DOI: 10.1111/j.1365-3180.2009.00718.x

Effects of pre- and post-emergence weed harrowing on annual weeds in peas and spring cereals

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Received 16 November 2008
Revised version accepted 3 April 2009

Summary

To assess the effects of timing and frequency of weed harrowing on weed abundance and crop yield, different pre- and post-emergence weed harrowing sequences were applied to spring cereals and peas in field experiments performed during 2003 and 2004 in Sweden. Post-emergence harrowing was performed at crop growth stages 2–3 and 5–6 true leaves respectively. The best weed control was obtained by a combination of pre- and post-emergence harrowing, but these treatments also caused yield losses of 12–14% in spring cereals, while no yield losses were observed in peas. Pre-emergence weed harrowing treatments alone or combined with weed harrowing shortly after crop emergence proved to be most effective against the early emerging annual weed species *Sinapis arvensis* and *Galeopsis* spp. Post-emergence harrowing alone in peas had no effect on *S. arvensis*. The late emerging annual weed species *Chenopodium album* and *Polygonum lapathifolium* were most effectively controlled when pre-emergence weed harrowing was combined with one or two weed harrowing treatments after crop emergence.

Keywords: *Avena sativa*, *Chenopodium album*, *Galeopsis* spp., oats, organic farming, *Pisum sativum*, *Polygonum lapathifolium*, *Sinapis arvensis*, timing, *Triticum aestivum*, mechanical weed control, wheat.

Lundkvist A (2009). Effects of pre- and post-emergence weed harrowing on annual weeds in peas and spring cereals. *Weed Research* **49**, 409–416.

Introduction

The increase in organic farming resulting from the European public's concern regarding pesticide use in farming has created more interest among farmers in physical weed control, including weed harrowing (Bond & Grundy, 2001; Melander *et al.*, 2005). The purpose of weed harrowing is to give crops a competitive advantage over weeds (Melander & Hartwig, 1995). Weed harrowing covers weeds and can kill weeds by uprooting them (Habel, 1954; Kees, 1962; Koch, 1964; Kurstjens & Kropff, 2001; Kurstjens *et al.*, 2004). During harrowing, crop plants are sometimes covered with soil, but often to a lesser extent than the weeds and the crop usually recovers more quickly and out-grows the weeds before they have recovered from the harrowing (Bond & Grundy, 2001). Smaller weeds are easier to control via harrowing. Under favourable conditions, weed harrowing may provide similar efficacy as herbicides, but usually the control effects from harrowing are lower than that which can be achieved with chemical control. Efficacy of harrowing depends on many factors, including crop species and weeds present, the development stages of crop and weeds, weather, soil type and harrow type (Rydberg, 1994; Rasmussen & Ascard, 1995; Cirujeda *et al.*, 2003; Jensen *et al.*, 2004; Hansen *et al.*, 2007). Weed harrowing may be divided into two categories; pre-emergence harrowing and post-emergence harrowing. Pre-emergence harrowing (pre-wh) occurs after the crop is sown, but before it emerges. This can be an

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effective control for early emerging weeds (Koch, 1959; Melander & Hartwig, 1995; Rasmussen, 1996) like *Sinapis arvensis* L., *Galeopsis* spp., *Raphanus raphanistrum* L. and volunteers including *Brassica napus* L. Pre-emergence harrowing may stimulate the germination of some weed species which can increase weed pressure (Kees, 1962). Post-emergence harrowing (post-wh) occurs after the crop has emerged and can be problematic. This is because both weeds and crop may be damaged by the harrow (Rasmussen *et al.*, 2008) and the most sensitive development stage for mechanical disturbance often coincides for both the crop and the weeds. For example, the 1–2 true leave stage in cereals (DC 11-12, Lancashire *et al.*, 1991) and the cotyledon stage in weeds often co-occur in northern Europe. Selective harrowing is a special case of post-wh in which only the spaces between the crop rows are harrowed (Rasmussen & Svenningsen, 1995). Selective harrowing is usually performed with a harrow with longer tines than in ordinary post-wh and at a later crop stage, when the crop rows are easily identifiable (e.g. at stem elongation in cereals; DC 30). This method may control small weed species like *Stellaria media* (L.) Vill. and *Viola arvensis* Murr., while larger species like *S. arvensis* and *Chenopodium album* L. are less affected (Rasmussen & Svenningsen, 1995). Many studies have been done on post-wh (e.g. Steinmann & Gerowitt, 1993; Wilson *et al.*, 1993; Rydberg, 1994; Rasmussen & Svenningsen, 1995; Rasmussen, 1998, 2004; Kurstjens *et al.*, 2000; Rasmussen *et al.*, 2008). In the relatively few studies done on combinations of pre- and post-wh, observations show that pre-wh sometimes provides satisfactory weed control, but a post-wh treatment is sometimes necessary. This is the case for late emerging weeds in winter wheat (e.g. Dastgheib, 2003). Rasmussen & Rasmussen (1995, 2000) reported greater reductions (61–74%) in weed dry weight in spring barley when post-wh treatments were combined with pre-wh. However, this was not true for all weed species and they were able to achieve a reduction in dry weight of *S. arvensis* of 78%, using only pre-wh. Hansen *et al.* (2007) showed that treatment effects on spring barley differed between crop varieties. Melander & Rasmussen (2001) observed effective weed control with pre-wh in leek and bulb onion, but noted that later flushes of weed seedlings could offset this control. There is an increasing need for harrowing as a means of weed control, but there is a lack of information on the effectiveness of the many combinations of pre-wh and post-wh treatments that are possible, particularly with respect to field sites in far northern Europe. This project was therefore initiated to study the effects of different combinations of weed harrowing before and after crop emergence on weed control in field sites in Sweden. The major hypotheses were (i) that combinations comprising both pre-wh and post-wh provide better weed control effect against annual weed infestations than treatments containing only pre-emergence harrowing and (ii) that pre-emergence harrowing alone or in combination with post-emergence harrowing provide better control of early emerging weed species versus post-emergence harrowing alone.

Material and methods

Experimental sites

Seven field experiments were conducted at two organic farm sites in the central part of Sweden (Enköping, 59°30′N, 17°18′E and Uppsala, 59°50′N, 17°46′E) in both the 2003 and 2004 seasons using spring cereals, either oats (*Avena sativa* L.) or spring wheat (*Triticum aestivum* L.) and peas (*Pisum sativum* L.) (Table 1). The experiments were sown at rates of 400 seeds m^2 (spring cereals) and 80–100 seeds m^2 (peas) with a row spacing of 12 cm. Sowing occurred at the end of April or in early May, depending on the weather conditions.

The soils at Enköping consisted of an organic soil (field experiment with oats, 2003) and a heavy clay soil with a relatively high organic matter content (5% C) (field experiments with peas, 2003–2004). At Uppsala, the soil conditions were typical for the area, consisting of relatively young lake sediments (50% clay) with a relatively high organic matter content (5% C) (Lundkvist *et al.*, 2008).

Experimental design

The weed control effects of seven different harrowing treatments (combinations of pre-wh and post-wh treatments) were studied (Table 1). Pre-wh treatments were performed 2–4 and/or 6–8 days after crop sowing. The pre-wh treatments were also combined with post-wh when the crop had two to three true and five to six leaves unfolded, DC 12-13 and DC 15-16 respectively (Zadoks *et al.*, 1974). Each experiment was arranged in a randomised complete block design with three blocks per experiment. For all experiments, each of the three blocks contained seven treatment plots and one untreated control plot and each plot measured 15 × 45 m. In the pea experiment at Enköping in 2003, post-whs at DC 12-13 and DC 15-16 were also included (Table 1).

Weed harrowing was carried out with a spring-tine harrow (Einböck, Dorf an der Pram, Austria) at both Enköping and at Uppsala, using the same adjustments. The driving speed was approximately 7–9 km h^{-1} in all experiments and treatments. The weed harrowing treatments were conducted at air temperatures ranging from

Table 1 Experimental treatments (pre- and post-emergence weed harrowing, pre-wh and post-wh, respectively) for the 7 field experiments

Field experiment Treatment	En 2003 Peas	Ua 2003 Peas	En 2004 Peas	Ua 2004 Peas	En 2003 Oats	Ua 2003 Spring wheat	Ua 2004 Oats
Control (no weed harrowing)	X	X	X	X	X	X	X
Early pre-wh (2–4 days after sowing)	X	X	X	X	X	X	X
Late pre-wh (6–8 days after sowing)	*	X	X	X	X	X	X
Early + late pre-whs	*	X	X	X	X	X	X
Early pre-wh + post-wh, at crop growth stage DC 12-13	X	X	X	X	X	X	X
Late pre-wh + post-wh, at crop growth stage DC 12-13	*	X	X	X	X	X	X
Early pre-wh + post-whs, at crop growth stages DC 12-13 and DC 15-16	X	X	X	†	X	X	†
Late pre-wh + post-whs, at crop growth stages DC 12-13 and DC 15-16	*	X	X	†	X	X	†
Post-wh at crop growth stage DC 12-13	X‡						
Post-wh at crop growth stage DC 15-16	X‡						
Post-whs at crop growth stages DC 12-13 and DC 15-16	X‡						

Four experiments were performed in peas and three in spring cereals (oats and spring wheat).
En, Enköping; Ua, Uppsala; X, experimental treatment was performed.
*Late pre-wh was not performed.
†Post-wh at crop growth stage DC 15-16 was not performed.
‡Post-wh without pre-wh, was performed in one experiment (En 2003, peas).

6 to 15°C. In Enköping in 2003, precipitation followed all treatments in peas and after late pre-wh in oats. In 2004, precipitation followed post-wh at DC 12-13 in both Enköping and Uppsala.

Weed and yield measurements

In the second part of June, which was 5–6 weeks after the last weed harrowing, the weed species were identified and the number of weed plants counted in two 0.25 m^2 quadrats randomly placed in each plot. The nomenclature of plant species is according to Flora Europaea (Tutin, 1964–80). However, in the field experiments at Uppsala in 2003, the weed plants were counted but not separated by species. The field experiments at Uppsala were harvested to estimate the effects of weed harrowing on crop yield by sampling a crop area of about 30 m^2 in each of the plots during August. The grain yield was weighed, the moisture content determined and the grain yield (kg ha^{-1}) was corrected to 15% moisture content. At Enköping, no yield estimates were obtained.

Statistical analysis

Prior to the statistical analyses, the variance of the number of weed plants (residual versus predicted) was plotted and data were transformed to square root, to stabilise the variance. The effects of pre-wh and post-wh on (i) the total number of weed plants; (ii) the number of individual weed species and (iii) crop yield were evaluated in a mixed model (SAS Institute, 1999) containing (a) the main factors experiment and treatment, the interaction experiment × treatment and with experiment × block as a random factor (analyses of several experiments) and (b) the main factor treatment with block as a random factor (analyses of each of the single field experiments). Least squares means of treatment or experiment × treatment were separated by the option PDIFF, i.e. all possible probability values for the hypothesis H0: LSM(i) = LSM(j). Statistical analysis on individual weed species was only performed when (i) the weed species occurred in all plots and (ii) the number of plants species were ≥10 m^{-2}. Means and standard errors presented in the tables were calculated using the PROC MEANS procedure in SAS (SAS Institute, 1999).

Results

Peas

The average total number of weed plants in the control plots were 133 and 158 plants m^{-2} at Uppsala and 120 and 747 plants m^{-2} at Enköping, in 2003 and 2004 respectively (Table 2). At Enköping, the single dominant weed species was *S. arvensis* in both years and at the assessment stage in 2004, 5 weeks after the last harrowing treatment, weed cover had reached almost 100%. No other weed species were found in those experiments. At Uppsala, *C. album* was the dominant species, with other common species being *Galeopsis* spp., *S. media*, *Matricaria inodora* L. and *Myosotis arvensis* (L.) Hill.

Table 2 Total number of weed plants (m^{-2}) in the four field experiments with peas treated with different combinations of pre- (pre-wh) and post-weed harrowing (post-wh) at Enköping (En) and at Uppsala (Ua) in 2003–2004

Treatment	En 2003 Peas	En 2004 Peas	Ua 2003 Peas	Ua 2004 Peas
Control (no weed harrowing)	120 (20)[a]	747 (55)[a]	133 (24)[a]	158 (37)[ab]
Early pre-wh (2–4 days after sowing)	21 (8)[b]	656 (65)[ab]	110 (35)[a]	151 (18)[abc]
Late pre-wh (6–8 days after sowing)	–	613 (257)[b]	135 (24)[a]	181 (22)[ab]
Early + late pre-whs	–	571 (114)[b]	137 (33)[a]	184 (28)[ab]
Early pre-wh + post-wh at crop growth stage DC 12-13	13 (1)[bc]	607 (67)[b]	59 (14)[b]	115 (26)[abc]
Late pre-wh + post-wh at crop growth stage DC 12-13	–	556 (60)[b]	33 (6)[bc]	93 (31)[c]
Early pre-wh + post-whs, at crop growth stages DC 12-13 and DC 15-16	10 (1)[c]	304 (101)[c]	13 (3)[cd]	–
Late pre-wh + post-whs, at crop growth stages DC 12-13 and DC 15-16	–	320 (141)[c]	7 (3)[d]	–
Post-wh at crop growth stage DC 12-13*	100 (1)[a]			
Post-wh at crop growth stage DC 15-16*	120 (1)[a]			
Post-whs at crop growth stages DC 12-13 and DC 15-16*	100 (1)[a]			

Values indicate mean (SE) with $n = 3$. Mean in the same column with different superscript letters are significantly different ($P < 0.05$).
–, treatment not performed in the experiment.
*Post-wh, without pre-wh, was performed in one experiment (En 2003, peas).

Table 3 Crop yields (kg ha^{-1}) in four field experiments, sown with peas and spring cereals (oats, spring wheat), and treated with different combinations of pre- (pre-wh) and post-weed harrowing (post-wh) at Uppsala (Ua) 2003 and 2004

Treatment	Peas Ua 2003	Peas Ua 2004	Spring wheat Ua 2003	Oats Ua 2004
Control (no weed harrowing)	4866 (468)[a]	2668 (497)[a]	5095 (448)[a]	4597 (368)[a]
Early pre-wh (2–4 days after sowing)	4728 (429)[a]	2987 (138)[a]	5018 (220)[a]	4619 (138)[a]
Late pre-wh (6–8 days after sowing)	4737 (480)[a]	2745 (281)[a]	5118 (510)[a]	4663 (172)[a]
Early + late pre-whs	4676 (265)[a]	3031 (354)[a]	5393 (615)[a]	4575 (225)[a]
Early pre-wh + post-wh at DC 12-13	4764 (351)[a]	2469 (581)[a]	4980 (491)[abd]	4354 (149)[ab]
Late pre-wh + post-wh at DC 12-13	4896 (680)[a]	2568 (321)[a]	4785 (511)[bcd]	3957 (83)[b]
Early pre-wh + post-whs at DC 12-13 and DC 15-16	4590 (240)[a]	–	4526 (287)[cd]	–
Late pre-wh + post-whs at DC 12-13 and DC 15-16	4393 (400)[a]	–	4587 (493)[d]	–

Values indicate mean (SE) with $n = 3$. Mean in the same column with different superscript letters are significantly different ($P < 0.05$).
DC, crop growth stage at treatment; –, treatment not performed in the experiment.

There were significant interactions between treatment and experimental site, showing that the different weed harrowing treatments gave different results depending on the experiment. The treatment effects were significant compared with the control plot and the best weed control was achieved with pre-wh alone or when a pre-wh was combined with one or two post-whs (Table 2).

At Uppsala, the pea yield in the control plots were 4866 and 2668 kg ha^{-1} in 2003 and 2004 respectively (Table 3). The statistical analysis showed no significant effects of the different weed harrowing treatments on pea yield.

Spring cereals

The average total number of weed plants in the control plot was 350 plants m^{-2} at Enköping in 2003, and 117 and 131 plants m^{-2} at Uppsala in 2003 and 2004 respectively (Table 4). At Enköping, *Polygonum lapathifolium* L. and *Galeopsis* spp. were the dominant species. Other common weed species at this site included *C. album*, *Fallopia convolvulus* (L.) A. Löve, *V. arvensis* and *Lapsana communis* L. At Uppsala, the dominant weed species was *C. album* and other weed species at this site included *Galeopsis* spp., *S. media*, *M. inodora* and *M. arvensis*.

As in the pea experiments, there were also significant interactions between treatment and experiment amongst the cereals. Treatment effects were significant. The best weed control was achieved when a late pre-wh was combined with one or two post-whs (Table 4).

At Uppsala, the cereal yield in the control plots was 5095 for spring wheat and 4597 kg ha^{-1} for oats in 2003 and 2004 respectively (Table 3). There were significant effects of the different weed harrowing treatments on the yield. The weed harrowing treatment that provided the

Table 4 Total number of weed plants (m^{-2}) in the three field experiments with spring cereals (oats, spring wheat) treated with different combinations of pre- (pre-wh) and post-weed harrowing (post-wh) at Enköping (En) in 2003, and at Uppsala (Ua) in 2003–2004

Treatment	En 2003 Oats	Ua 2003 Spring wheat	Ua 2004 Oats
Control (no weed harrowing)	350 (23)[a]	117 (14)[a]	131 (28)[a]
Early pre-wh (2–4 days after sowing)	168 (33)[b]	96 (46)[a]	106 (21)[ab]
Late pre-wh (6–8 days after sowing)	172 (112)[b]	117 (39)[a]	135 (50)[a]
Early + late pre-whs	161 (94)[b]	117 (45)[a]	133 (56)[a]
Early pre-wh + post-wh at crop growth stage DC 12-13	163 (84)[b]	32 (15)[b]	76 (27)[bc]
Late pre-wh + post-wh at crop growth stage DC 12-13	123 (33)[b]	28 (2)[b]	60 (18)[c]
Early pre-wh + post-whs, at crop growth stages DC 12-13 and DC 15-16	74 (28)[c]	10 (5)[bd]	–
Late pre-wh + post-whs, at crop growth stages DC 12-13 and DC 15-16	63 (35)[c]	5 (4)[cd]	–

Values indicate mean (SE) with $n = 3$. Mean in the same column with different superscript letters are significantly different ($P < 0.05$). –, treatment not performed in the experiment.

best weed control (late pre-wh + post-wh at DC12-13), also resulted in a significant decrease in cereal yield (Table 3).

Individual weed species

Sinapis arvensis

At Enköping in 2003 and 2004, the dominant weed species was *S. arvensis*. In 2003, *S. arvensis* density was significantly lower than the control plot for all treatments except the last weed harrowing at stage DC 15-16 (Table 5). Early pre-wh provided very good control of this species, resulting in an average decline of 82% (Table 5). A combination of pre-wh and post-wh(s) provided even better control with an average reduction of 89%. Using only weed harrowing after crop emergence provided poor control (population reduction of only 0–17%, Table 5).

In 2004, the number of *S. arvensis* plants in the experiment was extremely high (747 plants m^{-2} in the control plot) and the crop had poor establishment. Early or late pre-wh combined with two post-wh(s) provided the best weed control (a reduction of 57–59%) (Table 5).

Galeopsis *spp.*

In the oat experiment at Enköping in 2003, the dominant weed species were *Galeopsis* spp. and *P. lapathifolium*. The number of *Galeopsis* spp. plants in the control plot was 124 m^{-2}. Pre-wh combined with two post-whs significantly reduced the number of *Galeopsis* spp. plants (a reduction of 35–43%) (Table 5).

Polygonum lapathifolium

In the oat experiment at Enköping in 2003, *P. lapathifolium* plants were also dominant in the control plot

Table 5 Total number (m^{-2}) of four weed species (*Sinapis arvensis*, *Galeopsis* spp., *Polygonum lapathifolium*, *Chenopodium album*) in four field experiments treated with different combinations of pre- (pre-wh) and post-weed harrowing (post-wh) and sown with peas and spring cereals (oats) at Enköping (En) 2003 and Uppsala (Ua) 2004

Treatment	*S. arvensis* En 2003 Peas	*S. arvensis* En 2004 Peas	*Galeopsis* spp. En 2003 Oats	*P. lapathifolium* En 2003 Oats	*C. album* Ua 2004 Peas, oats
Control (no weed harrowing)	120 (20)[a]	747 (55)[a]	124 (13)[a]	192 (48)[a]	67 (7)[a]
Early pre-wh (2–4 days after sowing)	21 (8)[b]	656 (65)[ab]	87 (13)[a]	65 (13)[b]	61 (8)[a]
Late pre-wh (6–8 days after sowing)	–	613 (257)[b]	82 (29)[a]	85 (38)[b]	74 (14)[a]
Early + late pre-whs	–	571 (114)[b]	101 (42)[a]	51 (21)[bcd]	77 (14)[a]
Early pre-wh + post-wh at DC 12-13	13 (1)[bc]	607 (67)[b]	101 (26)[a]	55 (23)[bc]	54 (12)[a]
Late pre-wh + post-wh at DC 12-13	–	556 (60)[b]	70 (10)[b]	47 (14)[bcd]	23 (2)[b]
Early pre-wh + post-whs at DC 12-13, DC 15-16	10 (1)[c]	304 (101)[c]	53 (11)[c]	18 (7)[cd]	–
Late pre-wh + post-whs at DC 12-13, DC 15-16	–	320 (141)[c]	44 (13)[c]	15 (9)[d]	–
Post-wh at DC 12-13*	100 (1)[a]				
Post-wh at DC 15-16*	120 (1)[a]				
Post-whs at DC 12-13, DC 15-16*	100 (1)[a]				

Values indicate mean (SE) with $n = 3$ except for *C. album* where values indicate mean (SE) with $n = 6$ (two experiments). Mean in the same column with different superscript letters are significantly different ($P < 0.05$).
DC, crop growth stage at treatment; –, treatment not performed in the experiment.
*Post-wh, without pre-wh, was performed in one experiment (En 2003, peas).

with 192 plants m^{-2}. Significant effects on *P. lapathifolium* were achieved with pre-wh alone or combined with one or two post-wh(s) (Table 5). The best control of this species was achieved with pre-wh combined with two post-whs (reductions of 90% or more).

Chenopodium album

Chenopodium album dominated the weed population in the two field experiments at Uppsala in 2004. The number of *C. album* in the control plots at this site averaged 67 plants m^{-2}. The treatment effects were significant and the best weed control was achieved with a late pre-wh combined with one post-wh treatment (a reduction in *C. album* density of 66%) (Table 5). No significant interactions between treatment and experiment were observed.

Discussion

The major assumption underlying studies which use a reduction in the number of weeds to quantify the success of weed control measures in agriculture is the existence of a positive correlation between reduction in yield loss and reduction in weed numbers (Bastiaans *et al.*, 2008). In this study, the most successful treatment (in terms of reduction in weed numbers) also caused a yield reduction in spring cereals. The risk of yield reduction is highest when harrowing is performed at the most sensitive developmental stage of the crop, i.e. 1–2 true leaves stage in spring cereals and peas (Rasmussen, 1993). However, it may be argued that the purpose of weed control methods like weed harrowing is two-fold: (i) in the short-term, the aim is to disturb the development and growth of weeds to give the crop a competitive advantage and thereby achieve higher yield (Rasmussen & Ascard, 1995) and (ii) with the longer-term view, to reduce seed production by weeds to reach a situation where it is possible to grow a crop while minimising costs for weed control or risks for substantial yield reductions. Even when a treatment leads to reductions in both numbers of weeds and yield (thereby failing to fully meet the first goal), it may well contribute to the second goal to such an extent that yield losses will be lower during other phases of the crop rotation. Similarly, when a treatment does not affect yield at all, it may diminish the weed population. Dastgheib (2003) showed that pre- and post-emergence harrowing did not cause a yield loss in winter wheat, but reduced the weed cover, thereby contributing to the longer-term goal of reducing weed fecundity.

The short-term effect of weed harrowing on resource competition between crop and weeds depends on the weed flora, the development stage of crop and weeds, soil type and fertility, weather and soil moisture content (Melander *et al.*, 2005). Hansen *et al.* (2007) showed that the effects of pre-wh and post-wh on spring barley differed between crop varieties.

In the present study, the best weed control effect on the total number of weed plants was achieved when pre-wh was combined with post-wh. This was due to the fact that the weed flora in the field experiments consisted of both early and late emerging weed species. When pre- and post-wh was combined, it was possible to disturb the growth of both types of weed species at their most sensitive developmental stage (cotyledon stage). The importance of weed control timing in this respect was also shown by Dastgheib (2003), who observed that pre-wh in winter wheat sometimes provided satisfactory weed control, but a post-wh was required for late emerging weeds. Rasmussen and Rasmussen (1995) showed that with pre-wh in spring barley a reduction of 61% in weed dry weight was achieved, while a reduction of 74% was achieved when pre- and post-wh was combined. The weather conditions could not explain the effects of pre- and post-wh in the experiments.

The direct effect of harrowing on weed and crop seedling results from a combination of the magnitude of the mechanical impact of harrowing and from the sensitivity of seedlings to this impact. As the same driving speed was used for all treatments in our experiments, as plants grew and became more robust, the relative impact of harrowing decreased. Consequently, treatments combining pre-wh and post-wh at DC 15-16 showed a lesser effect on weed numbers than those combining pre-wh and post-wh at DC 12-13.

Pre-emergence harrowing was very effective against the early emerging tap-rooted species *S. arvensis* in the field experiment with peas at Enköping in 2003. Koch (1959) reported similar results. Rasmussen and Rasmussen (1995, 2000) also had similar results as well with reductions in dry weight of *S. arvensis* of 78% and 69% for crop row spacings of 12 and 20 cm respectively. When combined with post-wh, the control effect was reduced to 40% for 12 cm row spacing, but increased to 80% for 20 cm row spacing.

Cirujeda *et al.* (2003) studied the effects of pre- and post-wh on another tap-rooted weed species, *Papaver rhoeas* L., at two locations in Spain. They found a reduction of between 58% and 87% in weed density, but the control effects of pre-wh were quite variable and they provided no clear explanation for why. In our experiment in oats at Enköping in 2003, the number of early emerging *Galeopsis* spp. plants was only reduced by 30–37%, while for the late emerging species *P. lapathifolium*, the density was severely reduced by the pre-wh treatments. This is likely due to the fact that pre-wh was performed in the middle of May when *Galeopsis* spp.

had past its most susceptible stage (cotyledon stage), while *P. lapathifolium* was at its most susceptible stage. The late emerging weed species *C. album* was most effectively controlled when pre-wh was combined with one or two post-wh. The time at which the weed harrowing was performed prior to crop emergence did not influence these results, because *C. album* emerged late and in all cases after pre-wh.

In conclusion, according to our experiments, a combination of pre- and post-emergence harrowing treatments provided the best weed control (in terms of density). However, in spring cereals, this treatment also caused yield losses of 11–14%. The early emerging annual weed species *S. arvensis* and *Galeopsis* spp. were most effectively controlled by pre-emergence weed harrowing treatments alone or in combination with another harrowing shortly after crop emergence. Pre-emergence weed harrowing combined with one or two weed harrowing treatments after crop emergence proved to be most effective against later emerging annual weed species, such as *C. album* and *P. lapathifolium*.

Acknowledgements

This study was funded by the Swedish Board of Agriculture in Jönköping. I thank Professor Håkan Fogelfors for his co-operation within the study and I am grateful to the farmer Anders Karlsson, Enköping and farm manager Lennart Karlsson, Uppsala, for their technical assistance with the field experiments. The statistician PhD Johannes Forkman is kindly acknowledged for his valuable advice. I also want to thank Professor Theo Verwijst, and anonymous referees for their valuable comments on the manuscript.

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