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Weeds and yields of spring cereals as influenced by stubble-cultivation and reduced doses of herbicides in five long-term trials

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SUMMARY

The influence of herbicides at reduced rates and repeated stubble-cultivation on weeds and crop yields was estimated in five field trials with spring-sown cereals situated in the south of Sweden during the autumn of 1989 until the spring of 1997. Stubble-cultivation was accomplished during 1989–1996, while herbicides were applied at 0, 1/8, 1/4 or 1/2 of full dose during 1990–1996.

In the spring of 1997, i.e. after 7 years without herbicide application, seedling densities 3 weeks after weed emergence were 68–340/m² at three sites and 535–610/m² at two sites when averaged over tillage treatments.

Averaged over herbicide doses, stubble-cultivation reduced the plant density of annual broad-leaved weeds by 6–32% at three sites and increased the density by 25% at one site. At the remaining site, the density was not significantly influenced. Stubble-cultivation reduced the populations of two perennial and seven annual weed species, while one species was stimulated and nine species showed null, or inconsistent, responses. In the spring of 1997, i.e. one year after the last herbicide application, the densities of weed seedlings in 1/8, 1/4 and 1/2-doses were 34, 46 and 56% lower, respectively, than in the untreated controls.

Stubble-cultivation increased crop yields at four sites by 200 kg/ha as a mean over herbicide doses. At these four sites, averaged over 1993–1995, herbicides increased yields in plots that were not stubble-cultivated by 7, 8 and 10% in the 1/8, 1/4 and 1/2 of a full dose, respectively, relative to the untreated control. In 1996, herbicides increased yields at only two sites.

It is concluded that a fruitful way for weed management with a low input of agrochemicals is to combine the use of herbicides at reduced rates with repeated stubble-cultivation.

INTRODUCTION

Acceptable control of weeds can often be obtained by applying herbicides at lower doses than are normally recommended (Fogelfors 1990; Salonen 1992; Lundkvist 1997). This makes it possible to decrease the negative environmental impact of agrochemicals by using herbicides at reduced rates. However, in order to maintain crop-yield levels and to avoid increasing weed populations despite low herbicide inputs, it may be necessary to combine different weed-regulating practices. In regions of the world where the temperature allows continued weed growth and seed germination after crop harvest, it is likely that stubble-cultivation, i.e. working the stubble after harvest using a cultivator, may provide one component in an integrated weed management system (IWM).

Provided soil humidity is suitable, tillage initiates weed seed germination and seedling emergence. Soil disturbance may stimulate seed germination of several weed species and, at least for some of these species, the increase is caused by changes in soil conditions independent of the movement of seeds within the soil profile (Mohler & Galford 1997). Although only a limited part of the viable seeds in the seedbank gives rise to seedlings after tillage, often not more than 3–20% (Roberts & Ricketts 1979; Leguizamón & Roberts 1982; Dessaint *et al*. 1997), it may be possible to increase seed germination and seedbank depletion by repeated tillage. That seed decline is more rapid in ploughed than in uncultivated soil was demonstrated by Froud-Williams *et al*. (1983). A positive relationship between the soil-disturbance intensity and

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seedling density has been shown (Håkansson 1995; Jensen 1995), and it appears that intense tillage systems decrease the soil seedbank more than systems causing less disturbance (Feldman *et al*. 1997).

Established weeds must be destroyed before the onset of reproduction so that addition to the seedbank is prevented. As a result of one year of omitted weed control, a 14-fold increase of the seedbank has been estimated in the absence of competition from a crop (Leguizamón & Roberts 1982). Although the viability of seeds of many species in the soil is low (Barralis *et al*. 1988) and often declines exponentially with time (Wilson & Lawson 1992; Popay *et al*. 1994), high weed infestation may persist during 4 years or longer as a result of 1 year of poor weed control (Wilson & Lawson 1992).

The influence of tillage time on germination is, for some species, fairly predictable (Håkansson 1983), whereas other species show an inconsistent response (Roberts & Potter 1980; Pollard & Cussans 1981). Although stubble-cultivation may have a minor influence on annual weeds in the short term, it is plausible that the long-term effect of autumn cultivation may be to gradually reduce the seedbank through stimulation of germination of winter-annual weeds and, possibly, also by increasing the number of seeds germinating in spring.

The depletion of the seedbank caused by soil disturbance is probably not due to a simple effect on the number of emerged seedlings. Germination may be initiated so deep in the soil that the seedlings die before reaching the soil surface; also redistribution within the soil profile may alter the conditions for predation or attacks by fungi. Although tillage such as stubble-cultivation seldom kills perennial weeds immediately, the vegetative parts can be damaged and the storage of energy and nutrients can be reduced as the formation of new shoots is initiated.

The hypothesis of this study was that it is possible to reduce the input of herbicides in spring-sown cereals without sacrificing crop yields or risking dramatically increased weed populations when reduced rates of herbicides are combined with stubble-cultivation. The objective was to study the long-term effects on weeds and crop yields at sites with different weed communities in order to develop weed management strategies with lower input of herbicides than normally used in conventional agriculture.

MATERIALS AND METHODS

Treatments

Five field trials with reduced doses of herbicides in combination with stubble-cultivation were initiated in southern Sweden in the autumn of 1989 (Table 1). Henceforth, stubble-cultivated and non-cultivated plots are referred to as SC and NC, respectively.

Starting in 1990, herbicides were applied each spring until 1996, at appropriate development stages of crop and weeds, at rates of 0, 1/8, 1/4 and 1/2 of the dose recommended by the manufacturer. During the years 1990–1994, a mixture of bromoxynil 36 g/l, ioxynil 54 g/l, MCPA 120 g/l and dichlorprop-P 165 g/l (as Oxitril-P, Rhône-Poulenc) was used at reduced rates based on the 2·4 l/ha normally recommended. Due to prohibition of this preparation by the Swedish authorities, it was replaced in 1995 and 1996 by tribenuronmethyl 750 g/l (as Express 75 DF + 0·1 l of the surfactant Lissapol Bio, Du Pont) at reduced rates based on the 8 g/ha normally recommended. Herbicides were applied with a sprayer, delivering 200 l/ha at 200 kPa.

In the spring, secondary tillage was done with a harrow to 4 cm depth. The three-course rotation included only spring-sown crops; barley, oats and wheat. After harvest, the straw was chopped and evenly distributed within each treatment. Stubble-cultivation was accomplished with a stubble-cultivator to 4–7 cm depth, immediately after harvest, i.e. in August or September, and, if necessary, once or twice more during the autumn to prevent seed setting. Averaged over sites and years, SC was repeated twice each autumn during 1989–1996. The plots were ploughed in November with all tillage performed so that a minimum of soil was transported between treatments. The trials were fertilized each year to maintain fertility levels, while insecticides or fungicides were used when necessary.

The climate in the region is temperate and humid with a mean temperature during the growing season (from April until September) of 13·6 °C and a mean precipitation varying from 248 mm to 356 mm (Alexandersson *et al*. 1991).

Sampling

Crops were harvested each year by combine harvester and the yields estimated. The grain was analysed for moisture content and the yields of screenings, i.e. the refuse left after screening, were estimated. About 5 weeks after herbicide application, the numbers and/or fresh weights of the weed species present were estimated in 2–4 quadrats of 0·25 m^2 each, per plot. The highest number of quadrats was used at the lowest weed density. When species with a climbing or creeping growth form were present in high numbers, the percentage of surface cover for these species was estimated visually.

In the spring of 1997, after sowing the crop but before herbicide application, weed species were identified and seedlings or shoots were counted in 2–5 squares of 0·08–0·25 m^2 each. The sampling was done approximately 3 weeks after the first weed emerged.

Reported data on grain yields are corrected for screenings and adjusted to 15% moisture content. Data on weeds are reported as fresh weights.

Table 1. *Sites, position and particle-size distribution in the top soil*

Site	Position	Particle size distribution (g/100 g)			Organic matter (g/100 g)	Soil type
	Longitude ; latitude	< 2 μm	2–60 μm	60–2000 μm		
Lanna	58°20′ N ; 13°07′ E	28·0	49·0	23·0	3·6	Clay loam
Lönnstorp	55°39′ N; 13°05′ E	21·1	26·7	52·2	3·6	Sandy loam
Stenstugu	57°35′ N; 18°27′ E	26·8	25·8	47·5	3·1	Silt loam
Säby	59°51′ N; 17°43′ E	8·1	38·6	53·3	4·2	Sandy loam
Vreta	58°25′ N; 15°38′ E	—	—	—	—	Clay loam

Experimental design and statistical analyses

At each of five sites the trials were arranged in a completely randomized block design, with stubble cultivation and herbicide doses as two fully crossed treatment factors and with three replicates of the eight treatment combinations. The plot size was 6 m by 15 m. The same treatments were applied to the same plots throughout all years, i.e. stubble cultivation during 1989–1996 and herbicide applications during 1990–1996.

To standardize productivity for different sites and crops, relative yields were used for analysis of treatment effects on grain yields. For each site the relative yield (Y_r) was calculated by:

$$Y_r = (Y/Y_b) \times 100 \qquad (1)$$

where Y is the actual yield and Y_b is the mean yield, averaged over blocks, of the plots not stubble-cultivated or treated with herbicides. In addition, for 1995 and 1996 analyses of treatment effects on absolute grain yields were made.

Data were analysed using analyses of variance (SAS General Linear Models procedure) (SAS Institute Inc. 1995). As a level of significance, $P < 0{\cdot}05$ was used. In the statistical analysis, years were considered as repeated measurements (Crowder & Hand 1990).

To stabilize variances, data on weed weights were $\log_{10}(x+1)$ transformed, while weed counts were square root transformed. For percentages, the angular transformation was used (Mead & Curnow 1983). Data were back-transformed for presentation. Graphical analysis of the homogeneity of variance of the residuals revealed no need for transformation of data on the yields or relative yields. Data from the weed counts in the spring of 1997 were analysed separately.

RESULTS

Significant site by treatment interactions were found for total weed density and for most of the individual weed species ($P < 0{\cdot}05$). For many species, site by year by treatment interaction effects were observed ($P < 0{\cdot}05$).

Stubble-cultivation

Perennial weeds

In plots not stubble-cultivated or treated by herbicides, the occurrence of the perennial *Cirsium arvense* (L.) Scop. increased with time at three of the five sites. This species was efficiently controlled by SC, and significant differences ($P < 0{\cdot}05$) between tillage treatments were obtained by 1991 at Lönnstorp, and by 1993 and 1995 at Lanna and Säby, respectively (Table 2). Stubble-cultivation reduced the population of the species most in 0- or 1/8-dose, where density was reduced by 78–100%.

Stubble-cultivation was effective also against *Elymus repens* (L.) Gould at the two sites in which it was found. The species was absent during the first years of the trials and a significant influence of tillage was observed for the first time in 1993 at Stenstugu and in 1995 at Lönnstorp. At both sites, SC reduced the density or weight of the species by 90–100%.

The species *Sonchus arvensis* L. was found at three sites, but was significantly controlled by SC only at two of them. At Säby, SC reduced the density and weight of *S. arvensis* by 65–80% during the years 1994–1997 ($P < 0{\cdot}01$). At Lönnstorp, the population of the species was high enough for statistical analysis only in 1996, when shoot density and weight in SC was 65 and 95% lower, respectively, than in NC ($P < 0{\cdot}05$). At Lanna, SC seemed to increase the plant density but to decrease the weight of *S. arvensis* during 1993–1996, suggesting that SC resulted in more numerous, but smaller, shoots. However, the difference was statistically significant only for plant density. In 1997, the plant density of the species was twice as high in SC as in NC, 67 ± 25 and 33 ± 8 shoots/m², respectively ($P < 0{\cdot}001$).

Annual weeds

The species *Chenopodium album* L. was found at four sites. At Lanna and Vreta, the response to SC was inconsistent between years (Table 2). However, in 1997 the plant densities of the species were 18–60% lower in SC than in NC. At Lönnstorp, the plant density of *C. album* was significantly lower in SC than in NC by 1994, and by 1997 the difference was 20%

Table 2. *Positive* (*P*) *and negative* (*N*) *influences of stubble-cultivation on different weed species. Only statistically significant differences are included*

Species	Site: Lanna	Lönnstorp	Säby	Vreta	Stenstugu
Annuals					
Bilderdykia convolvulus	N	—	N	—	—
Capsella bursa-pastoris	—	—	—	N	—
Chenopodium album	P, N	N	P	P, N	—
Galeopsis spp.	—	—	P	—	—
Lamium spp.	—	—	—	N	—
Matricaria perforata	—	N	N	N	—
Senecio vulgaris	—	N	—	—	—
Silene noctiflora	—	N	—	—	—
Stellaria media	P	N	P	N	—
Viola arvensis	—	—	N	—	—
Perennials					
Cirsium arvense	N	N	N	—	—
Elymus repens	—	N	—	—	N
Sonchus arvensis	P	N	N	—	—

—, Species not present or showing no response to tillage.

($P < 0.05$). Only at Säby was the plant density of the species increased by SC, with an increase of as much as 55% in 1997. Also, the winter-annual *Stellaria media* (L.) Vill showed inconsistent response to tillage. In 1997, the difference between treatments was statistically significant only at Lönnstorp, where SC reduced the plant density by 30%. At Säby, SC decreased the plant density of *Viola arvensis* Murray but increased the plant density of *Galeopsis* spp. by 53% and 20%, respectively ($P < 0.05$) as a mean over the years 1990–1996. In plots receiving no herbicides or 1/8-dose, SC reduced the plant density of *Matricaria perforata* (L.) Mérat by 63 and 81%, respectively, as a mean over three sites, whereas no significant effect was observed at higher doses. Also, for several other species a statistically significant interaction between tillage and herbicide dose revealed that the response to SC was more marked for the 0 or 1/8-dose rates than for the higher dose rates.

Some species did not show any significant response to soil cultivation until the last sampling in the spring of 1997. At that time, the density of *Bilderdykia convolvulus* (L.) Dumort. was 29% lower in SC than in NC at Säby and Lanna, while at Vreta, SC reduced the plant densities of *Lamium* spp. and *Capsella bursa-pastoris* (L.) Medicus by 41 and 44%, respectively ($P < 0.01$).

In 1997, the density of annual broad-leaved weeds as a group was significantly influenced by SC at four sites. Only at Stenstugu, was weed density low and unaffected by tillage. Averaged over herbicide doses, SC increased weed density at Säby by 25% but reduced weed density at Lanna, Lönnstorp and Vreta by 6, 20 and 32%, respectively ($P < 0.05$). Figure 1 summarizes the herbicide and stubble-cultivation effects on annual broad-leaved weeds in 1997 averaged over the three sites Lanna, Lönnstorp and Vreta at which SC was effective.

Herbicides

In this paper, direct effects of herbicides on weeds during 1990–1996 are not reported. Only data from 1997 are presented. This sampling was done one year after the last herbicide application and reflects long-term influences on the part of the seedbank that produces emerged seedlings. For total weed density and for most of the individual species that were significantly influenced by herbicides, site by treatment interaction effects were observed in 1997 ($P < 0.05$). In plots where no herbicides had been used during the previous 7 years, plant densities of broad-leaved weeds, averaged over tillage treatments, were $68 \pm 11/m^2$ at Stenstugu, $311 \pm 25/m^2$ at Lönnstorp and Lanna, and $573 \pm 38/m^2$ at Vreta and Säby in 1997. At all sites, the use of herbicides reduced the density of weed seedlings, even when only 1/8 of the recommended dose was used ($P < 0.001$). Averaged over sites and tillage, the density of weed seedlings was reduced by 34% at the 1/8-dose, 46% at the 1/4-dose and 56% at the 1/2-dose.

Individual weed species were reduced by herbicides at reduced rates and the plant densities of all but one species were reduced even at the lowest dose. This was found for *B. convolvulus*, *Brassica napus* L., *C. album*, *Lamium* spp. and *S. media* ($P < 0.05$). However, for good control of the perennial *Sonchus arvensis*, 1/2 of a full dose was needed.

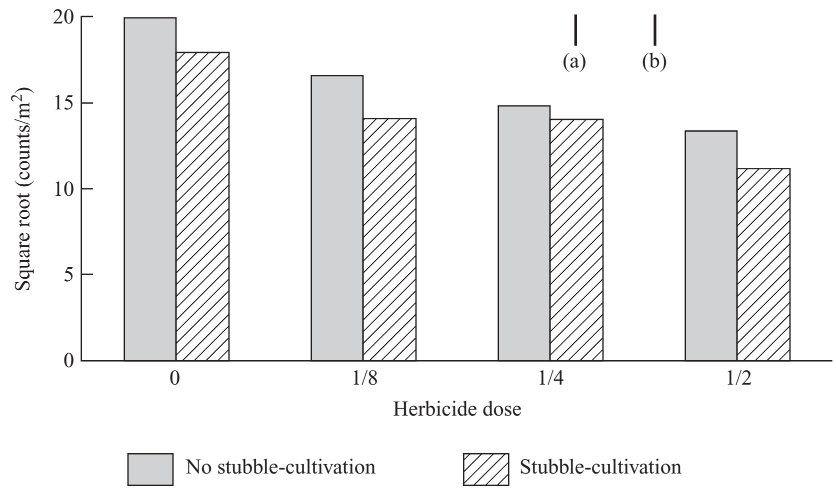

Fig. 1. Plant density of annual broad-leaved weeds in 1997 as means of the three sites where stubble cultivation reduced weed counts ($P < 0{\cdot}05$). Herbicides applied at reduced rates of a full dose during 1990–1996 and tillage applied during 1989–1996. Bars indicate the L.S.D. for (*a*) herbicide dose and (*b*) stubble-cultivation. (Error D.F. = 14.)

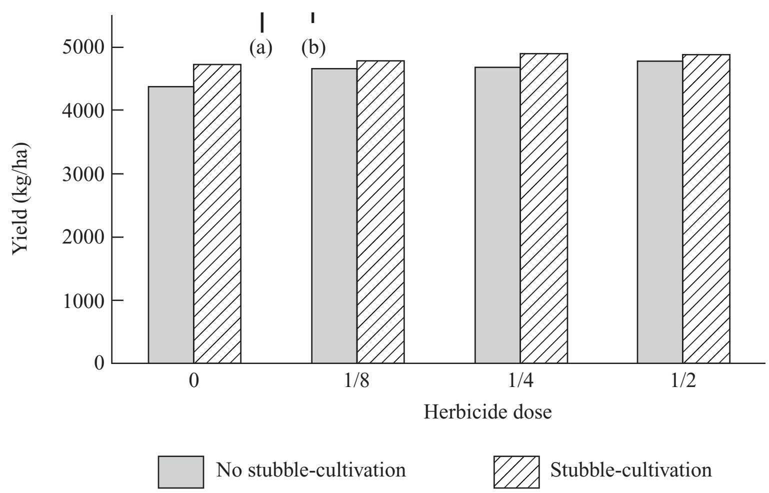

Fig. 2. Grain yields 1994–1996 as means of the four sites where stubble cultivation influenced yield ($P < 0{\cdot}05$). Herbicides applied at reduced rates of a full dose during 1990–1996 and tillage applied during 1989–1996. Bars indicate the L.S.D. for (*a*) herbicide dose and (*b*) stubble-cultivation. (Error D.F. = 21.)

Data from 1997 on a further nine weed species were statistically analysed, but no significant influences of SC or herbicides on plant densities were found. The species were *Erysimum cheiranthoides* L., *Fumaria officinalis* L., *Galeopsis* spp., *Galium aparine* L./*spurium* L., *Polygonum aviculare* L., *Silene noctiflora* L., *Sonchus asper* (L.) Hill, *Thlaspi arvense* L. and *V. arvensis*.

Yields

Averaged over years, the highest barley and oat yields were obtained at Lönnstorp, 5665 ± 882 and 6660 ± 358 kg/ha, respectively, while the highest wheat yield was obtained at Säby, 5453 ± 262 kg/ha. The lowest mean yields of barley and wheat were obtained at Lanna, 4380 ± 500 and 2265 ± 67 kg/ha, respectively, while the lowest mean yield of oats was obtained at Vreta, 4540 ± 272 kg/ha.

During the years 1990 and 1991, the relative yield (Y_r) was not significantly influenced by treatments, while in 1992 and 1993 the influences at different sites were inconsistent. In 1994, there was a significant site by dose by tillage interaction effect and at all sites except Stenstugu, SC increased yields in plots not

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treated by herbicides ($P < 0.05$). This also seemed to be the case in 1995 and 1996, although the differences were not statistically significant. The yield increase in non-herbicide plots caused by SC varied between sites and years but was, on average, 300 kg/ha. The highest yield increases were obtained at Vreta in 1994 and 1995, when SC, despite a modest weed infestation of 15–120 g/m^2, increased yields by an average of 570 kg/ha. In 1995, SC increased Y_r irrespective of herbicide treatment at four of the sites ($P < 0.05$). At these four sites, SC increased the crop yields, when averaged over the 2 last experimental years and over doses, by 200 kg/ha (Fig. 2).

With a few exceptions, all doses of herbicides increased Y_r during 1993–1996, the increase being more pronounced in NC than in SC. This was statistically significant only in 1994 but was apparent at most sites also in 1993 and 1995. Averaged over these 3 years and over the four sites, excluding Stenstugu, the yields in 1/8, 1/4 and 1/2 dose rates increased by 7, 8 and 10%, respectively, in NC. In SC, herbicides increased yields by 3–5% during 1993–1995. In 1996, herbicides increased yields only at two sites. No apparent correlation between yields and weed infestation was found at the three remaining sites where herbicides did not increase yields in 1996. At Stenstugu, where weed infestation was low during all years, herbicides had no consistent effect on the crop yields.

DISCUSSION

Other studies have also shown that autumn tillage can efficiently control *E. repens* (Håkansson 1982; Boström & Fogelfors 1999). The timing of tillage is less critical to species that do not show any innate dormancy, like *E. repens* (Håkansson 1982). The deep-rooted *C. arvense* may sometimes be more difficult to control by SC (Boström & Fogelfors 1999), not only because of its root system but also because the species shows a tendency to dormancy in the autumn (Kvist & Håkansson 1985). In the present study, SC reduced the weight of the perennial *S. arvensis* at all three sites where it was found, but increased the plant density at one of them. A pronounced dormancy of the underground regenerative organs in the early autumn (Håkansson & Wallgren 1972; Håkansson 1982) may prevent bud growth and depletion of food reserves otherwise initiated by tillage. Hence, there is a risk that SC may favour this species through breakage of the vegetative parts into smaller, but more numerous units.

The outcome of tillage effects on the weed community was sometimes confounded by interspecific competition effects. This was noticed in non-herbicide plots at Säby, where several weed species, dominated by the competitive *S. arvensis*, were efficiently controlled by SC. However, during the last 3 years SC favoured the population of *C. album*. Since autumn-tillage ought not to have any direct effect on this summer-annual species, the observed increase in SC may be a response to decreased competition from the more sensitive species. That certain weed species may proliferate in the absence of competition from other weeds is probably a common occurrence on arable land (Lintell-Smith *et al.* 1991; Wright *et al.* 1997; McCloskey *et al.* 1998). Another reason for the high population of *C. album* in SC may be the burrowing of seeds into the upper soil layer, making them less exposed to surface-feeding predators like birds (McEwen *et al.* 1986), mice (Povey *et al.* 1993) or insects (Marino *et al.* 1997).

In 1997, weeds were counted shortly after crop and weed emergence, i.e. 5 to 6 weeks earlier than during 1990–1996 and without a preceding herbicide application. At four of the sites, weed densities in all treatments were considerably higher in 1997 than during previous years. The higher densities were almost certainly a result of the earlier sampling date rather than a response to treatments. This situation is probably not unusual. At the time of seeding, soil conditions often favour seed germination, but many of the seedlings die shortly after emergence due to intra- and interspecific competition and to low humidity near the soil surface. Only at Stenstugu was weed density similar in 1997 to earlier years, and this might have been a result of dry soil conditions at time of weed emergence (SMHI 1997). During all years, the weed density was lower at Stenstugu than at other sites, possibly due to lower precipitation (Alexandersson *et al.* 1991; SMHI 1997).

Herbicides may reduce seed production more than shoot dry matter, and seed characteristics may be influenced at very low doses (Andersson 1995, 1996). Effects on seed production in *Thlaspi arvense* have been demonstrated at 1/16 of a full dose of MCPA (full dose = 1·5 kg a.i./ha) or tribenuron-methyl (full dose = 6 g a.i./ha) (Andersson 1995). In the present study, the lowest dose rate (1/8) reduced the plant density of many species and also reduced the germinating part of the seedbank significantly in 1997.

When herbicides were not used for 7 years, weed densities did not increase significantly at four of the sites. Only at Säby was the weed density in non-herbicide plots increased, being 2-fold higher in 1995–1996 than in 1990–1994. In 1996, weed densities in non-herbicide plots were less than 130/m^2 at four sites with only Säby showing a high weed density with counts as high as 285/m^2. Hence, it seems possible to omit herbicides for a few years without necessarily running the risk of having dramatically increased weed populations. This was, in fact, the situation in our study, i.e. under Swedish conditions in spring-sown cereals on loam soils. In a study in France, weed seedling densities in an arable field did not increase during the first 4 years without herbicide application

(Dessaint *et al.* 1997). Other studies have indicated that minimal or no weed control during 4 years may result in a considerable increase of the seedbank (Hill *et al.* 1989; Davies *et al.* 1993).

In our study, herbicides applied at reduced rates not only reduced the weed populations but also that part of the seedbank that produced emerged seedlings. Significant effects on weeds and yields were obtained at 1/8 of a full dose and the influence increased as herbicide dose increased. The risk of increased weed populations when using herbicides at lower doses than are normally recommended can be substantially reduced by simultaneous use of other weed management strategies, e.g. stubble-cultivation, and by use of guidelines (Boström 1994) for choice of appropriate dose and herbicide.

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