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RESEARCH PAPER

Influence of sowing density and spatial pattern of spring wheat (*Triticum aestivum*) on the suppression of different weed species

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To better understand the potential for improving weed management in cereal crops with increased crop density and spatial uniformity, we conducted field experiments over two years with spring wheat (*Triticum aestivum*) and four weed species: lambsquarters (*Chenopodium album*), Italian ryegrass (*Lolium multiflorum*), white mustard (*Sinapis alba*), and chickweed (*Stellaria media*). The crops were sown at three densities (204, 449, and 721 seeds m^{-2}) and in two spatial patterns (normal rows and a highly uniform pattern), and the weeds were sown in a random pattern at a high density. In most cases, the sown weeds dominated the weed community but, in other cases, naturally occurring weeds were also important. There were strong and significant effects regarding the weed species sown, the crop density, and the spatial distribution on the weed biomass in both years. The weed biomass decreased with increased crop density in 29 out of 30 cases. On average, the weed biomass was lower and the grain yield was higher in the uniform compared to the row pattern in both 2001 and 2002. Despite the differences in weed biomass, the responses of *L. multiflorum*, *S. media*, and *C. album* populations to crop density and spatial uniformity were very similar, as were their effects on the grain yield. *Sinapis alba* was by far the strongest competitor and it responded somewhat differently. Our results suggest that a combination of increased crop density and a more uniform spatial pattern can contribute to a reduction in weed biomass and yield loss, but the effects are smaller if the weeds are taller than the crop when crop–weed competition becomes intense.

Keywords: crop density, crop–weed competition, spatial distribution, spatial uniformity, *Triticum aestivum*, weed suppression.

INTRODUCTION

Public concern about the effects of herbicide use on the environment and human health has increased the interest in reducing the use of herbicides in agriculture and in developing alternative methods for weed control. One way to control weeds in cereals is to improve the ability of the crop itself to suppress weeds (Jordan 1993; Lemerle *et al*. 2001; Mohler 2001). The seeding rate of the crop is an important factor in determining the biomass production of weeds and most studies show a decreasing weed biomass at higher crop densities (Blackshaw 1993; Tollenaar *et al*. 1994; Doll 1997). The spatial distribution of the crop can also influence weed biomass production. Narrower row spacing usually results in a modest decrease in weed biomass (Malik *et al*. 1993; Murphy *et al*. 1996) and an increase in yield (Solie *et al*. 1991). Fischer and Miles (1973) modeled a plant's exploitation of resources in two dimensions as an expanding circle, centered at the point of seedling emergence. They predicted that the sowing of crops in a triangular pattern would result in the most efficient exploitation of space by crop plants and in the least amount of space available for weed growth.

Larger plants often have a disproportionate advantage in competition with smaller plants and suppress the growth of their smaller neighbors, a phenomenon called "size-

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asymmetric competition" (Weiner 1990; Schwinning & Weiner 1998). Recent studies showed that both increased crop density and reduced row spacing decreased the weed biomass and increased the yield of weed-infested spring wheat (Weiner *et al.* 2001; Olsen *et al.* 2005b). Under very high weed pressure, a combination of high crop-sowing density and increased spatial uniformity resulted in a 60% reduction in weed biomass and a corresponding reduction in crop losses due to weeds in comparison to normal sowing practise (Weiner *et al.* 2001). To understand the relationship between crop density, spatial distribution, and weed suppression, it is important to investigate the effects on different types of weeds. In a previous study with winter wheat (Olsen *et al.* 2005a), different weed species varied in their biomass and, therefore, their effects on crop biomass and yield, but the relative effects of crop density and sowing pattern on weed suppression were surprisingly consistent across the species. Here, we study how weed communities dominated by different weed species respond to increased crop density and spatial uniformity in spring-sown wheat.

MATERIALS AND METHODS

We used three crop densities (204, 449, and 721 seeds m^{-2}; hereafter, low, medium, and high density) of spring wheat (*Triticum aestivum* L. cv. Leguan), two spatial patterns (normal 12.8 cm rows and a uniform grid-like pattern), and four weed species with different sizes and growth forms: white mustard (*Sinapis alba* L.), Italian ryegrass (*Lolium multiflorum* Lam. cv. Liquattro), lambsquarters (*Chenopodium album* L.), and common chickweed (*Stellaria media* (L.) Vill.) in a complete randomized block design. We modified a precision seed drill (Kverneland Accord Corporation, Soest, Germany) to sow wheat in a uniform pattern (Weiner *et al.* 2001). The uniform pattern was achieved through narrow row spacings in which the spacing between the rows was as close as possible to the precision spacing within the rows for each density. The ratio of inter to intra row distance in the uniform pattern was 1:1 for the low density, 4:5 for the medium density, and 5:4 for the high density crops. We used a standard research seed drill with 12.8 cm row spacing to sow the normal row pattern.

The experiments were performed at the Royal Veterinary and Agricultural University's research farm in Taastrup, Denmark (55°40′N, 12°18′E). The soil is a sandy clay loam typical of eastern Zealand. The climate is temperate/maritime, with a mean temperature of 0°C in January and 16.5°C in July, and a mean annual precipitation of 613 mm. The plots were 1.31 × 8.0 m and there were four replicated blocks. The plots were sown on 3 May 2001. After sowing the wheat, the soil was rolled and the seeds of one of the four weed species were dropped on the soil surface, harrowed lightly, and rolled again. The seeds of the small-seeded weed species (*C. album* and *S. media*) were mixed with coarse flour before sowing. The weeds were sown in high densities to obtain high weed pressures (*S. alba* = 400 m^{-2}, *L. multiflorum* = 500 m^{-2}, *C. album* = 2000 m^{-2}, and *S. media* = 3000 m^{-2}) and to be on the flat part of the density–biomass relationship ("constant final biomass yield"). To ensure a high emergence rate of the small-seeded weed species, the plots were watered 7, 9, and 11 days after sowing (DAS). Twelve days after sowing, the experimental plots were fertilized at a rate of 80 kg N (nitrogen) ha^{-1}. The emergence of the crop and weeds was counted within single, randomly placed 0.25 m^2 quadrats in each plot in three blocks between 19 and 50 DAS in 2001 and 28–29 DAS in 2002. The height of the wheat, *C. album*, *S. alba*, and *S. media* was measured 20, 39, 50, and 56 DAS. We measured the biomass of the wheat, as well as naturally occurring and sown weeds, from 2 to 6 July 2001 by harvesting, drying, and weighing all above-ground biomass within a single, randomly placed 0.25 m^2 quadrat in each plot. At maturity in early September, the crop was harvested and the grain yield from each experimental plot was determined after cleaning.

The experiment was repeated in the following year (sown 9 April 2002). After sowing the wheat, the soil was rolled and planed before sowing the weeds to reduce rolling of the *S. alba* seeds. The experiment was watered immediately after sowing. Two weeks later, the experiment was fertilized at a rate of 80 kg N ha^{-1}. The emergence of the crop and weeds was counted within single, randomly placed 0.25 m^2 quadrats. We measured the biomass of the sown weeds, wheat, and naturally occurring weeds from 24 to 25 June 2002 in the same way as the previous year. At maturity in late August, the crop was harvested and the grain yield was determined after cleaning.

All data were analyzed using PROC MIXED (SAS 1996), which is based on likelihood principles, with block as a random factor. As weed biomass, wheat biomass, grain yield, and their variances differed greatly between the 2 years, we analyzed each year separately. To achieve homogeneity of variance, the weed biomass and grain yield data were square root-transformed, but the data are presented in the figures as untransformed means.

RESULTS

Weed and wheat emergence

In 2001, *S. alba*, *L. multiflorum*, *C. album*, and *S. media* started emerging 4, 7, 8, and 8 days later than the crop, respectively. In 2002, *S. alba* emerged in one flush 13 DAS, whereas the crop and the other weed species started emerging on that day.

The emergence rate (number of emerged plants/number of seeds sown, expressed as a percentage) of the crop was 96.2% in 2001 and 90.5% in 2002, whereas the emergence rate of the weed species was higher in 2002 than in 2001. The emergence rates of *S. alba* were 48% in 2001 and close to 100% in 2002, probably related to better soil coverage in the second year. The emergence rates of *L. multiflorum* were 37.3% in 2001 and 43.6% in 2002, the emergence rates of *C. album* were 13% in 2001 and 18.4% in 2002, and the emergence rates of *S. media* were 14.7% in 2001 and 23.1% in 2002.

Weed biomass

In 2001, the biomass of the sown weed species was 68, 97, 100, and 93% of the total weed biomass for *C. album*, *L. multiflorum*, *S. alba*, and *S. media*, respectively. In 2002, the biomass of the sown weed species was 32, 71, 97, and 70% of the total weed biomass. Naturally occurring weeds included spotted ladysthumb (*Polygonum persicaria* L.), black bindweed (*Polygonum convolvulus* L.), charlock mustard (*Sinapis arvensis* L.), *S. media*, and *C. album*.

2001

There were strong and significant effects of the weed species, sowing density, and sowing pattern on the weed biomass (Table 1). The weed biomass decreased with increasing crop density in both patterns, except in one case (*S. alba*, in rows from medium to high crop density; Fig. 1). There were weak but significant interactions between the crop density and weed species, and between the crop density and pattern. As *S. alba* was taller and had a much higher biomass than the other weed species, the data were also analyzed without *S. alba* (data not shown). Without *S. alba*, there were strong and significant effects of the weed species, sowing density, and sowing pattern, but no significant interactions involving the weed species. This means that the observed interaction between crop density and weed species in the complete analysis was primarily related to *S. alba*.

2002

In 2002, the emergence of *S. alba* and the biomass for all weed species were much higher than in 2001 (Fig. 1). Despite large differences in the weed biomass between the 2 years, the overall effects were similar. There were strong and significant effects of the weed species, sowing

Table 1. Test of fixed effects on the total above-ground dry mass of weeds (square root-transformed), the total above-ground dry mass of wheat, and the grain yield (square root-transformed) in 2001 and 2002, based on PROC MIXED (SAS [1996])

Source	d.f.	Weed dry mass		Wheat dry mass		Grain yield	
		F-value	*P*-value	*F*-value	*P*-value	*F*-value	*P*-value
2001							
Weed species (W)	3	202.60	<0.0001	50.22	<0.0001	195.72	<0.0001
Sowing density (D)	2	105.91	<0.0001	36.79	<0.0001	47.04	<0.0001
Sowing pattern (P)	1	24.39	<0.0001	12.19	<0.0001	10.04	0.0020
W × D	6	2.32	0.0410	2.53	0.0280	15.76	<0.0001
W × P	3	–	–	2.25	0.0890	2.22	0.0930
D × P	2	4.27	0.0170	–	–	–	–
W × D × P	6	–	–	–	–	2.07	0.0670
2002							
Weed species (W)	3	228.97	<0.0001	251.51	<0.0001	303.11	<0.0001
Sowing density (D)	2	104.23	<0.0001	138.03	<0.0001	85.71	<0.0001
Sowing pattern (P)	1	13.29	<0.0001	35.69	<0.0001	5.26	<0.0001
W × D	6	4.27	0.0150	–	–	–	–

Interactions with $P > 0.1$ are removed from the analyses.

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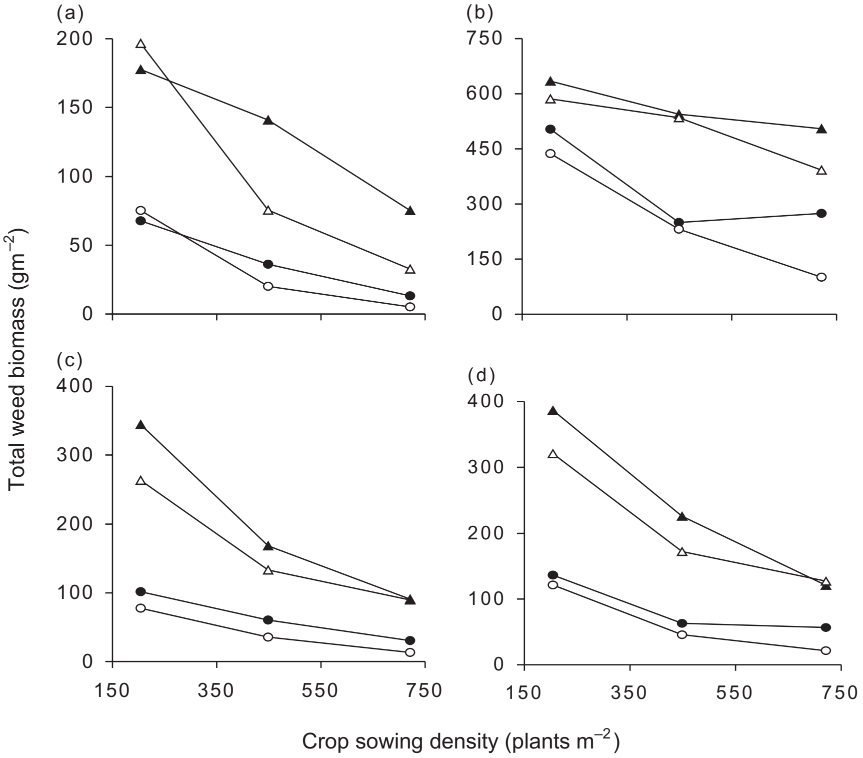

Fig. 1. Total weed biomass of four weed species, (a) *Chenopodium album*, (b) *Sinapis alba*, (c) *Stellaria media* and (d) *Lolium multiflorum*, sown in combination with spring wheat in two patterns and three crop densities (204, 449, 721 plants m^{-2}) in 2001 and 2002. (●), row pattern, 2001; (○), uniform pattern, 2001; (▲), row pattern, 2002; (△), uniform pattern, 2002.

density, and sowing pattern on the weed biomass. The only significant interaction was between the crop density and weed species (Table 1). In the analysis without *S. alba*, we found strong and significant effects of the weed species, sowing density, and sowing pattern but no interactions, again showing that the interaction between the density and species was related to *S. alba*.

Wheat biomass and grain yield

2001

There were strong and significant effects of the weed species, sowing density, and sowing pattern on the wheat biomass. There was also a weak but significant interaction between the crop density and weed species (Table 1).

There were strong and significant effects of the weed species, sowing density, and sowing pattern on the grain yield and a significant interaction between the crop density and weed species (Table 1). There were no significant differences in the crop yield among *C. album, L. multiflorum*, and *S. media*, only differences between *S. alba* and the other three weed species (Fig. 2). The weed biomass, on average, was 31% lower and the grain yield was 5% higher in the uniform pattern. The weed biomass was 71% lower and the yield was 7.5% higher in the high-density uniform pattern (treatment with the greatest weed suppression) than in the medium-density row pattern (treatment closest to standard practise).

2002

There were significant effects of the weed species, sowing density, and sowing pattern on the wheat biomass and grain yield in 2002 (Table 1). There was no evidence of interactions among the factors. Pair-wise comparisons of the crop yield for the different weed populations showed no differences in the yield between *C. album, L. multiflorum*, and *S. media*, but *S. alba* affected the crop yield much more than the other species (Fig. 2). In 2002, the weed biomass, on average, was 16% lower and the grain yield was 12% higher in the uniform pattern. The weed biomass was 46% lower and the grain yield was 25% higher in the high-density uniform pattern (treatment with the greatest weed suppression) than in the medium-density row pattern (treatment closest to standard practise).

Effects of crop density and spatial pattern on the biomass of individual weed species

There was no difference in the *S. alba* biomass between the two sowing patterns at low or medium density, but

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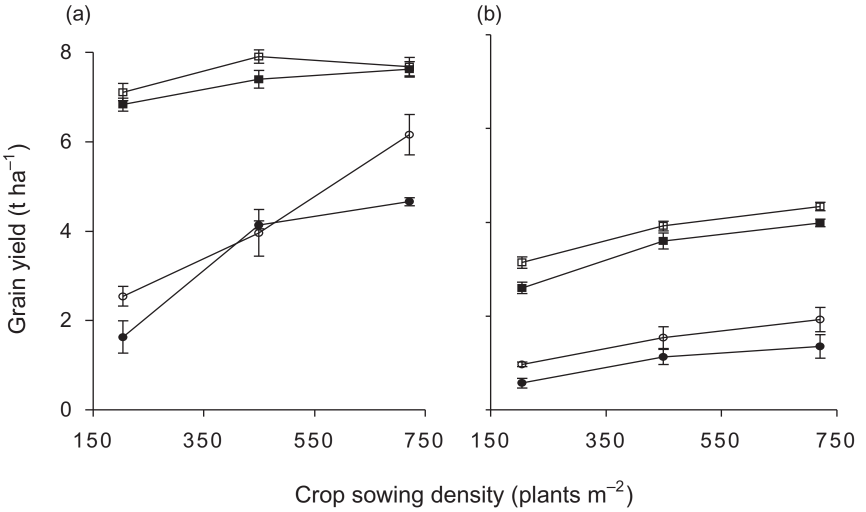

Fig. 2. Grain yield as a function of sowing density for spring wheat sown in two spatial patterns at three densities (204, 449, 721 plants m^{-2}) in (a) 2001 and (b) 2002. (■), row pattern, the mean of *Sinapis alba*; (□), unifrom pattern, the mean of *S. alba*; (●), row pattern, the mean of *Chenopodium album*, *Lolium multiflorum*, and *Stellaria media*; (○), uniform pattern, the mean of *C. album*, *L. multiflorum*, and *S. media*. The bars represent ±1 standard error.

there was a significant effect regarding the pattern at high density in both years (Table 2). For the row pattern, there was a significant effect by increasing the density from low to medium in 2001, but not in 2002, and there was no effect by increasing the density from medium to high in the row pattern in either of the years. We found a strong and significant effect of increasing crop density in the uniform pattern in 2001. In 2002, there was no effect by increasing the density from low to medium in the uniform pattern, but a strong and significant effect by increasing the density from medium to high.

For *L. multiflorum*, there was no difference between the patterns at the low and medium densities and a significant effect regarding the pattern at the high density in 2001, but not in 2002. For the row pattern, we found a significant effect of increasing density from low to medium in both years but only a significant effect of increasing the density from medium to high in 2002. For the uniform pattern, there was a significant effect of increasing the density from low to medium in both years and only weak evidence of an effect of increasing density from medium to high in 2001.

In 2002, more than half of the total weed biomass in the *C. album* treatment was contributed by other naturally occurring weed species. There was no effect of the pattern at any density in 2001 but an effect from the pattern in medium and high density in 2002. For the row pattern, there was only weak evidence for an effect of increasing density in 2001 but a significant effect of increasing density from medium to high in 2002. For the uniform pattern, there was a significant effect of increasing density, though it was only weak when the density was increased from medium to high in 2001.

In all cases, *S. alba* reacted differently to changes in the crop density and spatial pattern compared to the other three species ($P < 0.0001$).

Height of the crop and weeds

The *S. alba* seedlings started emerging 4 days after the crop in 2001. At the first measurement of height, 20 DAS, the wheat was taller than *S. alba*. Thirty-nine days after sowing, *S. alba* had achieved the same height as the wheat and, 50 DAS, *S. alba*, on average, was 19 cm taller than the crop in the low-density plots and 5 cm taller in the medium-density and high-density plots (Fig. 3). At this time, the crop was generally the same height at all densities, but 3 cm taller in the uniform pattern. At the last measurement, 56 DAS, *S. alba* had gained further in height in comparison to the wheat.

The *C. album* seedlings started emerging 8 days after the crop. The height of the crop and *C. album* was measured 39, 50, and 56 DAS. The crop was always taller than *C. album*. At the two higher crop densities, *C. album* was almost twice as high (13.5 cm) in the row pattern as in the uniform pattern. There was a naturally occurring population of individuals of *C. album* that emerged earlier and the plants were therefore larger than the sown population, thus increasing the variation within the *C. album* population.

The *S. media* seedlings also started emerging 8 days later than the crop and were always smaller than the crop. The *S. media* plants were tallest 56 DAS in the low density, uniform pattern, but the difference in height between the wheat and *S. media* was similar in both patterns and at all crop densities.

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Table 2. Least-square means and 95% confidence intervals (in parentheses) of the square root of the weed biomass of four weed species (*Chenopodium album*, *Lolium multiflorum*, *Sinapis alba*, and *Stellaria media*) when sown in combination with spring wheat. The spring wheat was sown in two patterns (row and uniform pattern) at three densities (low, medium, and high: 204, 449, and 721 plants m^{-2})

Year	Low density		Medium density		High density	
	Row	Uniform	Row	Uniform	Row	Uniform
2001						
Chenopodium album	4.06 (3.24–4.88)	4.22 (3.41–5.04)	2.97 (2.16–3.80)	2.13 (1.31–2.95)	1.80 (0.99–2.62)	1.05 (0.23–1.87)
Lolium multiflorum	5.80 (4.98–6.61)	4.50 (4.68–6.31)	3.95 (3.13–4.77)	3.31 (2.49–4.12)	3.66 (2.84–4.48)	2.24 (1.42–3.06)
Sinapis alba	11.10 (10.20–11.90)	10.40 (9.59–11.20)	7.89 (6.94–8.83)	7.57 (6.76–8.39)	8.26 (7.31–9.21)	4.97 (4.15–5.79)
Stellaria media	5.01 (4.19–5.83)	4.39 (3.57–5.21)	3.79 (2.97–4.61)	2.96 (2.14–3.78)	2.74 (1.92–3.56)	1.76 (0.95–2.58)
2002						
Chenopodium album	6.53 (5.53–7.44)	6.88 (5.97–7.78)	5.85 (4.94–6.75)	4.22 (3.32–5.13)	4.18 (3.28–5.08)	2.85 (1.95–3.76)
Lolium multiflorum	9.80 (8.90–10.70)	8.94 (8.04–9.85)	7.50 (6.59–8.40)	6.54 (5.63–7.45)	5.44 (4.54–6.35)	5.63 (4.72–6.53)
Sinapis alba	12.60 (11.70–13.50)	12.10 (11.20–13.00)	11.70 (10.80–12.60)	11.50 (10.60–12.40)	11.20 (10.30–12.10)	9.86 (8.95–10.80)
Stellaria media	9.24 (8.34–10.10)	8.11 (7.20–9.01)	6.44 (5.53–7.34)	5.75 (4.84–6.65)	4.68 (3.77–5.58)	4.72 (3.81–5.62)

DISCUSSION

The *S. alba* populations were close to pure stands in both years. The *L. multiflorum* and *S. media* populations were also close to pure stands in the first year, but comprised ≈ 70% of the weed biomass in the second year. The *C. album* population comprised 68% of the total weed biomass in the first year but less than one-third of the total weed biomass in the second year. Thus, we must consider the *C. album* treatment as a naturally occurring weed community with the addition of *C. album*.

The four weed species/communities differed in their biomass and, therefore, their effects on crop growth and yield, but there was a general consistency in their responses to increased crop density and spatial uniformity in both years, as in a previous study with winter wheat (Olsen *et al.* 2005a). The weed biomass almost always decreased with increasing crop density and with increased crop spatial uniformity. Both effects were important and highly significant. The interactions between the factors were not very important, even when they were significant. *Sinapis alba* responded somewhat differently than the other weed species/communities: the significant interactions between the weed species and the other treatments were primarily related to *S. alba*, which showed an effect from the crop-sowing pattern at high density, but not at low or medium densities.

Although there are many possible explanations for the similarity of the behavior of three of the weed species/communities and the differences with *S. alba*, the simplest explanation is simply the effects from initial size differences, especially differences in height, on competition. The role of initial size differences between the crop and the weed is the theoretical basis for the prediction of increased weed suppression with increased crop density and spatial uniformity (Weiner *et al.* 2001). The few exceptions to the general trends of increased weed suppression with increased crop density and increased spatial uniformity observed in the present study are consistent with the theory. As a result of its early germination, vigorous growth, and large stature (Didon & Bostrom 2003), *S. alba* was the only species that was able to catch up in size with the wheat early in the growing season and lose its height disadvantage before crop–weed competition became intense (Fig. 3), which can explain the difference in behavior between *S. alba* and the other weed populations. If the weeds are taller than the crop when crop–weed competition becomes intense, then increased crop density should not benefit the crop very much. This is especially the case in rows, where high crop density increases intraspecific

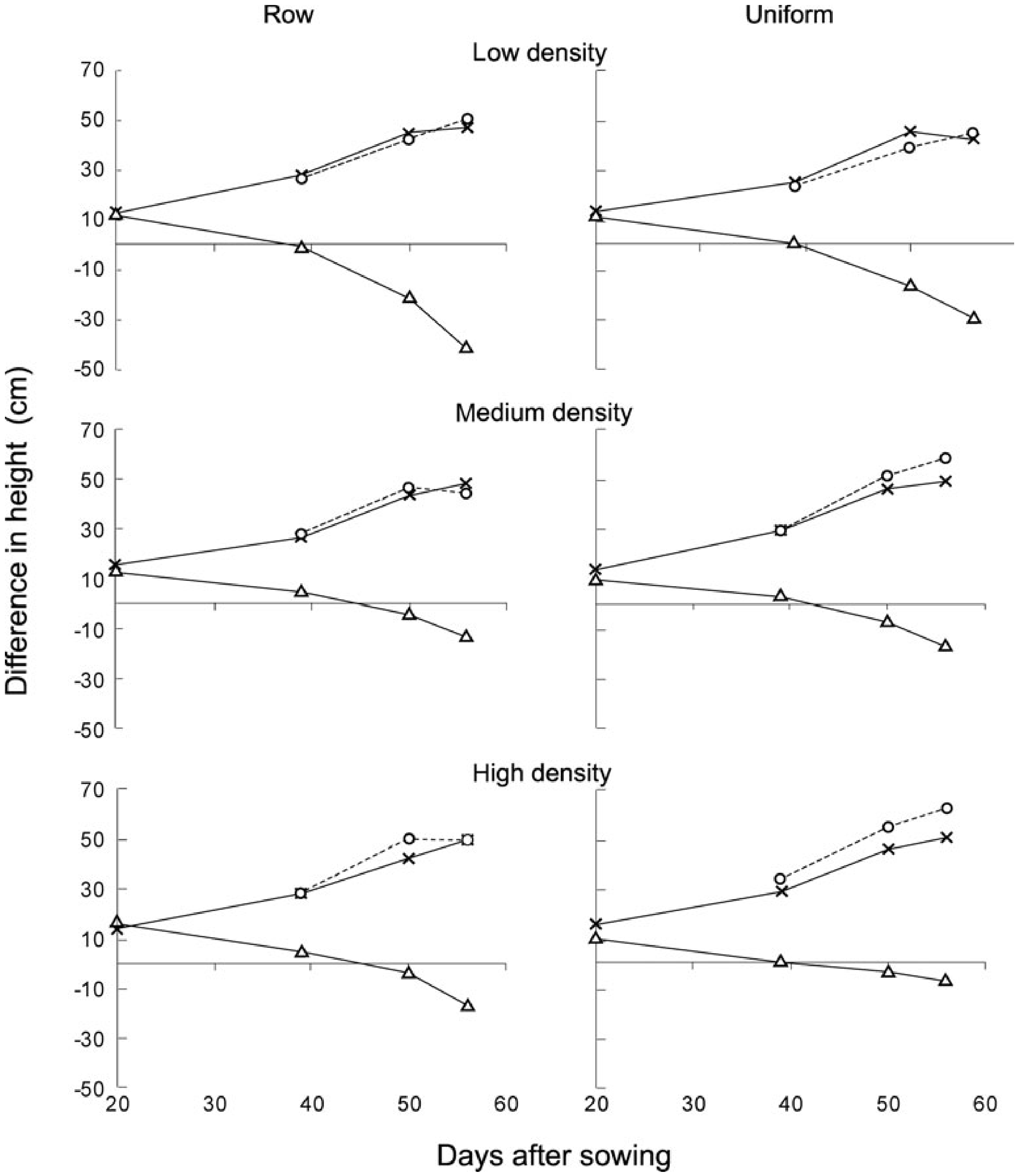

Fig. 3. Differences in height in 2001 between wheat and three weed species measured at 20, 39, 50, and 56 days after sowing (DAS) at three sowing densities: 204, 449, and 721 plants m^{-2}. *Chenopodium album* was not measured at 20 DAS. Spring wheat, *Sinapis alba*, *Stellaria media*, and *C. album* started emerging at 7, 11, 15, and 15 DAS, respectively. (△), *S. alba*; (×), *S. media*; (○), *C. album*.

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competition within the row more than it increases crop–weed competition (Fischer & Miles 1973; Weiner *et al.* 2001). Increased crop density and spatial uniformity together can keep weeds that are initially smaller than the crop from catching up because crop–weed competition starts earlier while the crop still has a size advantage: the ground will be covered sooner than when rows are used (Fischer & Miles 1973; Weiner *et al.* 2001; Olsen & Weiner 2006). This can explain why large effects of crop spatial uniformity were observed only at high density for *S. alba*. The wheat could only maintain its height advantage over *S. alba* when it was growing at high density in a uniform pattern. At the two lower densities, *S. alba* gained a substantial height advantage over the crop, so the effects of crop uniformity were smaller. This is strong support for the role of initial height differences when crop–weed competition becomes intense. Many studies have emphasized the role of height in crop–weed competition, but we propose that it is not the weed's potential height that is critical, but its height when crop–weed competition intensifies. *Chenopodium album* germinated late and was effectively suppressed by the wheat, especially at higher densities in the uniform pattern. In the absence of such suppression, *C. album* can be taller than wheat (Colquhoun *et al.* 2001). Cereal crops can suppress even potentially large weeds if the crop has an initial size advantage and crop–weed competition intensifies quickly.

Lolium multiflorum, a tillering grass, and *S. media*, a dicot with a creeping growth form, reacted very similarly to density and pattern and had similar effects on the crop biomass and yield. Both had their leaves below those of the wheat, suggesting that height is more important for crop–weed competition than the weed's growth form per se. Although *C. album* established poorly and late and was therefore smaller, the response of *C. album* and its associated naturally occurring weed community was very similar to that of *L. multiflorum* and *S. media*, as were the effects on yield.

Our results support the notion that a combination of increased crop density and a more uniform distribution of the crop increases weed suppression and can play a role in weed management in cereals. The results also suggest that the relative size of the crop and weed plants when crop–weed competition becomes intense is critical in determining the effects of crop density and pattern on weed biomass. When the crop has an initial size advantage, increasing crop density and spatial uniformity can help the crop maintain its advantage and suppress the weeds. When weeds have or can quickly gain a height advantage over the crop, then the effects of increased crop density and spatial uniformity will be smaller.

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REFERENCES

Blackshaw R.E. 1993. Safflower (*Carthamus tinctorius*) density and row spacing effects on competition with green foxtail (*Setaria viridis*). *Weed Sci.* **41**, 403–408.

Colquhoun J., Stoltenberg D.E., Binning L.K. and Boerboom C.M. 2001. Phenology of common lambsquarters growth parameters. *Weed Sci.* **49**, 177–183.

Didon U.M.E. and Bostrom U. 2003. Growth and development of six barley (*Hordeum vulgare* ssp. *vulgare* L.) cultivars in response to a model weed (*Sinapis alba* L.). *J. Agron. Crop Sci.* **189**, 409–417.

Doll H. 1997. The ability of barley to compete with weeds. *Biol. Agric. Hortic.* **14**, 43–51.

Fischer R.A. and Miles R.E. 1973. The role of spatial pattern in the competition between crop plants and weeds. A theoretical analysis. *Math. Biosci.* **18**, 335–350.

Jordan N. 1993. Prospects for weed control through crop interference. *Ecol. Applic.* **3**, 84–91.

Lemerle D., Gill G.S., Murphy C.E. *et al.* 2001. Genetic improvement and agronomy for enhanced wheat competitiveness with weeds. *Aust. J. Agric. Res.* **52**, 527–548.

Malik V.S., Swanton C.J. and Michaels T.E. 1993. Interaction of white bean (*Phaseolus vulgaris* L.) cultivars, row spacing, and seeding density with annual weeds. *Weed Sci.* **41**, 62–68.

Mohler C.L. 2001. Enhancing the competitive ability of crops. In: *Ecological Management of Agricultural Weeds* (ed. by Liebman M., Mohler C.L. and Staver C.P.). Cambridge University Press, Cambridge, 231–269.

Murphy S.D., Yakubu Y., Weise S.F. and Swanton C.J. 1996. Effect of planting patterns and inter row cultivation on competition between corn (*Zea mays*) and late emerging weeds. *Weed Sci.* **44**, 856–870.

Olsen J.M., Kristensen L. and Weiner J. 2005a. Effects of density and spatial pattern of winter wheat on suppression of different weed species. *Weed Sci.* **53**, 690–694.

Olsen J.M., Kristensen L., Weiner J. and Griepentrog H.-W. 2005b. Increased density and spatial uniformity increases weed suppression by spring wheat (*Triticum aestivum*). *Weed Res.* **45**, 316–321.

Olsen J.M. and Weiner J. 2006. The influence of *Triticum aestivum* density, sowing pattern and nitrogen fertilization on leaf area index and its spatial variation. *Basic Appl. Ecol.* **7** (in press).

SAS Institute. 1996. *SAS System for Mixed Models*. SAS Institute, Cary, NC.

Schwinning S. and Weiner J. 1998. Mechanisms determining the degree of size-asymmetry in competition among plants. *Oecologia* **113**, 447–455.

Solie J.B., Solomon S.G., Self K.P., Peeper T.F. and Koscelny J.A. 1991. Reduced row spacing for improved wheat yields in weed-free and weed-infested fields. *Trans. ASAE* **91**, 1654–1660.

Tollenaar M., Dibo A.A., Aguilera A., Weise S.F. and Swanton C.J. 1994. Effect of crop density on weed interference in maize. *Agron. J.* **86**, 591–595.

Weiner J. 1990. Asymmetric competition in plant populations. *Trends Ecol. Evol.* **5**, 360–364.

Weiner J., Griepentrog H.-W. and Kristensen L. 2001. Suppression of weeds by spring wheat (*Triticum aestivum*) increases with crop density and spatial uniformity. *J. Appl. Ecol.* **38**, 784–790.

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