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Crop Density, Sowing Pattern, and Nitrogen Fertilization Effects on Weed Suppression and Yield in Spring Wheat

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Recent studies have shown major advantages of increased crop density and spatial uniformity for competition of wheat with weeds. Field experiments were performed over 3 yr to determine whether the effects of crop density and sowing pattern on weed suppression are influenced by nitrogen fertilization. The independent variables were crop sowing pattern (normal rows and a highly uniform pattern), seeding density (204, 449, and 721 seed m^{-2}) and nitrogen fertilization (0 and 80 kg nitrogen ha^{-1}) of spring wheat, grown under high weed pressure. Increased crop density had strong and consistent negative effects on weed biomass and positive effects on crop biomass and yield. At the highest crop density, weed biomass was less than half that at the lowest density. Weed biomass was generally lower, and yield higher, in the uniform pattern, except in one case in which a combination of factors gave one weed species an early size advantage over the crop. When weeds were controlled with herbicide, no effects of crop density or spatial uniformity on crop biomass or yield were observed. Nitrogen fertilization increased weed biomass in 2 of 3 yr, and it also increased crop biomass in 2 of 3 yr, but there was little evidence that the relative effects of crop density and spatial pattern on weed suppression were influenced by nitrogen fertilization. In the presence of weeds, the highest yields were obtained with high crop density, high spatial uniformity and nitrogen fertilization. The results indicate that increased weed suppression through increased crop density and spatial uniformity will occur over a wide range of nitrogen levels.

Nomenclature: Spring wheat, *Triticum aestivum* L. 'Leguan'.
Key words: Cultural weed control, crop density, spatial pattern, crop–weed competition.

A series of recent studies have demonstrated the potential for increased weed suppression by wheat through a combination of increased crop density and spatial uniformity (Olsen et al. 2005a,b, 2006; Weiner et al. 2001). Weed suppression by crops appears to be enhanced by size-asymmetric competition, in which the larger crop plants suppress the initially smaller weed plants (Schwinning and Weiner 1998; Weiner 1990). At high-density, size-asymmetric competition is stronger and starts earlier, whereas the crop still has a large size advantage. At relatively low crop densities, crop cover early in growing season is low, leaving a larger amount of resources available for the weeds, thus enabling them to establish and grow quickly. Many studies have shown increased suppression of weeds at higher crop densities (Doll 1997; Erviö 1972; Håkansson 1997; Lemerle et al. 2001; Medd et al. 1985; Murphy et al. 1996; Wax and Pendelton 1968; see review by Mohler 1996). Crop spatial uniformity (hyperdispersion; Diggle 2003) decreases competition within the crop population early in the growing season (Olsen and Weiner 2007) and maximizes the total shade cast by the crop by reducing self-shading (Weiner et al. 2001).

Nutrient level is often important for crop–weed competitive interactions (Lintell-Smith et al. 1992), and managing the application of fertilizers in both space and time can be a tool in managing weeds (Angonin et al. 1996; Liebman and Mohler 2001). Fertilization increases total biomass production in the field, and that can occur as either increased crop or weed biomass or both. Many weed species are more effective than crops in capturing nutrients added as fertilizers (Blackshaw et al. 2003; DiTomaso 1995), so addition of fertilizer can sometimes reduce crop yield if it increases weed growth and competition more than it increases crop growth. On the other hand, in some situations crops can be more efficient in taking up fertilizers than weeds (Dhima and Eleftherohorinos 2001; Jørnsgard et al. 1996). In a study of the response of 21 weed species, wheat and oil-seed rape (*Brassica napus* L.) to nitrogen fertilization, wheat was among the least responsive species (Blackshaw et al. 2003). Thus, many weed species may be more effective in taking up high levels of soil nitrogen than is wheat. Several studies have addressed the interactions between fertilization strategies and crop–weed competition, looking for strategies in which nitrogen (Blackshaw et al. 2002; Petersen 2003; Rasmussen 2002), or other nutrients (Cralle et al. 2003), can be applied in ways unfavorable to the weeds.

One might expect the effects of high crop density and spatial uniformity on weeds to be more pronounced at low soil nitrogen levels because weeds grow more slowly at low-fertilization levels (Blackshaw et al. 2003). Conversely, high-nutrient conditions could result in an earlier onset of size-asymmetric competition, thus increasing the effects of high crop density and spatial uniformity. To ask whether the effects of crop sowing density and spatial pattern on weed suppression and yield are influenced by soil nutrient level, we investigated the effects of sowing pattern and seeding density at different nitrogen fertilization levels in weed-infested spring wheat. This question is important to our understanding of the potential role of increased crop density and spatial uniformity in weed management and to evaluating the potential for such a strategy in low-input organic cropping systems vs. higher-input conventional systems.

Materials and Methods

Design of Field Experiments. Field experiments were performed over 3 yr 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 experimental design was factorial with crop-sowing density, spatial pattern, and nitrogen fertilization as factors in

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randomized blocks with four replicates. There were three crop sowing densities (204, 449, and 721 seeds m^{-2}) of spring wheat ('Leguan').

Two spatial patterns (normal rows and a uniform pattern) were investigated. We modified a precision seed drill[1] to sow wheat in a uniform pattern by using a combination of narrow row spacing and individual placement of seeds within rows (Weiner et al. 2001). In the uniform pattern at low density, rows were spaced 7 cm apart, and distance between seeds within rows was 7 cm; at medium density, row spacing was 4.2 cm, and intrarow distance was 5.3 cm; at high density, row spacing was 4.2 cm, and intrarow distance was 3.3 cm. A standard research seed drill[2] with 12.8-cm row spacing was used to sow the normal row pattern in 2001 and 2002, and a pneumatic seed drill[3] with the same row spacing was used in 2003.

Two levels of nitrogen application, 0 and 80 kg N ha^{-1}, were used in the first 2 yr, and three levels, 0, 40 and 80 kg N ha^{-1}, were used in the third year, applied as 24–0–0 (N–P–K) fertilizer, applied on the soil surface 12, 14, and 30 d after sowing the experiment in the 2001, 2002, and 2003, respectively.

The experiments were sown on May 4, 2001, April 9, 2002, and March 31, 2003. Plots were 1.31 by 8.0 m. Treatments were arranged randomly within blocks with 0.5 m between plots within each block and 4 m between blocks. After sowing the wheat, the soil was rolled, and the weed seeds were sown on the soil surface. To sow the weeds in a random pattern, coulters were removed from a conventional seed drill,[4] and the seeds were dropped from a height of 72 cm. A bar was mounted below the seed outlets, so that seeds bounced off the bar before falling to the ground. After sowing the weed seeds, the soil was harrowed lightly and rolled again. In the first year (2001), we observed that many of the sown weeds appeared in rows instead of the desired random-like pattern. Harrowing immediately after sowing the seeds on the surface had created grooves on the soil surface in which many of the weed seeds collected. The weed-sowing technique was changed the following years. After sowing the wheat, the soil was rolled, and then, a plank with a 50-kg weight on it was dragged over the surface. Weed seeds were mixed with flour and then sown as in the first year, and then the soil was rolled again. This resulted in a more random spatial pattern of weeds in 2002 and 2003.

In all experiments, high weed densities were sown to achieve high weed pressure. In 2001, white mustard (*Sinapis alba* L.) was sown at a density of 400 seeds m^{-2}. In 2002, chickweed [*Stellaria media* (L.) Vill.] and wild mustard (*Sinapis arvensis* L.) were sown at densities of 3,000 seeds m^{-2} and 350 seeds m^{-2}, respectively. Wild mustard germinated poorly, and in some treatments, the sown species comprised < 30% of the total weed biomass. In 2003, a mixture of weed species was used: chickweed was sown at a rate of 1,500 m^{-2}, common lambsquarters (*Chenopodium album* L.) at 1,000 m^{-2}, and annual ryegrass (*Lolium multiflorum* Lam. 'Liquatro') at 300 m^{-2}, giving a total sowing density of 2,800 weed seeds m^{-2}. As in experiments with naturally occurring weeds, differences among years may, in part, be the result of differences in the weed community. Results from our previous studies on the effects of crop density and spatial pattern on weed biomass suggest these effects are general across different weed communities (Olsen 2006; Olsen et al. 2005a).

In 2002, an herbicide treatment was added to the experimental design to compare crop performance under weed-free conditions. All treatments were performed with and without herbicide application. Herbicide-treated plots were sprayed on May 15 with clorpyralid plus fluoroxypyr plus ioxynil (22 + 75 + 90 g ai ha^{-1})[5], and again on May 30 with tribenuron (2.5 g ai ha^{-1})[6], with 0.1% alkyl ethoxylate[7] L^{-1} as an additive. Sprayer[8] settings were 304 kPa and a volume rate of 200 L ha^{-1}.

In 2002, many volunteer red clover (*Trifolium pratense* L.) plants appeared in the plots. The reason was presumably a very heavy load of red clover seeds in the field from a previous red clover seed crop. The red clover plants were still small and did not constitute a major fraction of the weed biomass when the crop and weed biomass were measured in July. The weather was unusually dry later in the growing season, resulting in very favorable conditions for the red clover. Some plots became dominated by red clover, and it was not possible to harvest those plots.

At the time of maximum weed biomass (early July), we harvested crop and total weed biomass within a single randomly placed 0.25-m^2 square in each plot by clipping plants at the soil surface. Harvested material was dried for 24 h at 80 C in a drying oven and weighed. Wheat was harvested at maturity in September with a plot combine, and seeds were dried and cleaned before yield was determined.

Statistical Analyses. All data were analyzed using PROC MIXED in SAS,[9] which is based on likelihood principles (SAS 1996), with block as a random effect. Higher-order interactions with $P > 0.1$ were sequentially removed from the analyses. Because of large variation in weed and crop biomass among years, as well as some experimental changes over the 3 yr, the results for each year were analyzed separately. Herbicide-treated plots (2002) were excluded from the analysis of weed biomass. To homogenize variances, weed biomass data were square-root transformed in 2001 and log transformed in 2002 and 2003, and crop biomass data were square-root transformed in 2002. Other variables were not transformed. Data are presented as untransformed means.

Results and Discussion

Both wheat and weeds began emerging simultaneously in 2001 and 2002, but in 2003 wheat emerged a few days earlier than the weeds.

Effects of Density, Pattern, and Nitrogen on Weed and Crop Biomass. Weed biomass averaged of 234 g m^{-2} in 2001, 221 g m^{-2} in 2002 (no herbicide plots), and 160 g m^{-2} in 2003, which is high weed pressure compared with recent studies under similar conditions (Jørnsgard et al. 1996; Rasmussen 2002).

Higher crop density resulted in reduced weed biomass in all 28 cases (Figures 1–3, Table 1). Although a reduction in weed biomass with increased crop density has been documented in numerous studies (Doll 1997; Erviö 1972; Håkansson 1997; Lemerle et al. 2001; Medd et al. 1985; Murphy et al. 1996; Wax and Pendelton 1968), there is no agreement among researchers about the mechanisms involved. Our theoretical framework emphasizes the role of size-asymmetric competition, but the weed fraction of total crop

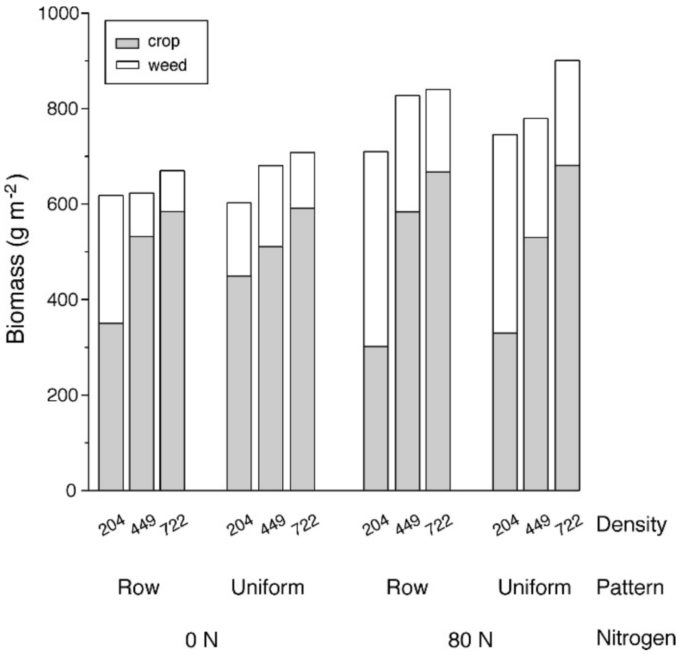

Figure 1. Crop (gray) and weed (white) biomass in 2001 in relation to sowing density (plants per square meter) and sowing pattern under low (0 N) and high (80 N) fertilization regimes.

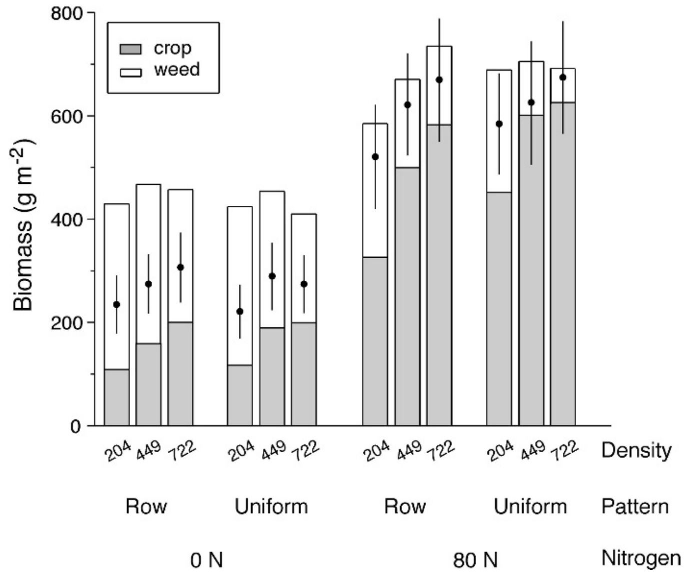

Figure 2. Crop (gray) and weed (white) biomass in 2002 in relation to sowing density (plants per square meter) and sowing pattern under low (0 N) and high (80 N) fertilization regimes. Circles with bars represent crop biomass ± 1 standard error in herbicide-treated plots.

+ weed biomass will decrease with increasing crop density, even if competition is not size asymmetric (Mohler 2001). We argue that effective weed suppression, as observed in some of the treatments in the present study and several previous studies (Olsen et al. 2005a,b, 2006; Weiner et al. 2001), can only occur if crop–weed competition is size asymmetric, but research into the mechanisms of crop–weed competition is necessary to resolve this issue.

Weed biomass was lower ($P < 0.001$) in the uniform pattern than in rows in 2002 (Figure 2) and 2003 (Figure 3) but was not affected by sowing in 2001 (Table 1; Figure 1). The 2001 result deviates from all our previous studies, in which a uniform-sowing pattern resulted in less weed biomass than normal rows (Olsen et al. 2005a,b, 2006; Weiner et al. 2001). Because of one or more specific circumstances in 2001 (the late sowing date, subsequent high temperatures, the row-like weed-sowing pattern), the weed species, white mustard, caught up in size with the wheat plants, which thereby lost their initial size advantage before canopy closure. White mustard grows especially fast early in the season under high-nitrogen conditions (Blackshaw et al. 2003; Olsen et al. 2006). The early size advantage of the crop is the theoretical basis for our prediction of positive effects of increased density and spatial uniformity on weed suppression (Weiner et al. 2001). But when weeds are taller than the crop early in the growing season, size-asymmetric competition will be to the advantage of the weeds. Thus, although the effects of pattern in 2001 are very different from all our previous studies, they are consistent with the theory on which we base this strategy. We conclude that increased crop density and uniformity will not lead to effective weed suppression when weeds have the initial size advantage (e.g., perennial weeds), or are able to

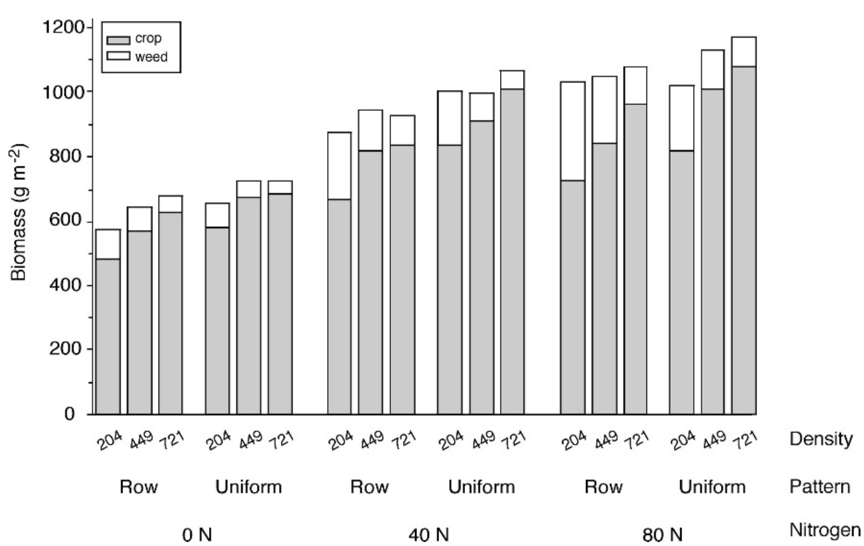

Figure 3. Crop (gray) and weed (white) biomass in 2003 in relation to sowing density (plants per square meter) and sowing pattern under low (0 N), medium (40 N), and high (80 N) fertilization regimes.

Table 1. Test of fixed effects on weed biomass per square meter, crop biomass per square meter, proportion of weed biomass, and grain yield (tons per hectare) in 2001, 2002, and 2003. Weed biomass was square root–transformed (2001) and log transformed (2002 and 2003), crop biomass was square root–transformed (2002) and untransformed (2001 and 2003), proportion of total biomass that is weed biomass was arcsine transformed, and grain yield was untransformed. Interactions with P > 0.1 were sequentially removed from the analyses.

		Weed biomass		Crop biomass		Proportion weed biomass		Grain yield	
Effect	df	F	P	F	P	F	P	F	P
2001									
Nitrogen	1	23.9	< 0.001	0.1	0.742	37.3	< 0.001	6.1	0.016
Density	2	11.1	< 0.001	9.6	< 0.001	78.5	< 0.001	423.1	< 0.001
Pattern	1	0.5	0.483	< 0.1	0.830	1.1	0.288	0.3	0.572
Density × nitrogen	2	NS	NS	NS	NS	NS	NS	19.5	< 0.001
Density × pattern		NS	NS	NS	NS	NS	NS	6.8	0.002
2002									
Nitrogen	1	0.3	NS	906.1	< 0.001	86.5	< 0.001	1,126.1	< 0.001
Density	2	7.3	< 0.001	35.9	< 0.001	94.5	< 0.001	6.9	0.002
Pattern	1	4.7	0.030	7.1	0.009	48.3	< 0.001	< 0.1	0.834
Herbicide	1	—	—	42.0	< 0.001	—	—	361.9	< 0.001
Density × herbicide	2	—	—	2.6	0.082	—	—	4.5	0.015
Pattern × herbicide	1	—	—	3.0	0.085	—	—	NS	NS
Nitrogen × herbicide	1	—	—	NS	NS	—	—	79.3	0.001
2003									
Nitrogen	2	101.8	< 0.001	127.9	< 0.001	17.9	< 0.001	345.0	< 0.001
Density	2	71.6	< 0.001	42.5	< 0.001	73.9	< 0.001	38.0	< 0.001
Pattern	1	40.2	< 0.001	52.7	< 0.001	43.1	< 0.001	9.1	0.004
Density × nitrogen	4	NS	NS	NS	NS	NS	NS	6.6	< 0.001
Density × pattern	2	NS	NS	NS	NS	NS	NS	4.0	0.025

catch up in size with the crop before competition becomes intense, as in our 2001 experiments.

Weed biomass was increased by nitrogen fertilization in 2001 and 2003 ($P < 0.001$; Table 1), but there was no effect of N on weed biomass in 2002. Thus, weeds usually benefited from added N to some degree, and the crop usually benefited as well (see below).

It is notable that there were no significant interactions among crop density, pattern, and nitrogen in affecting weed biomass over the 3 yr of the experiment (Table 1). Effects of these three factors on weed biomass were generally additive in our experiments.

In the presence of weeds, crop biomass increased significantly with increased crop density and spatial uniformity (Table 1). Crop biomass increased with nitrogen fertilization in 2002 and 2003, but not 2001 (Table 1). At low density, crop biomass was highest in unfertilized plots in 2001 because fertilization benefited the weeds at the expense of the crop, whereas at high density, crop biomass was highest in fertilized plots because both crop and weeds benefited from increased nutrients (Figure 1).

Effects of Density, Pattern, and Nitrogen on Total Biomass and Weed Fraction. Total (crop + weed) biomass increased with crop density in 24 out of 28 cases. Addition of nitrogen always increased total (crop + weed) biomass production.

The weed fraction of total (crop + weed) biomass always decreased with increased crop density and with crop uniformity in 2002 and 2003. Nitrogen fertilization increased the weed proportion of the total biomass in 2001 (Figure 1) and 2003 (Figure 3) but decreased it in 2002 (Figure 2). The absence of any interactions among the three factors in influencing the weed fraction of the total biomass is noteworthy because effects of nitrogen addition on crop vs. weed growth will be influenced by the relative size of crop and weeds and their relative abilities to take up nitrogen under low and high soil nitrogen levels. The effects of crop density, spatial uniformity, and nitrogen addition were generally additive, so there was no evidence that the effects of increased crop density and spatial uniformity on weed biomass were altered by nitrogen level within any year. This suggests that the effects of increased crop density and uniformity on weed biomass are not highly dependent on the amount of nitrogen fertilization.

Grain Yield. Grain yield was negatively correlated with weed biomass. Despite large differences in the means, the slope of the relationship between yield and weed biomass was not significantly different among years or treatments (Figure 4). When weed pressure is high, weed biomass is at the expense of yield.

Grain yield generally increased with crop density in the presence of weeds. An exception was the no-fertilizer treatments in 2003, where there was no effect of density on grain yield. Sowing pattern had no effect on grain yield in 2001 or 2002, but yield was higher in the uniform pattern in 2003 ($P = 0.004$), where there were also significant density by pattern ($P = 0.025$) and density by nitrogen ($P < 0.001$) interactions (Table 1). In general, the effect of pattern on yield was most pronounced at low densities. On average, the uniform pattern had 7 to 8% higher grain yield than rows at low and medium density, whereas pattern had no effect at high density.

Grain yield usually increased with nitrogen (Table 1; Figure 5), but low density in 2001 was an exception. In that year, the density by nitrogen interaction was stronger than the nitrogen main effect; N at 80 kg ha^{-1} fertilizer yielded only 77% of the no-fertilizer yield at low density, but the data show no differences between fertilization treatments at high densities.

Effects of Herbicide. Herbicide-treated plots (2002) had, on average, 21% more crop biomass and much higher yields than weed-infested plots ($P < 0.001$). Crop biomass and yield in herbicide-treated plots were almost three times higher in

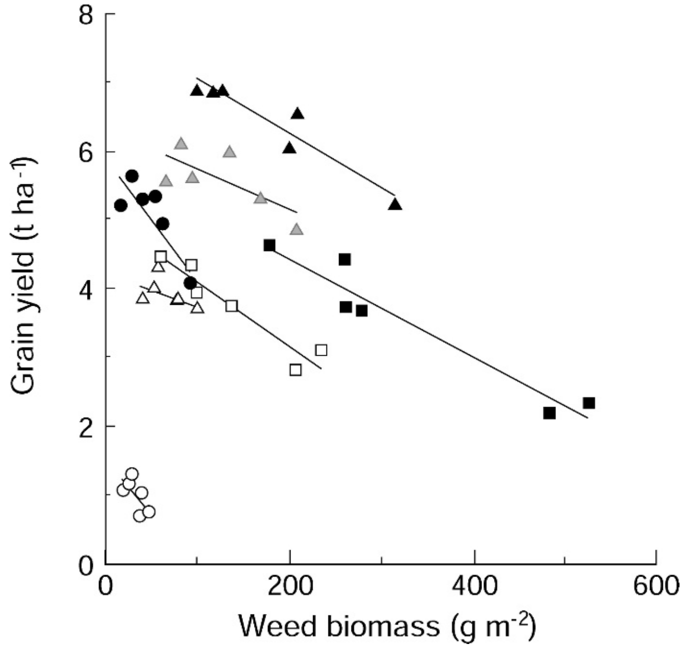

Figure 4. Grain yield at harvest vs. weed biomass in early July over all 3 yr; in 2001: (□) 0 kg nitrogen ha^{-1}, (■) 80 kg N ha^{-1}; in 2002: (○) 0 kg N ha^{-1}, (●) 80 kg N ha^{-1}; in 2003, (△) 0 kg N ha^{-1}, (▲) 40 kg N ha^{-1}, (▲) 80 kg N ha^{-1}. There were no significant differences among slopes for the different treatments. ANOVA on grain yield with treatment–year as a factor and weed biomass as covariate: $P < 0.001$ for both, $r^2 = 0.97$.

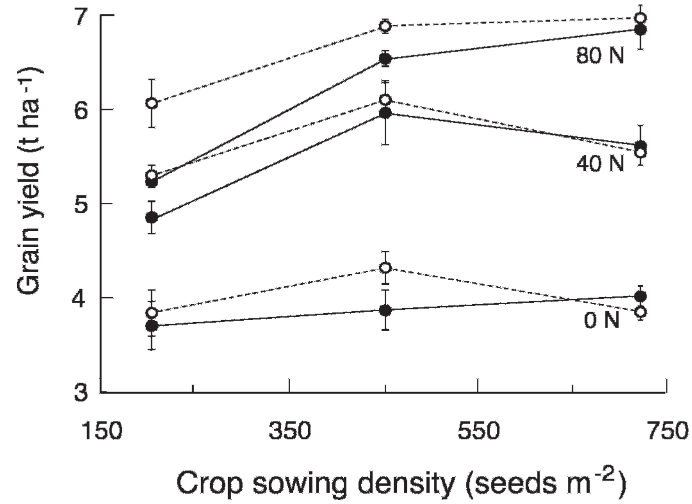

Figure 5. Grain yield in 2003 in relation to sowing density (plants per square meter) under low (0 N ha), medium (40 N), and high (80 N) fertilization regimes in row (closed symbols and solid lines) and in uniform (open symbols and dashed lines) sowing pattern. Bars represent ± 1 standard error.

fertilized than in unfertilized plots (herbicide by nitrogen interaction, $P < 0.001$; Table 1). In plots receiving no nitrogen fertilizer, herbicide treatment increased grain yield threefold. In contrast, herbicide treatment increased grain yield by only 31% in plots fertilized with 80 kg N ha^{-1}. The very low yield in the treatment without nitrogen fertilizer and without herbicide was due, in part, to the above-mentioned problems with volunteer red clover. With N fertilizer, crop biomass at high density (and medium density in the uniform pattern) was almost the same with and without herbicide application. We conclude that, although the effects of crop density and uniformity occur at both high and low N levels, the potential for using increased crop densities and spatial uniformity to replace or reduce herbicide application may be greater at higher N levels.

There was a significant herbicide by sowing density interaction ($P = 0.015$). In herbicide-treated plots, there were no differences among the crop densities, whereas in weedy plots, the grain yield increased by 22% from low to medium and high density. When there are no weeds, there is no advantage of increased crop density. Similar yields could probably be obtained at even lower densities. When weeds are abundant, there is a clear advantage of higher crop densities.

In the presence of weeds, highest crop biomass and yield were obtained under high density, high spatial uniformity, and high nitrogen levels. Increased sowing density and uniformity had much larger effects on crop biomass and yield when weeds were present than under weed-free conditions. If no weeds are present, plasticity in the growth of crop plants allows them to produce more tillers at low density and to occupy all available space when growing in a nonuniform pattern (Weiner et al. 2001), so the effects of crop density or sowing pattern are small or nonexistent. If weeds are present, they will be more suppressed at high crop density and spatial uniformity. Thus, the effects of crop density and spatial uniformity on crop biomass and yield are mediated by weed biomass. If weeds are present but not abundant and, therefore, not limiting crop growth, then increased weed suppression, no matter how effective, will not have major effects on crop biomass and yield. This explains why the effects of crop density and spatial pattern on weed biomass are more similar among years than effects on crop biomass and yield.

Study Implications. These results are consistent with those of our other studies (Olsen et al. 2005a,b, 2006; Weiner et al. 2001), and they also support the notion that increased wheat density and spatial uniformity can play an important role in weed management under a wide range of nitrogen inputs. Increased crop density strongly and consistently reduced weed biomass both with and without nitrogen fertilizer. Increased crop spatial uniformity reduced weed biomass in 2 of 3 yr. A strategy based on increased crop density and spatial uniformity can reduce or eliminate herbicide application in conventional cereal production. Such a strategy also offers an environmentally friendly alternative to mechanical weed control in organic farming, reducing traffic on the field, labor, fuel consumption, and CO_2 emissions.

Sources of Materials

[1] Pecision seed drill, Kverneland Accord Corporation, Soest, Germany.

[2] Research seed drill, Hege, Waldenburg, Germany.

[3] Pneumatic seed drill, Kuhn Cooperation, Saverne, France.

[4] Seed drill, Kongskilde Nordsten, Sorø, Denmark.

[5] Ariane Super, Dow AgroScience, Lyngby, Denmark.

[6] Express formulation, DuPont Danmark, Kastrup, Denmark.

[7] Lissapol Bio Express formulation, Syngenta Crop Protection, Copenhagen, Denmark.

[8] 4110-16 nozzle, Hardi International, Taatrup, Denmark.

[9] SAS, Version 8.2, SAS Institute, Cary, NC 27513-8617.

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