control effect. For *E. repens* it has been shown earlier that mouldboard ploughing in autumn versus spring gave more or less equal weed control (Njøs and Ekeberg, 1980). Tørresen et al. (2003), however, concluded that *E. repens* was controlled better by mouldboard ploughing in autumn than in spring. However, their spring mouldboard ploughing was relatively shallow, thus making adequate comparisons between seasons more difficult. For *S. palustris,* very few studies exist, and none deals with the experimental factors included in our study. Among the four weed species discussed in present paper, *S. palustris* seems to represent least problems. Its occurrence, however, appears to be more frequent in organic compared to conventional cereals in the Nordic countries (Hyvönen et al., 2003).

When designing field experiments including different treatments in autumn and spring, it is very important to be conscious on all aspects that may significantly affect the results. For example, in our study all plots were mowed after grain harvest to prevent the weed species to exceed their compensation point during autumn. This aspect was probably most important for *E. repens*, since undisturbed stands have a potential to increase the dry matter content of their regenerative structures (rhizomes) between harvest and mouldboard ploughing in late autumn or the next spring (Håkansson, 1969, 1967). Boström et al. (2013), however, recommended removal of the aerial shoots of *E. repens* (and the perennial weeds *Equisetum arvense* L. (Field horsetail) and *Tussilago farfara* L. (Colt's-foot)) early in the autumn to interrupt the upload of storage compounds to the rhizomes. In our study, other results may have occurred if the plots had not been mowed after grain harvest.

The treatment effect on crop yield can principally be ascribed to two main factors. The first is how the control methods affect the weeds, and hence indirectly influence the competition between crop and weeds. The second consists of influences directly on the crop, e.g. sowing date, N-mineralization and soil structure, especially relevant when ploughing on heavy clay in spring. Generally, both at the start and during the experimental period, the total weed biomass was high at site Ås (cf. Table 5). The weed level was in general higher than in many other studies on weed control in organic cereals, but equal to levels specified in Kaut et al. (2009) and partially Salonen et al. (2011). High weed levels in our study, clearly higher than the competition threshold (Brandsæter et al., 2011), may justify a harrowing period in spring. In our study, however, stubble cultivation prior to mouldboard ploughing in spring gave the overall best weed control, but had a negative effect on the oat biomass. The likely reason is that spring cereals are sensitive to late sowing under Nordic conditions with a relatively short growing season (e.g. Eltun, 1997). This disadvantage, however, might have been smaller if the stubble cultivation had been combined with early maturing spring cereal varieties. Another approach would be to develop other, less time-consuming stubble cultivation methods. Since the weed pressure, with a mix of different weed species, was rather high, we may have expected that the interspecific competition between the weed species played a role. This was not detected in current study.

5. Conclusions

Mouldboard ploughing in spring decreased the populations of *C. arvense* and *S. arvensis* significantly compared to ploughing in autumn. For *E. repens,* however, the season of tillage had no significant effect; the importance was whether stubble cultivation was conducted (best control) or not before ploughing. The overall best strategy for controlling the present perennial weed flora and infestation levels was a stubble cultivation period before ploughing in spring. However, this strategy caused delayed sowing of the cereal crop and subsequently a lower crop yield in terms of dry matter. In situations with mixed weed populations of *C. arvense, S. arvensis* and *E. repens,* it seems reasonable to believe that stubble cultivation in autumn and ploughing the following spring - a combination not included in our study - would give the best weed control and highest spring cereal yields.

Acknowledgements

Technicians at Kimen Såvarelaboratoriet AS, Ås, contributed substantially to the field work. We thank farmer Svein Bjerke, who rented out and operated the Väderstad "Carrier Disc harrow" during the experimental period, and Norsk Landbruksrådgivning Øst, Per Ove Lindemark and Bjørn Inge Rostad, who were responsible for the experiment at Øsaker. The study received financial support from the Research Council of Norway (181918) through the project 'Reduced pesticide loads and risks in cropping systems' (short name REDUCE) and NIBIO.

The authors thank anonymous referees for valuable comments on earlier versions of the paper.

References

Armengot, L., Jose-Maria, L., Chamorro, L., Sans, F.X., 2013. Weed harrowing in organically grown cereal crops avoids yield losses without reducing weed diversity. Agron. Sustain. Dev. 33, 405–411.

Bacher, S., Heizmann, A., Nentwig, W., 1997. Problemunkräuter in ökologischen Ausgleichsflächen im Ackerbau. Agrarforschung 4, 91–94 (In German).

Boström, U., Andersson, L., Forkman, J., Hakman, I., Liew, J., Magnuski, E., 2013. Seasonal variation in sprouting capacity from intact rhizome systems of three perennial weeds. Weed Res. 53, 387–398.

Brandsæter, L.O., Bakken, A.K., Mangerud, K., Riley, H., Eltun, R., Fykse, H., 2011. Effects of tractor weight, wheel placement and depth of mouldboard ploughing on the infestation with perennial weeds in organic farmed cereals. Eur. J. Agron. 34, 239–246.

Brandsæter, L.O., Fogelfors, H., Fykse, H., Graglia, E., Jensen, R.K., Melander, B., Salonen, J., Vanhala, P., 2010. Seasonal restrictions of bud growth on rhizomes of *Elymus repens* and roots of *Cirsium arvense* and *Sonchus arvensis*. Weed Res. 50, 102–109.

Brandsæter, L.O., Goul Thomsen, M., Wærnhus, K., Fykse, H., 2012. Effects of repeated clover undersowing in spring cereals and stubble treatments in autumn on *Elymus repens, Sonchus arvensis* and *Cirsium arvense*. Crop Prot. 32, 104–110.

Børresen, T., Njøs, A., 1994. The effect of mouldboard ploughing depth and seedbed preparation on crop yields, weed infestation and soil properties from 1940 to 1990 on loam soil in south eastern Norway. Soil Till. Res. 32, 21–39.

Cormack, W.F., 1999. Testing a stockless arable organic rotation on a fertile soil. DARCOF Report No. 1 (1999). In: Olesen, J.E., Eltun, R., Gooding, M.J., Steen Jensen, E., Köpke, U. (Eds.), Designing and Testing Crop Rotation for Organic Farming. Proceedings from an International Workshop.

Ekeberg, E., Riley, H., Njøs, A., 1985. Plogfri jordarbeiding til vårkorn: I. Avling og kveke. Fors. Forsk. Landbr. 36, 45–51 (In Norwegian).

Eltun, R., 1997. Verknad av jordarbeiding og såtid på avling og ugras. In: Abrahamsen, U. (Ed.), Jord- Og Plantekultur 1997 S, pp. 111–114 (In Norwegian).

Fykse, H., 1977. Untersuchungen über *Sonchus arvensis* L., *Cirsium arvense* (L.) Scop. und *Tussilago farfara* L. Sci. Rep. Agric. Univ. Nor. 56 (no 27) (In German).

Gruber, S., Claupein, W., 2009. Effect of tillage intensity on weed infestation in organic farming. Soil Till. Res. 105, 104–111.

Hyvönen, T., Ketoja, E., Salonen, J., Jalli, H., Tiainen, J., 2003. Weed species diversity and community composition in organic and conventional cropping of spring cereals. Agric. Ecosyst. Environ. 97, 131–149.

Håkansson, I., Stenberg, M., Rydberg, T., 1998. Long-term experiments with different depths of mouldboard mouldboard ploughing in Sweden. Soil Till. Res. 46, 209–223.

Håkansson, S., 1967. Experiments with *Agropyron repens* (L.) Beauv. 1. Development and growth and the response to burial at different developmental stages. Lantbrukshögskolans Ann. 33, 823–867.

Håkansson, S., 1969. Experiments with *Agropyron repens* (L.) Beauv. IV. Response to burial and defoliation repeated with different intervals. Lantbrukshögskolans Ann. 35, 61–78.

Håkansson, S., 2003. Weeds and Weed Management on Arable Land: an Ecological Approach. CABI Publishing, Wallingford, Oxon, UK.

Kaut, A.H.E.E., Mason, H.E., Navabi, A., O'Donovan, J.T., Spaner, D., 2009. Performance and stability of performance of spring wheat variety mixtures in organic and conventional management systems in western Canada. J. Agric. Sci. 147, 141–153.

Korsmo, E., Vidme, T., Fykse, H., 2001. Korsmos Ugrasplansjer, third ed. Landbruksforlaget AS. (including text in English), Oslo. (In Norwegian).

Korsaeth, A., Eltun, R., 2008. Synthesis of the Apelsvoll cropping system experiment in Norway – nutrient balances, use efficiencies and leaching. In: Kirchmann, H., Bergström, L. (Eds.), Organic Crop Production – Ambitions and Limitations. Springer Science + Business Media B.V, UK, p. 244, 2008.

Kouwenhoven, J.K., Perdok, U.D., Boer, J., Oomen, G.J.M., 2002. Soil management by shallow mouldboard mouldboard ploughing in The Netherlands. Soil Till. Res. 65, 125–139.

Melander, B., Holst, N., Rasmussen, I.A., Hansen, P.K., 2012. Direct control of perennial weeds between crops – implications for organic farming. Crop Prot. 40, 36–42.

Melander, B., Rasmussen, I.A., Barberi, P., 2005. Integrating physical and cultural methods of weed control - examples from European research. Weed Sci. 53, 369–381.

Njøs, A., Ekeberg, E., 1980. Forsøk med pløying til to dybder høst og vår på morenejord i Stange i årene 1969-1975. Fors. Forsk. Landbr. 31, 221–242 (In Norwegian).

Pedersen, T.R., Gustavsson, A.M.D., 2003. Rotogräs: Råd i praktiken. Jordbruksv. Jordbruksinformation 19-2003 (In Swedish).

Pekrun, C., Claupein, W., 2006. The implication of stubble tillage for weed population dynamics in organic farming. Weed Res. 46, 414–423.

Permin, O., 1961. Jordbearbejdningens betydning for bekæmpelse af rodukrudt. Tidsskrift Planteavl 64, 875–888.

Ringselle, B., Bergkvist, G., Aronsson, H., Andersson, L., 2016. Importance of timing and repetition of stubble cultivation for post-harvest control of *Elymus repens*. Weed Res. 56, 41–49.

Salonen, J., Hyvonen, T., Jalli, H., 2001. Weeds in spring cereal fields in Finland - a third survey. Agr. Food Sci. 10, 347–364.

Salonen, J., Hyvonen, T., Jalli, H., 2011. Composition of weed flora in spring cereals in Finland - a fourth survey. Agr. Food Sci. 20, 245–261.

Thomsen, M.G., Brandsæter, L.O., Fykse, H., 2013. Regeneration of Canada Thistle *(Cirium arvense)* from intact root system and root fragments at different soil depths. Weed Sci. 61, 277–282.

Thomsen, M.G., Mangerud, K., Riley, H., Brandsæter, L.O., 2015. Method, timing and duration of bare fallow for the control of *Cirsium arvense* and other creeping perennials. Crop Prot. 77, 31–37.

Tørresen, K.S., Skuterud, R., Tandsæther, H.J., Hagmo, M.B., 2003. Long-term experiments with reduced tillage in spring cereals. I. Effect on weed flora, weed seedbank and grain yield. Crop Prot. 22, 185–200.

Ulén, B., Aronson, H., Bechmann, M., Krogstad, T., Øygarden, L., Stenberg, M., 2010. Soil tillage methods to control phosphorus loss and potential side-effects: a Scandinavian review. Soil Use Manag. 26, 94–107.

World Reference Base, 2006. A framework for international classification, correlation and communication. Food and agriculture organization of the United Nations, Rome,. World Soil Resour. Rep. 103, 145.