



Interactions between pre- and post-emergence weed harrowing in spring cereals

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Summary

Pre- and post-emergence weed harrowing were studied in spring cereals in different environments and with two types of harrows in Norway during 2004–2006. The objectives were to investigate interactions between pre- and post-emergence weed harrowing and the importance of harrow type. We hypothesised that pre- and post-emergence harrowing interact positively, that a combination gives more stable weed control effects than pre- and post-emergence weed harrowing used alone, and that a harrow type with bent tines is more aggressive and suitable on hard-packed soils than a harrow with strait tines. The results only supported the last of these hypotheses. Post-emergence weed harrowing controlled a certain percentage of the present weeds, and this percentage was not dependent on pre-emergence weed harrowing. On average, pre-emergence harrowing reduced weed density by 26% and weed biomass by 22%, while the average effect of post-emergence harrowing was 47% on weed density and 41% on weed biomass. The combined effect of pre- and

post-emergence weed harrowing was 61% on weed density and 54% on weed biomass. The combination did not give more stable weed control effects than pre- and post-emergence weed harrowing used alone. Pre-emergence harrowing increased the average crop yield by 6.2%, post-emergence harrowing by 4.0% and the combined effect was 10%. Crop yield was mainly increased on hard-packed soils. Weed and crop responses varied strongly among experiments, but the efficacy of pre- and post-emergence weed harrowing was positively correlated across experiments. Weed species composition was of minor importance regarding weed control. The study indicates that one aggressive post-emergence cultivation may be as good as one pre-emergence and one less aggressive post-emergence cultivation. However, little is known about the interactions between cultivation at different crop and weed growth stages.

Keywords: integrated weed management, machinery, mechanical weed control, non-herbicide weed management, organic farming.

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Introduction

In Scandinavia, weed harrowing has been used to control weed seedlings in cereals since the beginning of the 20th century. Harrowing was recommended in the first half of the twentieth century because field

experiments showed efficient weed control and increased crop yields. Korsmo (1926) summarised 55 Norwegian field experiments in spring cereals in 1919–1920 and reported that the weed control effect of pre-emergence weed harrowing averaged 53% and that the combined weed control effect of pre- and post-emergence

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harrowing averaged 81%. The corresponding increases in grain yield averaged 16% for pre-emergence harrowing and 29% for the combination of pre- and post-emergence harrowing. Another review of old experiments showed similar grain yield responses (Rydberg, 1985).

In the old experiments, pre-emergence weed harrowing was carried out just before crop emergence and post-emergence was carried out when cereals had 2–3 leaves. The same approach is used today, but harrows are now modern flex-tine harrows (Van Der Schans *et al.*, 2006). The old experiments were carried out with rigid-tine types of harrows, which were commonly used in Scandinavia up to the 1950s (Rydberg, 1985; Rasmussen, 1992).

Rasmussen (1992) showed that rigid-tine and flex-tine harrows are active through the same mode of operation and cannot be separated in terms of crop-weed selectivity, where selectivity is defined as the ratio between percentage weed control and percentage crop burial in soil immediately after harrowing. The crop burial measure (also called crop soil cover) expresses the immediate crop response associated with post-emergence harrowing. The selectivity concept ignores uprooting of crop plants, because uprooting is considered negligible for strongly anchored crops such as cereals (Jensen *et al.*, 2004), even if it is acknowledged to play a role with weakly anchored plants (Kurstjens & Kropff, 2001).

After the Second World War, herbicides gradually outcompeted weed harrowing. Research on harrowing almost stopped in Scandinavia until the emergence of organic agriculture in the 1980s. In Norway, conventional farmers are now subsidised to use weed harrows instead of herbicides in some areas, to protect the environment (Fylkesmannen i Oslo og Akershus, 2011). Besides weed control, weed harrowing may also have other positive impacts on crops, such as breaking the soil crust. In areas with heavy soils, the main benefit of weed harrowing is ascribed to soil loosening if a soil crust is present (Mangerud, 2006). Canadian trials showed that cultivating tillage with a rotary hoe in weed-free soyabean (*Glycine max* (L.) Merr.) increased crop yield (Leblanc & Cloutier, 2001).

Field experiments with weed harrowing in the herbicide era have not shown the same convincing results, in terms of crop yield, as experiments in the pre-herbicide era. This is probably due to a tremendous increase in agricultural productivity, improved crop competition and changes of weed flora (Andreassen & Streibig, 2011). Many competitive dicotyledons (e.g. *Sinapis arvensis* L. and *Brassica napus* ssp. *campestris* (L.) A.R.) have been effectively controlled since the breakthrough of auxin herbicides and are now less common. In organic agriculture, this might be different because weed species

susceptible to herbicides are much more common (Hyvönen *et al.*, 2003), although many reports have shown that positive crop yield responses are rare in experiments with weed harrowing in organic crops (Dierauer, 1990; Lundkvist, 2009; Rasmussen *et al.*, 2010; Johnson & Holm, 2010).

Lack of positive crop yield responses might be due to low weed competition and/or crucial crop damages associated with harrowing. Many studies have focused on post-emergence weed harrowing and the associated crop damages (Jensen *et al.*, 2004; Rasmussen *et al.*, 2010), whereas the competitive ability of weeds and thereby the need for weed control is seldom quantified in experiments with weed harrowing (Rueda-Ayala *et al.*, 2011).

Pre-emergence weed harrowing has been the subject of only limited research, but has proven to be effective against early emerging weed species under Scandinavian growing conditions (Lundkvist, 2009). However, under other growing conditions, pre-emergence harrowing has proven to be without any effect, because of lack of weed germination at the time of cultivation (Johnson & Holm, 2010). Pre-emergence harrowing may also stimulate flushes of new weed seedlings (Kees, 1962), which makes it difficult to predict the effects of pre-emergence weed harrowing. Rasmussen (1996) showed that the results of pre-emergence harrowing may depend on the dynamic patterns of weed and crop germination and that pre-emergence weed harrowing only can be expected to be effective if the majority of weeds germinate earlier than the crop.

The objectives of this study were to investigate the possible benefits from pre-emergence weed harrowing in spring cereals, the interactions between pre- and post-emergence weed harrowing and the importance of harrow type. It was hypothesised that pre- and post-emergence harrowing interacts through synergism and that the combination gives more stable weed control effects than pre- and post-emergence weed harrowing used alone. The assumption behind this hypothesis is that pre-emergence weed harrowing increases the chances for efficient post-emergence weed harrowing. If weeds germinate early, pre-emergence harrowing is expected to control the earliest emerging weeds, which are supposed to be more difficult to control by post-emergence harrowing than late emerging weeds. If weeds germinate late, pre-emergence harrowing is expected to have low efficiency, but post-emergence harrowing is still expected to be efficient, because of late weed emergence and small weeds at the 2–4 leaf growth stage of cereals. Because of the risks of hard-packed and/or crusted soils and thereby difficult conditions for weed harrowing, two different types of harrows were tested in the experiments: one with long, straight tines and one with short, bent

tines. It was hypothesised that bent tines are more aggressive, resulting in higher weed control effects on hard-packed or crusted soils.

Materials and methods

Experiments

A total of eight experiments were carried out from 2004 to 2006 at three different locations in Norway (Table 1).

Three experiments were carried out at the Norwegian University of Life Sciences, Ås (59°40'N, 10°46'E, 90 m a.s.l.) in spring barley (*Hordeum vulgare* L.) on a loam-sandy soil. Three experiments were carried out at Stange (60°67'N, 11°21'E, 210 m a.s.l.) in spring barley on a gravely morainic loam soil, and two experiments were carried out at Bjørkelangen (59°55'N, 11°34'E, 132 m

a.s.l.) in oats (*Avena sativa* L.) on a clay loam soil. Three additional experiments were also planned at Bjørkelangen, but because of rain and wet soil conditions, it was not possible to accomplish timely treatments in 2006, which resulted in two experiments only.

Spring barley (cv. Kinnan) at Ås and Stange (cv. Edel) was grown conventionally and fertilised annually with 95 kg N ha⁻¹ and 18 kg P ha⁻¹. Crop rotations were dominated by cereals at Ås and by cereals and leys at Stange. Spring oats (cv. Belinda) at Bjørkelangen were grown organically and not fertilised, but green manure was grown every fourth year to maintain soil fertility. Red clover (*Trifolium pratense* L.) or white clover (*Trifolium repens* L.) was undersown to fix nitrogen, but there was no undersowing in the experimental plots because of harrowing.

All experimental plots were ploughed in early November, and the seedbed was prepared in the following spring. Approximately 350 seeds m⁻² were sown in spring barley and 400 seeds m⁻² in spring oat. Row width was 12.5 cm and plots were rolled with a Cambridge roller after sowing and before pre-emergence weed harrowing. Plots were 1.5 by 10 m and the net area, which was combine harvested, measured 1.5 by 6 m. A wide-frame tractor was used, which allowed for traffic-free plots from sowing to harvest. Normal precipitation in the growing season (May–September) is 382 mm at Ås, 336 mm at Bjørkelangen and 313 mm at Stange, and mean temperatures in the growing season are 13.3, 12.7 and 12.5°C respectively. Precipitation before and after weed harrowing is specified in Table 2.

Table 1 Dates of field operations and weed and crop assessments

	Location experiment		
	2004	2005	2006
	Ås		
	1	2	3
Seedbed preparation	3 May	20 April	4 May
Sowing	3 May	21 April	5 May
Pre-emergence weed harrowing	10 May	1 May	11 May
Post-emergence weed harrowing	27 May	24 May	29 May
Weed assessment	11 June	15–17 June	20–21 June
Crop harvest	21 August	12 August	8 August
	Bjørkelangen		
	4	5	
Seedbed preparation	8–9 May	12 May	
Sowing	10 May	13 May	
Pre-emergence weed harrowing	16 May	3 June*	
Post-emergence weed harrowing	14 June	20 June	
Weed assessment	28 June	19 July	
Crop harvest	9 September	9 September	
	Stange		
	6	7	8
Seedbed preparation	11 May	13 May	8–9 May
Sowing	12 May	13 May	10 May
Pre-emergence weed harrowing	18 May	23 May	28 May*
Post-emergence weed harrowing	4 June	10 June	10 June
Weed assessment	18 June	29 June	28 June
Crop harvest	23 August	31 August	26 August

*Delayed because of rain, weed harrowing at 1–2 leaf stage.

Treatments

All experiments were with three factors, each at two levels, and three block replications, giving 24 plots per experiment. The experiments were carried out with a completely randomised factorial design. Factors were type of harrow (straight and bent tines), pre-emergence weed harrowing (with and without) and post-emergence weed harrowing (with and without). The two harrows were (i) the CMN harrow (CMN Maskintec, Thyholm, Denmark), which represents harrows with long (650 mm) and straight tines and (ii) the Einböck harrow (Einböck, Dorf an der Pram, Austria), which represents harrows with short (450 mm) and bent tines. The tines of the CMN harrow can be adjusted from vertical (90°) to 45° backwards, and the tines of the Einböck harrow can also be adjusted in forward angles to make it more aggressive. The distance between tines was 50 mm on the CMN harrow and 25 mm on the Einböck harrow.

Pre- and post-emergence weed harrowing were carried out with 1.5 m wide harrows. Driving speed was 12 km h⁻¹ for the Einböck harrow and 16 km h⁻¹ for

Table 2 Shear strength and soil moisture before pre- and post-emergence weed harrowing, precipitation before and after weed harrowing and density of dominating weed species in uncultivated plots

Experiment	Shear strength (kPa)		Soil moisture (volume %)		Precipitation* (mm)						Weed species (m ⁻²)
	Pre	Post	Pre	Post	Pre			Post			
					-2	0	2	-2	0	2	
1	12.6	7.5	14.6	12.0	0	0	5.6	3.4	0	2.8	<i>Matricaria discoidea</i> DC. (189) <i>Chenopodium album</i> L. (73)
2	5.2	8.5	16.1	28.5	8.6	0	4	3.8	0.2	10.8	<i>C. album</i> L. (99) <i>Lamium purpureum</i> L. (85)
3	3.5	18.8	19.7	24.5	0	0	0	0	1.2	0.4	<i>C. album</i> L. (346) <i>Fumaria officinalis</i> L. (85) <i>Viola arvensis</i> Murr. (83) <i>Lamium purpureum</i> L. (65) <i>Thlaspi arvense</i> L. (59) <i>Galeopsis tetrahit</i> L. (14)
4	22.0	24.7	19.8	14.7	0.1	0	0	0	0	0.4	(very few weeds, no dominating species)
5	8.9	19.0	25.4	20.4	0	0.5	7	0.1	0	0.1	<i>Polygonum persicaria</i> L. (127) <i>Polygonum aviculare</i> L. (54) <i>Lamium purpureum</i> L. (27)
6	2.4	3.8	15.2	10.7	0	0	2.3	0	0	0	<i>C. album</i> L. (70) <i>Stellaria media</i> (L.) Vill. (41) <i>Polygonum persicaria</i> L. (12) <i>Polygonum aviculare</i> L. (11)
7	3.8	5.4	19.8	13.1	11.6	2	3.8	0	0	25.4	<i>C. album</i> L. (97) <i>Stellaria media</i> (L.) Vill. (16) <i>Polygonum aviculare</i> L. (13)
8	8.0	11.0	19.4	10.6	0	0.2	0	0	0	0	<i>C. album</i> L. (219) <i>Stellaria media</i> (L.) Vill. (61) <i>Polygonum aviculare</i> L. (34) <i>Viola arvensis</i> Murr. (32) <i>Thlaspi arvense</i> L. (12)

*Precipitation on the 2 days before weed harrowing (= -2), the day of harrowing (= 0) and on the 2 days after weed harrowing (= 2).

the CMN harrow. The higher driving speed for the CMN harrow was in accordance with a recommendation from the manufacturer. The tine angle and wheel depth (on harrows) were adjusted to achieve the desirable harrowing depth of 20 mm at very low speed ($\approx 1 \text{ km h}^{-1}$). Adjustments were carried out in plots that had not previously been harrowed. Pre-emergence harrowing was carried out as close to crop emergence as practically possible and post-emergence harrowing was carried out at the 3–4 leaf stage of cereals (Table 1). Pre- and post-emergence harrowing were both carried out along crop rows.

Crop, weed and soil assessments

Weed density and weed biomass were assessed in all experiments at growth stage 49 of cereals according to the Zadoks scale (Zadoks *et al.*, 1974). Weed density was counted in four randomly selected 0.125 m² subplots (0.50 by 0.25 m) in each plot. The density of the

dominating weed species were counted separately and the remaining weeds were pooled to calculate the total number of weeds per m² (Table 2). The total weed biomass was harvested in the same subplots and weed dry matter was estimated after drying at 80°C for 72 h. Grain yield was harvested from 1.5 × 6 m subplots by a combine harvester from early August to early September (Table 1). Grain samples were dried and yield was recorded, based on 15% water content.

To evaluate the degree of hard-packed and/or crusted soils, shear strength was measured with a 'Vane shear auger' before pre- and post-emergence weed harrowing. The Vane shear auger tool consists of two thin metal blades attached to a vertical shaft. The test was carried out by pushing the tester into the soil (3 cm depth) and applying a torque to the vertical shaft. In each experiment, 45 measurements were taken before pre- and post-emergence in control plots without harrowing (Table 2). Measurements were taken outside the net-plots where weeds and yield were recorded.

Soil moisture was measured using a soil moisture sensor (ThetaProbe soil moisture sensor, Type ML1-UM-2; AT Delta-T Devices Ltd, Cambridge, UK). The soil moisture measurement were taken with 15 measuring points in each block (45 measurements in each experiment), immediately before weed harrowing.

Statistics

Analysis of variance was performed with PROC MIXED in SAS (SAS version 9.1; SAS Institute, Cary, NC, USA). Mixed models with fixed and random effects were used, because block was considered random. All response variables, weed density, weed biomass and crop yield were log-transformed to stabilise variance. For each response variable, all data were analysed in one model with number of experiment, type of harrow, pre-emergence harrowing and post-emergence harrowing as fixed effects and block effects as random. Two-way, three-way and four-way interactions were analysed in the full four-way analysis of variance. Experiments were also analysed individually, because of significant interactions between experiment and experimental treatments. A mixed model with pre- and post-emergence harrowing as fixed effects and block effects as random was used. To test whether different weed species responded differently to harrowing, experiments 1–8 were analysed separately. Weed density was analysed in a mixed model with weed species, pre-emergence and post-emergence harrowing as fixed factors. Type of harrow and block effects were considered random.

To evaluate the weed harrowing effects and the precision of the estimated effects, differences of the least squares means (LS-means) and the corresponding 95% confidence intervals (95%-CI) were estimated. As all response variables were log-transformed, the back-transformed difference between two levels of either pre-emergence weed harrowing or post-emergence weed harrowing reflects the multiplicative effects of harrowing. For example, if the difference of LS-means for weed density in plots that have been harrowed and plots that have not is -0.883 , the effect of harrowing is $100(1 - \exp(-0.883)) = 58.6\%$. To visualise and analyse the interactions between pre- and post-emergence weed harrowing, main effects (%) of post-emergence weed harrowing were plotted against main effects (%) of pre-emergence weed harrowing, and the relationship was subjected to linear regression. Each observation represented one experiment (no block replications). Linear regression was used to analyse how shear strength influenced weed control. Percentage weed control was the response variable, and shear strength and type of harrow were the independent variables.

Results

Interaction between pre- and post-emergence cultivation

The interaction between pre- and post-emergence weed harrowing was not influenced by the type of harrow for either weed density, weed biomass or crop yield (Table 3). The log-transformed data indicate that pre- and post-emergence weed harrowing have multiplicative effects. If post-emergence weed harrowing controls 60% of the weeds without preceding weed harrowing, it will also control 60% of the present weeds in plots that have been harrowed before crop emergence. Hence, if pre-emergence weed harrowing controls 40% of the weeds and post-emergence harrowing controls 60% of the weeds, the combined effect will be 84%.

On average, the main effect of pre-emergence harrowing was 26% (95%-CI: 16–36%) ($P < 0.001$) weed density decline and 22% (95%-CI: 10–33%) weed biomass decline. The average effect of post-emergence harrowing was 47% (95%-CI: 37–51%) weed density decline and 41% (95%-CI: 31–49%) weed biomass decline. The combined effect of pre- and post-emergence weed harrowing was 61% (95%-CI: 53–68%) on weed density and 54% (95%-CI: 43–60%) on weed biomass. The performance of pre- and post-emergence weed harrowing, however, varied between different experiments (Table 3). The interaction between pre- and post-emergence weed harrowing was also influenced by experiment (three-way interactions) (Table 3). Therefore,

Table 3 ANOVA table with *P*-values for the analysis of weed and crop responses

Fixed effects	d.f.	<i>P</i> -value		
		Total weed density	Weed biomass	Crop yield
Harrow (H)	1	0.0106	0.0214	0.1386
Pre-emergence (Pre)	1	<0.0001	<0.0001	0.0003
Post-emergence (Post)	1	<0.0001	<0.0001	0.0165
Experiment (E)	7	<0.0001	<0.0001	<0.0001
H × Pre	1	0.7899	0.8792	0.0128
H × Post	1	0.0323	0.3503	0.3882
H × E	7	0.2597	0.0486	0.7563
Pre × Post	1	0.1667	0.1783	0.2670
Pre × E	7	0.0105	0.0003	<0.0001
Post × E	7	0.2532	0.0049	0.0017
H × Post × Pre	1	0.4885	0.2148	0.8578
H × E × Pre	7	0.9451	0.5694	0.3219
H × E × Post	7	0.0300	0.2022	0.3411
E × Pre × Post	7	0.0028	<0.0001	0.1108
E × Pre × Post × H	7	0.3190	0.7110	0.9462

weed control effects for each experiment are shown in Tables 4 and 5. Pre-emergence weed control effects varied from about 50% to non-significant effects (positive and negative) and post-emergence weed control effects varied from about 60% to non-significant effects (Tables 4 and 5).

The three-way E × Pre × Post interaction in Table 3 shows that the effect of post-emergence harrowing was influenced by the effect of pre-emergence harrowing in a site-specific way. This is illustrated in Fig. 1, which shows a linear positive correlation between the weed control effects of pre-emergence harrowing. This applies for both weed control calculated on the basis of weed density

($r = 0.936^{***}$) and weed biomass ($r = 0.923^{***}$). Sites resulting in high effects of pre-emergence harrowing also resulted in high effects of post-emergence harrowing. There were no indications that the combination of pre- and post-emergence weed harrowing stabilised the weed control effects (Tables 4 and 5).

Experiment 4 showed the lowest weed control effect, and weed biomass was even increased after the combination of pre- and post-emergence weed harrowing (Table 5). At the same time, Experiment 4 was characterised by soil with high shear strength (Table 2), low weed density in untreated plots (Table 4) and insignificant amounts for weed biomass (Table 5).

Table 4 Weed density in untreated plots and predicted main effects of pre-emergence and post-emergence weed harrowing and the combined effect of pre- and post-emergence weed harrowing (95% confidence intervals in parentheses)

Experiment	Weed density in untreated plots (g m ⁻²)	Weed control (%)		
		Pre-emergence harrowing	Post-emergence harrowing	Combined effect
1	332	49 (25 to 66) ^{***}	59 (39 to 72) ^{***}	78 (54 to 89) ^{***}
2	278	-6 (-54 to 28) ^{NS}	29 (-4 to 50) ^{NS}	24 (-12 to 48) ^{NS}
3	689	27 (-7 to 50) ^{NS}	43 (18 to 60) ^{**}	59 (37 to 75) ^{***}
4	27	-22 (-80 to 17) ^{NS}	27 (-5 to 50) ^{NS}	11 (-37 to 42) ^{NS}
5	239	51 (29 to 67) ^{***}	56 (37 to 70) ^{***}	79 (63 to 88) ^{***}
6	157	24 (-15 to 50) ^{NS}	54 (29 to 70) ^{***}	64 (14 to 85) [*]
7	135	29 (-4 to 52) ^{NS}	53 (32 to 67) ^{***}	67 (46 to 79) ^{***}
8	363	30 (-2 to 53) ^{NS}	46 (30 to 63) ^{***}	63 (29 to 81) ^{***}

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; NS, non-significant ($P > 0.05$).

Table 5 Weed biomass in untreated plots and predicted main effects of pre-emergence and post-emergence weed harrowing and the combined effect of pre- and post-emergence weed harrowing (95% confidence intervals in parentheses)

Experiment	Weed biomass in untreated plots (m ⁻²)	Weed control (%)		
		Pre-emergence harrowing	Post-emergence harrowing	Combined effect
1	8.9	51 (32 to 65) ^{***}	45 (22 to 61) ^{***}	73 (52 to 85) ^{***}
2	6.1	-2.0 (-43 to 28) ^{NS}	20 (-13 to 43) ^{NS}	19 (-16 to 42) ^{NS}
3	47.9	29 (0 to 49) ^{NS}	31 (16 to 58) ^{**}	58 (37 to 71) ^{***}
4	0.3	-31 (-83 to 7) ^{NS}	-7 (-48 to 27) ^{NS}	-46 (-96 to 0) [*]
5	14.0	45 (22 to 60) ^{***}	53 (34 to 66) ^{***}	74 (60 to 83) ^{***}
6	29.2	29 (-1 to 51) ^{NS}	56 (38 to 70) ^{***}	68 (33 to 84) ^{***}
7	7.8	34 (1 to 53) [*]	44 (21 to 60) ^{***}	63 (36 to 79) ^{***}
8	21.6	13 (-22 to 32) ^{NS}	22 (-10 to 44) ^{NS}	32 (-30 to 63) ^{NS}

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; NS, non-significant ($P > 0.05$).

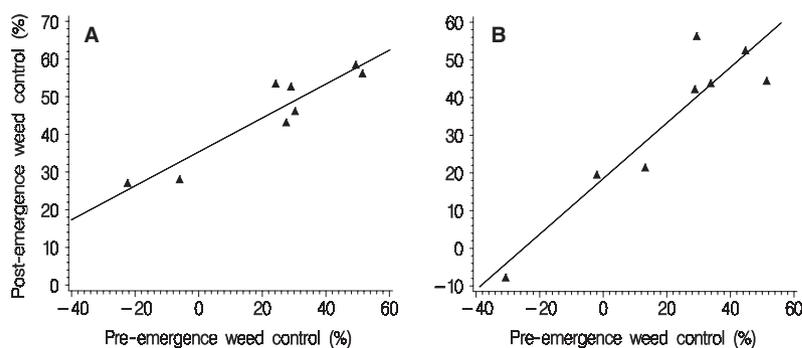


Fig. 1 Relationship between main effects of pre- and post-emergence weed harrowing calculated on the basis of weed density (A) and weed biomass (B).

Type of harrow and soil shear strength

The average weed density was 16% (95%-CI: 5–27%) lower in plots that were harrowed with the Einböck harrow, as compared with the CMN harrow ($P < 0.05$), and the weed biomass was 13% (95%-CI: 2–23%) lower ($P < 0.05$) (data not shown). A significant interaction between type of harrow and post-emergence weed harrow showed that the Einböck harrow only gave higher weed control effects than the CMN harrow when it was used post-emergence ($P < 0.05$), whereas there were no significant differences between harrows when they were used pre-emergence (Table 3). The Einböck harrow reduced the weed density by 54% (95%-CI: 48–59%) when used post-emergence, whereas the CMN reduced the weed density by 39% (95%-CI: 27–47%). The corresponding values for weed biomass were 48% (95%-CI: 35–58%) and 33% (95%-CI: 16–46%), respectively, but this difference was not statistically significant (Table 3).

An interaction between type of harrow and pre-emergence harrowing (Table 3) revealed that the Einböck harrow improved the average yield by 10.1% (95%-CI: 5.7–14.3%) when it was used pre-emergence, whereas there was no yield effect after pre-emergence harrowing with the CMN harrow ($P = 0.40$) (data not shown). There was no difference between harrows in terms of crop yield response for post-emergence harrowing (Table 3).

Regression analysis showed that the CMN harrow was more sensitive to soils with high shear strength (hard-packed and/or crusted soils) (Table 2) than the Einböck harrow. Weed control (calculated on the basis of weed density) declined by 2.6% (95%-CI: 0.1–3.4%) for each unit of increase in shear resistance ($P = 0.042$), whereas weed control was unaffected by the shear strength when the Einböck harrow was used ($P = 0.796$).

Weed species

In general, the different weed species responded similarly to weed harrowing (Table 6). Interaction between weed

species and harrowing was only found for pre-emergence weed harrowing in Experiment 1, where *Chenopodium album* L. was unaffected by pre-emergence harrowing ($P = 0.96$) and *Matricaria discoidea* DC. was reduced by 89% (95%-CI: 76–95%).

Two weed species, *C. album* and *Polygonum aviculare*, appeared in three experiments (Experiments. 6–8). When these experiments were analysed together, only *C. album* was influenced by weed harrowing. *Polygonum aviculare* did not respond to either pre-emergence or post-emergence harrowing. The average effect of pre-emergence harrowing on *C. album* was 36% (95%-CI: 5–58%) and the average effect of post-emergence harrowing was 62% (95%-CI: 43–71%).

Crop yield

Pre-emergence harrowing increased the average crop yield by 6.2% (95%-CI: 2.9–9.2%), post-emergence harrowing increased yield by 4.0% (95%-CI: 0.8–7.2%), and the combined effect was 10% (95%-CI: 3.5–12.1%). However, the yield effects were strongly influenced by experiment, as shown in Table 7. When experiments were analysed separately, only Experiments 1 and 4 showed significant yield increase due to harrowing. Both experiments were characterised by hard-packed soils and low yields in untreated plots. Experiment 4 was furthermore characterised by low weed density (Table 4) and low weed biomass (Table 5) in untreated plots. When the experiments without hard-packed and crusted soils were analysed together, weed harrowing had no impact on crop yield either for pre-emergence harrowing ($P = 0.27$) or post-emergence harrowing ($P = 0.74$), and there were no interactions between pre- and post-emergence harrowing ($P = 0.95$).

Discussion

The experiments did not support the hypothesis that post-emergence weed harrowing is more efficient if it is preceded by pre-emergence harrowing. Synergism

Fixed effects	Experiment number							
	1	2	3	5	6	7	8	
Species (S)	0.2164	0.5470	<0.0001	0.0747	<0.0001	<0.0001	<0.0001	
Pre-emergence (Pre)	0.0002	0.4347	0.1381	0.0099	0.0175	0.4840	0.0063	
Post-emergence (Post)	<0.0001	<0.0001	<0.0001	<0.0001	0.0006	0.0026	<0.0001	
Pre × Post	0.4549	0.5848	0.4656	0.4461	0.0002	0.3575	0.6069	
Pre × S	0.0002	0.6799	0.3110	0.2735	0.8680	0.4560	0.0505	
Post × S	0.5343	0.4776	0.8683	0.2057	0.2707	0.8363	0.8767	
Post × Pre × S	0.7914	0.8456	0.9883	0.5632	0.5449	0.5346	0.0844	

Table 6 ANOVA table with P -values for the analysis of weed species density

Table 7 Crop yield in untreated plots and predicted main effects of pre-emergence and post-emergence weed harrowing and the combined effect of pre- and post-emergence weed harrowing (95% confidence intervals in parentheses)

Experiment	Grain yield in untreated plots (t ha ⁻¹)	Yield increase (%)		
		Pre-emergence harrowing	Post-emergence harrowing	Combined effect
1	3.21	10.3 (1.8 to 18.1)*	17.3 (9.4 to 24.4)***	25.8 (13.7 to 36.3)***
2	4.88	-2.4 (-12 to 6.5) ^{NS}	-4.6 (-13.9 to 4.2) ^{NS}	-7.4 (-0.6 to 12.7) ^{NS}
3	5.06	0.7 (-8.7 to 8.0) ^{NS}	6.9 (-2.0 to 14.9) ^{NS}	7.7 (-5.7 to 19.1) ^{NS}
4	1.25	35.2 (28.1 to 41.1)***	12.1 (2.8 to 20.6)*	42.7 (30.1 to 53.0)***
5	3.44	3.5 (-6 to 12.6) ^{NS}	-1.4 (-11.6 to 7.6) ^{NS}	2.1 (-17.5 to 18.6) ^{NS}
6	5.69	-0.3 (-11.6 to 10.4) ^{NS}	7.1 (-3.4 to 16.4) ^{NS}	7.2 (-1.4 to 15.2) ^{NS}
7	7.37	0.3 (-8.7 to 8.9) ^{NS}	0.3 (-7.8 to 9.5) ^{NS}	0.6 (-6.0 to 6.9) ^{NS}
8	5.1	-5.5 (-13.8 to 3.4) ^{NS}	-6.6 (-17.2 to 7.3) ^{NS}	-13.2 (-29.5 to 1.2) ^{NS}

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; NS, non-significant ($P > 0.05$).

between pre- and post-emergence harrowing was expected, because pre-emergence weed harrowing is mainly effective against early germinating weeds, which are supposed to be the most difficult ones to control later on. Buhler *et al.* (1992) showed that pre-emergence cultivation with a rotary hoe increased the effectiveness of subsequent inter-row cultivations in soyabean (*Glycine max* (L.) Merr.), but apart from this report, it is difficult to find experimental support for the hypothesis. Rasmussen *et al.* (2012) showed that pre-emergence flame weeding had no impact on the efficiency of post-emergence weed harrowing in sugar beets, even if flame weeding reduced the average weed size by 31%. Neither pre-emergence flame weeding nor pre-emergence weed harrowing improved the efficacy of subsequent mechanical intra-row cultivation in vegetables (Melander, 1998; Melander & Rasmussen, 2001). Therefore, the importance of pre-emergence weed control appears to be without practical importance for the efficiency of post-emergence cultivation and the hypothesis that the combination of pre- and post-emergence harrowing gives more stable weed control effects than pre- and post-emergence weed harrowing used alone could not be supported.

A major challenge in weed harrowing is the considerable site-year variability often found (Navntoft *et al.*, 2007). We also found that the efficacy of pre- and post-emergence weed harrowing was highly dependent on site and year variations. We also found that the variability in pre- and post-emergence weed control effects was correlated across experiments. If pre-emergence harrowing for some site-specific reason gave a low weed control effect, post-emergence weed harrowing also gave a low effect and vice versa (Fig. 1). A similar site-specific correlation between the effects of repeated cultivations has also been reported by Navntoft *et al.* (2007). Our study cannot reveal the exact reasons, but the soil shear strength influenced the efficacy of the CMN harrow with strait tines, whereas weed species responded similarly to

weed harrowing within each experiment (Table 6). This may suggest that soil properties play a key role in the site and year variation in experiments with weed harrowing. We found that bent tines resulted in higher weed control effects and were less influenced by hard-packed and/or crusted soil than harrowing with strait tines. However, one major drawback of bent tines, which was not investigated in the present studied, is that they bring more stones to the soil surface on stony soils than strait tines.

Another major challenge in weed harrowing is to understand and predict the relationship between cultivation intensity and crop yield response. Predictive models assume that the crop yield response to harrowing is a function of crop damage associated with harrowing and reduced weed competition (Rueda-Ayala *et al.*, 2011). However, this study showed that weed harrowing also may have positive impacts on crop yield due to soil loosening. In Experiment 4, the combined effect of pre- and post-emergence harrowing increased crop yield by 43% (Table 7) even if weeds were considered without competitive ability. Experiment 4 was conducted in oats, which has been shown to less tolerant to weed harrowing than spring barley (Rasmussen *et al.*, 2009), but the soil loosening effect totally overwhelmed this aspect.

In this study, it was decided to standardise driving speed and cultivation depth. It is likely that a more adaptive approach could have reduced the variability in weed control effects among experiments. In Rasmussen *et al.* (2008, 2009, 2010), an adaptive approach to cultivation intensity was used, based on the idea that setting and use of a weed harrow should be adapted to the immediate crop and weed responses. A hard-packed clay soil requires more aggressive cultivation than a soft sandy soil, because it is difficult to bring packed heavy soil into motion, which is important for weed control. The majority of weeds are not killed by the tines themselves, but by the soil that the tines force into

motion. In consequence, setting and use of the harrow should not be the same on different soils, if the adaptive approach is used. It is, however, unclear to what extent the variable weed control effects could have been stabilised by use of the adaptive approach to cultivation. It is also unclear how the approach should have been used in relation to pre-emergence weed harrowing, because crop and weed impact cannot be easily measured prior to crop and weed emergence.

The main purpose of this study was to investigate whether there was a positive interaction between pre- and post-emergence weed harrowing under different environmental conditions, and the answer is clear: no evidence of such an interaction was found. In consequence, one may ask whether pre-emergence weed harrowing is worthwhile? Would it be possible to achieve the same results with just one aggressive, post-emergence cultivation as compared with two less aggressive cultivations carried out before and after crop emergence? Unfortunately, this question cannot be answered in this study and the literature offers little help if one wants to evaluate whether repeated cultivations with a certain time interval are better than one aggressive cultivation. Farmers seem to prefer repeated cultivations, but there is no scientific evidence that this is a preferable strategy. Hence, much still has to be learned about weed harrowing, to increase the knowledge base required to improve the performance of this widely-used method of weed control.

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