Increased density and spatial uniformity increase weed suppression by spring wheat

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Summary

It has been hypothesized that increased crop density and spatial uniformity can increase weed suppression and thereby play a role in weed management. Field experiments were performed over 2 years to investigate the effects of the density and spatial arrangement of spring wheat (*Triticum aestivum*) on weed biomass and wheat yield in weed-infested fields. We used three crop spatial patterns (normal rows, random and uniform) and three densities (204, 449 and 721 seeds m^{-2}), plus a fourth density (1000 seeds m^{-2}) in the random pattern. Increased crop density reduced weed biomass in all three patterns. Weed biomass was lower and crop biomass higher in wheat sown in the random and uniform patterns than in normal rows in both years. At 449 seeds m^{-2}, weed biomass was 38% lower in the uniform and 27% lower in the random pattern than in rows. There was evidence of decreasing grain yield due to intraspecific competition only at 1000 seeds m^{-2}. The results not only confirm that increasing density and increasing crop spatial uniformity increase the suppression of weeds, but also suggest that a very high degree of spatial uniformity may not be necessary to achieve a major increase in weed suppression by cereal crops. Rows represent a very high degree of spatial aggregation. Decreasing this aggregation increased weed suppression almost as much as sowing the crop in a highly uniform spatial pattern. While the random pattern produced as much crop biomass and suppressed weeds almost as well as the uniform pattern, the uniform pattern gave the highest yield.

Keywords: *Triticum aestivum*, crop–weed competition, seeding rate, spatial distribution.

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Introduction

Crop density and spatial arrangement affect crop competition with weeds (Mohler, 2001). According to one current hypothesis, when weed seedlings are smaller than crop seedlings, as is usually the case, weed suppression by the crop should increase with crop spatial uniformity and density (Weiner *et al.*, 2001). In a perfectly uniform grid pattern, where the distance between individual crop plants within the row and between the rows is equal, competition with weeds will begin sooner than in a row pattern and competition between individual crop plants will be delayed as long as possible (Fischer & Miles, 1973). In normal row sowing patterns, seed distribution within the row is close to random (Poisson distribution) but the overall two-dimensional pattern of seeds with normal crop rows is highly clumped (Griepentrog, 1999; Weiner *et al.*, 2001). In theory, reducing row distance will make the two-dimensional pattern less clumped, approaching a two-dimensional random pattern as row distance approaches zero (Griepentrog, 1995).

A decrease in row spacing often results in decreased weed biomass (Andersson, 1986; Putnam *et al.*, 1992; Teich *et al.*, 1993; Murphy *et al.*, 1996) and higher yields (Putnam *et al.*, 1992; Murphy *et al.*, 1996), but in some cases there is no effect on yield (Vander Vorst *et al.*, 1983; Teich *et al.*, 1993). Increasing crop density usually

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results in decreased weed biomass (Radford *et al.*, 1980; Samuel & Guest, 1990; Blackshaw, 1993; Murphy *et al.*, 1996; Doll, 1997).

When a crop is sown in rows and weeds are absent, plasticity allows crop plants to grow towards areas of high resource availability (Ballaré, 1994; Hutchings & de Kroon, 1994), reducing intraspecific competition within the crop population. Therefore, in the absence of weeds, the disadvantage of the clumped, row pattern is small. When weeds are present, however, crop plants distributed in a clumped pattern will suppress weeds less than if the same plants were distributed in a uniform pattern. Furthermore, the clumped pattern reduces the potential for increasing weed suppression with higher crop densities, because increasing crop density within rows increases intraspecific competition within the crop population more than it increases competition with the weeds (Weiner *et al.*, 2001).

In a recent study, increased crop density combined with a highly uniform sowing pattern decreased weed biomass in spring wheat by 60% compared with normal sowing practice (Weiner *et al.*, 2001). The relationship between the degree of spatial uniformity and weed suppression is not known, however. Standard crop rows represent a very high degree of spatial aggregation. It could be that a very high degree of spatial uniformity is necessary to achieve a major increase in weed suppression (Fig. 1A), in which case new sowing technology will be required if this approach to weed management is to be used in production. In contrast, it could be that a smaller increase in spatial uniformity, which could be achieved through narrow row spacing plus improved evenness in the distribution of seeds within the rows, will improve weed suppression almost as much as a highly uniform pattern (Fig. 1B). If this is the case, significant increases in weed suppression can probably be achieved with minor modifications of current sowing technology. This question can only be addressed by looking at sowing patterns with intermediate degrees of uniformity. A random pattern is a theoretically important reference point in studies of spatial arrangements (Ripley, 1981; Diggle, 2003). The goal of the present study is to extend our investigations of the role of crop density and uniformity on weed suppression to include a random, as well as row and highly uniform patterns. We compared weed and crop biomass and grain yield in weed-infested spring wheat grown under (i) normal sowing practice (12.8 cm rows), (ii) highly uniform pattern and (iii) spatially random distribution of seeds, at several crop densities.

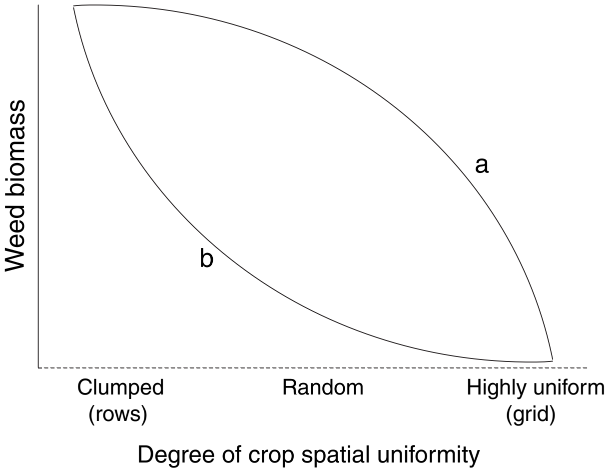

Fig. 1 Two possible theoretical relationships between the degree of crop spatial uniformity and weed suppression. In model a, a very high degree of uniformity is necessary to achieve a major increase in weed suppression. In model b, most of the increase in weed suppression can be achieved by reducing the degree of aggregation. A random pattern represents an intermediate degree of uniformity between a row and highly uniform pattern. The theory is still general at this point because there is currently no agreement on how to measure the degree of spatial uniformity within a crop.

Materials and methods

Field experiments were performed in 2002 and 2003 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. We used three spatial patterns (normal rows, a random pattern, highly uniform pattern) and three crop densities (204, 449, 721 seeds m^{-2}) of spring wheat (*Triticum aestivum* L. cv. Leguan). We added an additional treatment of 1000 seeds m^{-2} in the random pattern. To sow the normal row pattern with 12.8 cm row spacing, we used a standard plot research grain drill (Hege, Waldenburg, Germany) in the first year and a standard pneumatic grain drill (Kuhn Corporation, Saverne, France) in the second year. To create a two-dimensional random pattern we used a modified standard grain drill (Nordsten; Kongskilde Industries, Sorø, Denmark) sowing machine in which the coulters were removed and a bar mounted below the outlets. Wheat seeds were dropped from a height of 72 cm and bounced off the bar before falling to the ground. After dropping the wheat seeds on the ground, the soil was covered with 4 cm of topsoil, spread with a manure truck and then levelled manually with a broad rake. A highly uniform pattern was achieved through a combination of narrow row spacing and individual placement of seeds within rows (Weiner *et al.*, 2001), using a modified precision seeder (Kverneland Accord Corporation, Soest, Germany). The ratio of inter to intrarow distance in the grid-like pattern was 1:1 for the low and medium density and 5:4 for the high density.

The experiments were sown on 9 April 2002 and 31 March 2003. Plots were 1.31 × 8.0 m and there were four replicated blocks in both years. After sowing the wheat, the soil was rolled and levelled before weeds were sown in a random pattern on the soil surface. The weed seeds were sown in the same manner as wheat in the random pattern. After sowing the weed seeds, the soil was rolled again. In all experiments high weed densities were sown to achieve high weed pressure. In 2002, *Sinapis arvensis* L. was sown at a density of 350 seeds m^{-2}. In 2003, a mixture of weed species was sown at a total density of 2800 seeds m^{-2}. The mixture included *Stellaria media* (L.) Vill. at 1500 m^{-2}, *Lolium multiflorum* L. at 300 m^{-2} and *Chenopodium album* L. at 1000 m^{-2}. The experiment was fertilized at a rate of 80 kg N ha^{-1} applied 14 and 30 days after sowing the experiment in 2002 and 2003 respectively. We harvested crop and weed biomass within a single randomly placed 0.25 m^2 quadrat in each plot, close to the time of weed biomass maximum (early July, the wheat was at Feekes growth stage 11). Grain harvest was carried out at maturity in late August and grain yield was determined after cleaning.

Data were analysed using PROC MIXED in SAS version 8.2. which is based on likelihood principles (SAS, 1996), with year and block as random effects (block nested within year). The procedure SATTERTH was used to calculate DDF in *F*- and *t*-tests. To achieve homogeneity of variance weed biomass was square root transformed and crop biomass was squared. Data are presented as untransformed mean values. Differences between treatments were evaluated by pdiff LSMEANS option in the PROC MIXED procedure.

Results

Only a few *S. arvensis* germinated in 2002 and the total number of weeds was not counted. When harvested, the weed community consisted of a mixture of *Polygonum maculosa* Gray, *Fallopia convolvulus* (L.) A. Löve, *Trifolium pratense* L., *S. arvensis*, *S. media* and *C. album*. Due to a late assessment in 2003 (24 June), the total number of weeds that germinated was measured in 12 plots only (low crop density) and the mean number of weeds was 1132 plants m^{-2} (±49.8). While some naturally occurring weeds appeared, the three sown species dominated the weed community in 2003.

Weed biomass

Table 1 Test of fixed effects on total aboveground dry mass of weeds in spring wheat in both years, based on PROC MIXED in SAS (1996)

Effect	Num DF	Den DF	*F*-value	*P*-value
Pattern	2	55.2	12.64	<0.001
Density	2	55.2	88.15	<0.001
Pattern × density	4	55.2	1.66	0.1728

Data square root transformed (Num DF and Den DF: numerator and denominator degrees of freedom respectively).

There were strong effects of crop density ($P < 0.001$) and crop pattern ($P < 0.001$) on weed biomass (Table 1). Weed biomass decreased with increasing crop density (Fig. 2, Table 2) for all crop patterns with one exception (from medium to high density in the uniform pattern). Weed biomass also decreased with a further increase in crop density from 721 to 1000 seeds m^{-2} in the random pattern ($P = 0.042$). Weed biomass was lower in uniform pattern than in rows ($P < 0.001$), lower in random pattern than in rows ($P = 0.005$), but the difference in weed biomass between the uniform and random patterns was only marginally significant ($P = 0.052$). Averaged over the three crop densities, weed biomass was highest in the row pattern and lowest in the uniform pattern.

Although weed biomass production was greater in 2003 than in 2002, weed biomass comprised 20% of the total (weed + crop) biomass in the row pattern in both years, 13% and 15% in random pattern and 12% and 13% in uniform pattern in 2002 and 2003 respectively.

Wheat biomass

There were strong effects of crop density ($P < 0.001$) and crop pattern ($P < 0.001$) on wheat biomass in early July (Table 3). As an average of the three densities, wheat biomass was higher in the uniform ($P < 0.001$) and random patterns ($P = 0.001$) than in rows, but similar in the uniform and random patterns ($P = 0.469$).

Wheat biomass increased with crop density up to 721 seeds m^{-2} in all three sowing patterns (Fig. 3, Table 4), but did not increase further at 1000 crop seeds m^{-2} in the random pattern ($P = 0.842$). The random and uniform patterns produced the same crop biomass at every density, and this was higher in both patterns than in rows, except in one of six cases (row vs. random pattern at medium density; $P = 0.173$).

Grain yield

There were strong effects of crop pattern ($P < 0.001$), crop density ($P < 0.001$) and their interaction ($P = 0.02$) on grain yield (Table 5). Grain yield was lower in 2002 than in 2003 (Fig. 4) presumably due to a very heavy load of volunteer *T. pratense*, which was not a problem when weed and crop biomass were harvested

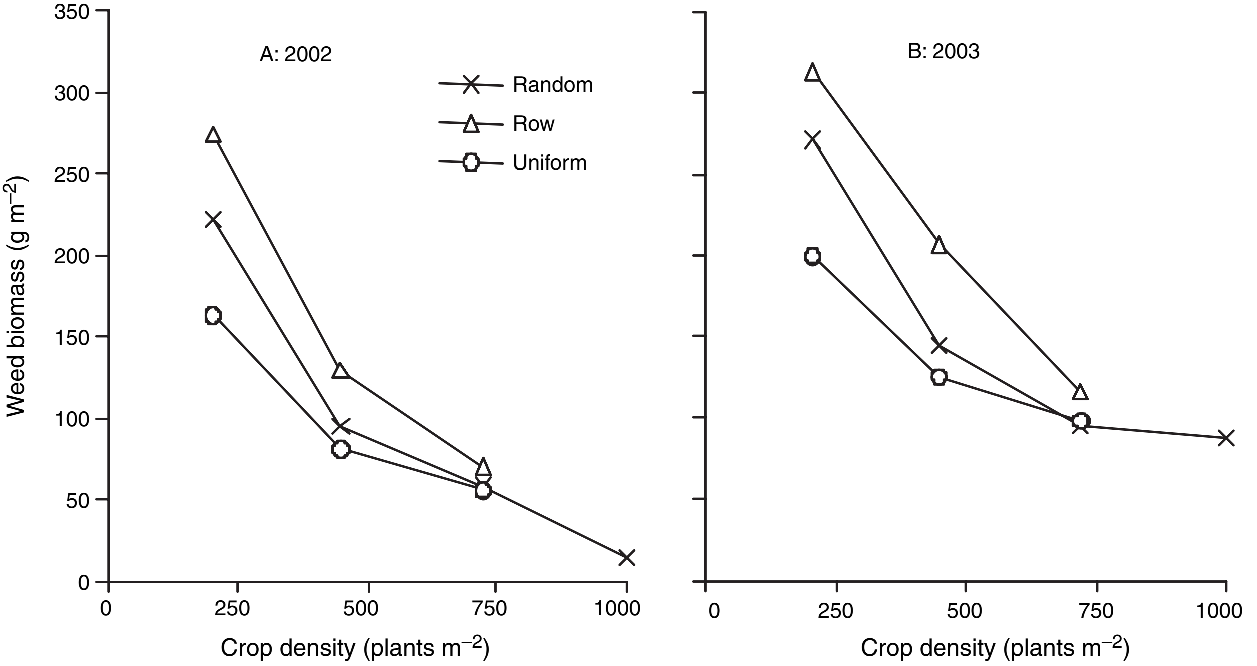

Fig. 2 Dry weight of weed biomass sown in combination with spring wheat. Crop sown at four densities [204, 449, 721 and 1000 (random pattern only) plants m^{-2}] and three crop patterns (Δ row; × random and ○ uniform) in A: 2002 and B: 2003.

Table 2 Least squares means [LSM; back-transformed values (g m^{-2}) in parenthesis] and significance levels between treatments (*t*-tests) of weed biomass in both years sown in combination with spring wheat. Crop sown at four densities [204, 449, 721 and 1000 (random pattern only) plants m^{-2}] and three crop patterns (row, random and uniform)

Crop pattern	Crop density	Treatment	Weed biomass LSM (g m^{-2})	Significance between treatments (*t*-test)
Row	204	1	17.01 (289)	1 vs. 2, $P < 0.001$; 1 vs. 4, $P = 0.100$
	449	2	12.77 (163)	2 vs. 3, $P < 0.001$; 2 vs. 5, $P = 0.022$
	721	3	9.433 (89.1)	3 vs. 6, $P = 0.287$
Random	204	4	15.55 (242)	4 vs. 5, $P < 0.001$; 4 vs. 8, $P = 0.016$
	449	5	10.78 (116)	5 vs. 6, $P = 0.01$; 5 vs. 9, $P = 0.339$
	721	6	8.528 (72.7)	6 vs. 7, $P = 0.042$; 6 vs. 10, $P = 0.958$
	1000	7	6.489 (42.1)	
Uniform	204	8	13.38 (179)	8 vs. 9, $P < 0.001$; 1 vs. 8, $P < 0.001$
	449	9	9.968 (99.4)	9 vs. 10, $P = 0.103$; 2 vs. 9, $P = 0.002$
	721	10	8.572 (73.5)	3 vs. 10, $P = 0.311$

Table 3 Test of fixed effects on total aboveground dry mass of wheat in both years, based on PROC MIXED in SAS (1996)

Effect	Num DF	Den DF	*F*-value	*P*-value
Pattern	2	62	13.88	<0.001
Density	2	62	71.23	<0.001
Pattern × density	4	62	0.89	0.4757

Data square root transformed (Num DF and Den DF: numerator and denominator degrees of freedom respectively).

(early July), but became a problem in the latter part of the 2002 growing season (L. Kristensen, J. Olsen, and H.-W. Griepentrog, unpubl. obs.).

Grain yield increased with increasing crop density for all crop patterns, and this increase was significant ($P < 0.05$) in all cases but two. A further increase in crop density from 721 to 1000 seeds m^{-2} in the random pattern resulted in a decrease in grain yield ($P = 0.032$;

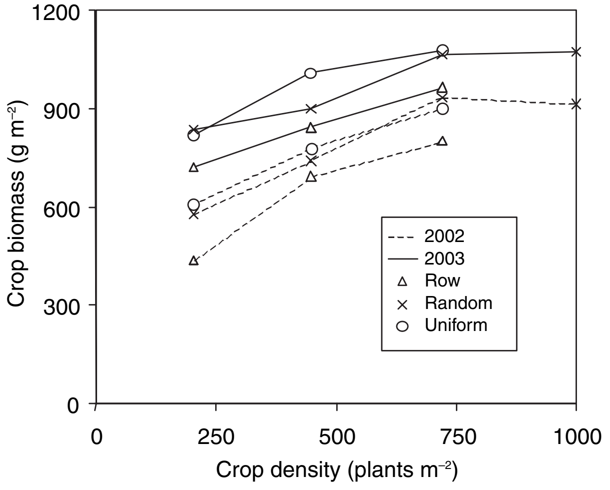

Fig. 3 Crop biomass plotted against crop density [204, 449, 721 and 1000 (random pattern only) plants m^{-2}] and crop pattern (Δ row; × random and ○ uniform) in 2002 (- - -) and 2003 (—).

Table 4 Least squares means [LSM; back-transformed values (g m^{-2}) in parenthesis] and significance levels between treatments (*t*-test) of spring wheat biomass in both years. Crop sown at four densities [204, 449, 721 and 1000 (random pattern only) plants m^{-2}] and three crop patterns (row, random and uniform)

Crop pattern	Crop density	Treatment	Wheat biomass LSM (g m^{-2})	Significance between treatments (*t*-test)
Row	204	1	364 650 (604)	1 vs. 2, $P < 0.001$; 1 vs. 4, $P = 0.015$
	449	2	597 242 (773)	2 vs. 3, $P = 0.003$; 2 vs. 5, $P = 0.173$
	721	3	797 285 (893)	3 vs. 6, $P = 0.002$
Random	204	4	535 479 (732)	4 vs. 5, $P = 0.029$; 4 vs. 8, $P = 0.806$
	449	5	687 752 (829)	5 vs. 6, $P < 0.001$; 5 vs. 9, $P = 0.064$
	721	6	1 008 566 (1004)	6 vs. 7, $P = 0.842$; 6 vs. 10, $P = 0.726$
	1000	7	992 632 (996)	
Uniform	204	8	518 734 (720)	8 vs. 9, $P < 0.001$; 1 vs. 8, $P = 0.022$
	449	9	811 294 (901)	9 vs. 10, $P = 0.01$; 2 vs. 9, $P = 0.002$
	721	10	985 490 (993)	3 vs. 10, $P = 0.006$

Table 5 Test of fixed effects on grain yield of spring wheat in both years, based on PROC MIXED in SAS (1996)

Effect	Num DF	Den DF	*F*-value	*P*-value
Pattern	2	53.6	21.05	<0.001
Density	2	53.6	141.96	<0.001
Pattern × density	4	53.6	3.19	0.0201

Data square root transformed (Num DF and Den DF: numerator and denominator degrees of freedom respectively).

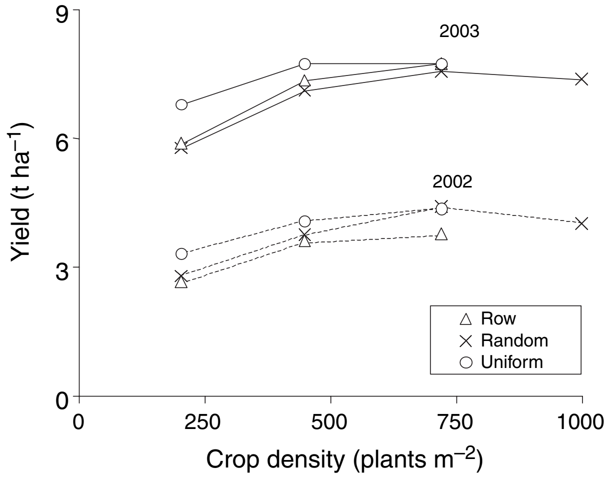

Fig. 4 Grain yield plotted against crop density [204, 449, 721 and 1000 (only random pattern) plants m^{-2}] and crop pattern (Δ row; × random and ○ uniform) in 2002 (- - -) and 2003 (—).

Table 6). On average, grain yield was higher in the uniform pattern than in the row and random patterns ($P < 0.001$), whereas grain yield was similar in the row and random patterns ($P = 0.467$) at all densities.

Discussion

Although weed biomass, crop biomass and grain yield differed between the 2 years, results from both confirm previous studies that show distributing the crop in a more uniform pattern and increasing crop density increase weed suppression (Weiner *et al.*, 2001). Weed biomass was 38% lower in the uniform and 27% lower in the random pattern than in the rows at 449 seeds m^{-2}, which is the treatment closest to normal practice in Denmark. Weed biomass was 54% lower and grain yield 9.5% higher in the best performing treatments (uniform and random patterns at high density) than in rows at 449 seeds m^{-2}. Despite differences in total (weed + crop) biomass between the 2 years, the weeds produced 20% of total biomass in the row pattern in both years. The effect of sowing pattern on weed biomass was smallest at high crop density where no differences in weed suppression between the three patterns were observed (Table 2). The random pattern was intermediate in suppressing weeds.

A 'flat' (non-decreasing) yield–density relationship over a range of densities above standard practice is necessary if increased crop densities are to be used in

Table 6 Least squares means (LSM), and significance levels between treatments (*t*-test) of grain yield in both years. Crop sown at four densities [204, 449, 721 and 1000 (random pattern only) plants m^{-2}] and three crop patterns (row, random and uniform)

Crop pattern	Crop density	Treatment	Grain yield LSM (t ha^{-1})	Significance between treatments (*t*-test)
Row	204	1	4.26	1 vs. 2, $P < 0.001$; 1 vs. 4, $P = 0.92$
	449	2	5.48	2 vs. 3, $P = 0.059$; 2 vs. 5, $P = 0.69$
	721	3	5.75	3 vs. 6, $P = 0.116$
Random	204	4	4.28	4 vs. 5, $P < 0.001$; 4 vs. 8, $P < 0.001$
	449	5	5.42	5 vs. 6, $P < 0.001$; 5 vs. 9, $P = 0.001$
	721	6	5.98	6 vs. 7, $P = 0.032$; 6 vs. 10, $P = 0.638$
	1000	7	5.68	
Uniform	204	8	5.05	8 vs. 9, $P < 0.001$; 1 vs. 8, $P < 0.001$
	449	9	5.90	9 vs. 10, $P = 0.309$; 2 vs. 9, $P = 0.004$
	721	10	6.05	3 vs. 10, $P = 0.043$

weed management (Weiner *et al.*, 2001). We have found no evidence for yield loss due to intraspecific competition in the wheat population at 721 seeds m^{-2}, which is twice the standard sowing density. The results indicate that competition within the crop population is becoming a problem at 1000 seeds m^{-2}.

Grain yield increased with crop uniformity. As predicted, the random pattern was intermediate in performance in comparison with the uniform and row patterns. While the random pattern behaved more like the uniform pattern with respect to weed suppression, grain yield responded more like rows. This indicates that there may be other advantages to a uniform spatial distribution of the crop in addition to increased weed suppression, such as better utilization of nutrient and space resources (Griepentrog, 1999).

Our results support the hypothesis that increases in crop density and spatial uniformity can increase weed suppression and grain yield. The results also indicate that a very high degree of uniformity may not be necessary to achieve a major increase in weed suppression. If this is correct, a reduction in the degree of spatial aggregation may be sufficient to give major improvements in weed suppression. This can be achieved through a combination of reduced row spacing and increased uniformity within the rows. A high degree of uniformity seems to have small but significant positive effects on yield, however. While we have demonstrated the benefits of increased uniformity, the optimum degree of uniformity will depend on the costs of increasing uniformity in the field.

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