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How Important are Crop Spatial Pattern and Density for Weed Suppression by Spring Wheat?

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Previous research has shown that both the density and spatial pattern of wheat have an influence on crop growth and weed suppression, but it is not clear what degree of uniformity is necessary to achieve major improvements in weed suppression. Field experiments were performed over 3 yr to investigate the effects of crop density and different spatial distributions on weed suppression. The spatial pattern of spring wheat sown in five patterns and three densities in small weed-infested plots were analyzed with the use of digitized photographs of field plots to describe the locations of individual wheat plants as *x* and *y* coordinates. We used a simple quantitative measure, Morisita's index, to measure the degree of spatial uniformity. Increased crop density resulted in reduced weed biomass and increased crop biomass every year, but crop pattern had significant effects on weed and crop biomass in the first year only. Weather conditions during the second and third years were very dry, resulting in very low weed biomass production. We hypothesize that water deficiency increased the importance of belowground relative to aboveground competition by reducing biomass production, making competition more size symmetric, and reducing the effect of crop spatial pattern on weed growth. The results indicate that increased crop density in cereals can play an important role in increasing the crop's competitive advantage over weeds, and that spatial uniformity maximizes the effect of density when low resource levels or abiotic stress do not limit total biomass production.

Nomenclature: Spring wheat, *Triticum aestivum* L.
Key words: Crop–weed competition, crop sowing pattern, Morisita index, crop density.

Concerns about the effects of herbicides on the environment and the evolution of herbicide resistance in weeds have led to increased regulation of herbicide use, creating a need for new strategies for weed control. Increasing the ability of the crop itself to suppress weeds is one potential approach (Mohler 2001). Although there have been several investigations into variation in the ability of different crop varieties to compete with weeds (Christensen 1995; Lemerle et al. 1996, 2001b) it has become clear that the effects of agronomic practices for crop–weed competition are even more important (Lemerle et al. 2001a), and that the competitive abilities of different crop varieties will vary with agronomic practices. Weed suppression increases with crop density (Auškalnienė and Auškalnis 2008; Auškalnienė et al. 2010; Blackshaw 1993; Boyd et al. 2009; Lemerle et al. 2004; Mohler 2001; Olsen et al. 2005b; Tanji et al. 1997), and agricultural researchers have been urging farmers and agricultural advisors to use higher sowing densities as part of their weed management strategies (Lemerle et al. 2004).

Most experiments investigating the effect of crop density on weed losses have varied crop density but not the sowing methods. Increasing crop density without decreasing row distance results in a more crowded distribution of plants within the row. This increases the intraspecific competition among the crop plants and the competitive pressure of the crop plants on weeds within the row, but not on weeds between the rows. It is expected that a more uniform spatial distribution, e.g., reduced row distance, should improve the effects of increasing crop density on weeds (Olsen et al. 2005b; Weiner et al. 2001). Reducing row distance often results in decreased weed biomass (Malik et al. 1993; Murphy et al. 1996; Olsen et al. 2005a,b) and increased yield (Champion et al. 1998; Seiter et al. 2004) under high weed pressure, but not in every study (Champion et al. 1998; Hashem et al. 1998). The outcome of competition between crop and weeds depends on the competitive ability of the species. If the weed is a good competitor, reduced row distance can be a disadvantage for the crop, but not in all cases (Olsen et al. 2006).

Assuming that two-dimensional area reflects resources available, the average quantity of resources available to each crop plant is the same in different planting patterns at the same density (Regnier and Bakelana 1995), but the sizes and shapes of the areas available for individual plants varies from a hexagon or square of uniform size in a highly uniformly distributed pattern, to highly rectangular and variable in a row pattern (Fischer and Miles 1973). Crop cover early in the growing season is important if effective weed suppression is to be obtained. Therefore, the crop should germinate quickly after sowing, before fast-growing weeds can catch up with the crop. Crop cover occurs sooner when the crop is sown in a more uniform pattern because (1) the crop plants are already out there in between the rows and (2) intraspecific competition and self-shading within the crop population is reduced and delayed as long as possible.

In our previous experiments (Olsen et al. 2005a,b, 2006; Weiner et al. 2001) we had highly significant effects of increased crop uniformity on weed growth, but the degree of uniformity was not quantified, so we have no information on the quantitative relationship between crop spatial uniformity and weed suppression except that it is monotonic. Results with three crop spatial patterns (uniform, random, and rows) suggest that a very high degree of uniformity is not necessary to achieve a major improvement in weed suppression, and a sufficient improvement in crop-sowing uniformity could be achieved through a combination of a reduction in row distance and an increased uniformity within the rows (Olsen et al. 2005b), but this has not been tested. A quantitative measure of crop spatial uniformity is needed.

Morisita's index of dispersion has proved useful in describing the degree of spatial aggregation/uniformity (Diggle 2003; Kristensen et al. 2006; Mead 1966; Ripley

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1981). Morisita's index is based on random or regular quadrat counts and has the advantage of simplicity as a single measure of uniformity (Kristensen et al. 2006). It ranges from 0 (completely uniform) over 1 (random pattern) up to the total number of quadrats in the sampling area, if all plants occur in one quadrat.

Here we have examined the relationship between weed and crop biomass and the spatial distribution of the crop expressed as Morisita's index. We have compared crop and weed biomass in weed-infested spring wheat grown at three crop densities in five different spatial crop patterns ranking from normal sowing practice (12.5-cm rows, a highly aggregated pattern) to a highly uniform pattern.

Materials and Methods

The experiments were performed over 3 yr at the University of Copenhagen'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 and spatial pattern as factors in randomized blocks with three replicates.

We used three crop densities (196,441 [close to the standard sowing density of approximately 400], 729 plants m^{-2}) of spring wheat ('Amaretto') and five spatial crop patterns with increasing uniformity: Rows: 12.5-cm row distance with random distribution of seeds within the rows; Half row: 6.25-cm row distance with random distribution of seeds within the rows; unirow: row distance like the uniform pattern (7.1 cm at 196 plants m^{-2}, 4.8 cm at 441 plants m^{-2} and 3.7 cm at 729 plants m^{-2}), and a random distribution of seeds within the rows; random: two-dimensional random pattern; Uniform: a highly regular (uniform) pattern where the row distance and the distance between seeds within the rows are the same. The degree of spatial uniformity was calculated by Morisita's index of dispersion, I_δ,

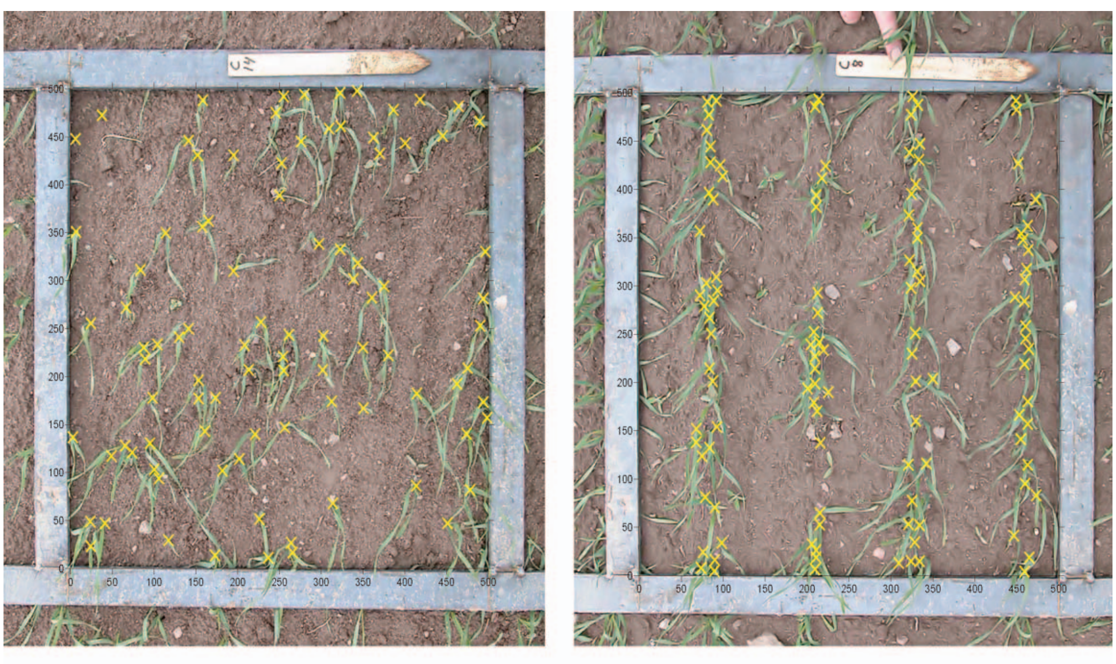
$$I_\delta = Q\frac{\sum_{i=1}^{0} n_i(n_i-1)}{N(N-1)},$$

where Q is the number of quadrats in the sampling area, n_i is the number of plants in quadrat i, and N is the total number of plants in the sampling area.

In the first year we did not use the half-row pattern. Instead of the half-row pattern we had a pattern very similar to unirow, but with a slightly improved distribution of seeds within the rows. Results for this pattern were deemed too similar to the unirow, so it was replaced with the half row in the second and third year. Thus results presented below consist of four crop patterns in the first year and five crop patterns in the following 2 yr.

Each pattern was sown through a 1 by 1–m plywood sheet template on which computer-generated *x*–*y* positions had been marked and holes drilled through the template. If more than one seed was to be placed at the same position this was marked on the template.

Before sowing the soil was harrowed and leveled. Rocks and big clods were removed and the templates were placed on the soil surface. The experiments were sown on April 17 and 18, 2007, April 16 and 17, 2008, and April 7 and 8, 2009. Crop seeds were placed by hand in the holes on the template, pressed into the soil to a depth of 3½ cm with a metal rod, and carefully covered with soil. In order to achieve a high weed pressure a mixture of five weed species common in Denmark was sown by hand in a random pattern in all plots. The mixture included 500 seeds of each of the following species: Common lambsquarters (*Chenopodium album* L.), common chickweed [*Stellaria media* (L.) Vill.], scentless chamomile (*Matricaria perforata* Mérat),



A B

Figure 1. Photographs of two field plots showing the locations of individual wheat plants marked for digitizing to *x* and *y* coordinates. (A) Random pattern, 441 seeds m^{-2}; (B) 12.5-cm rows, 729 seeds m^{-2}.

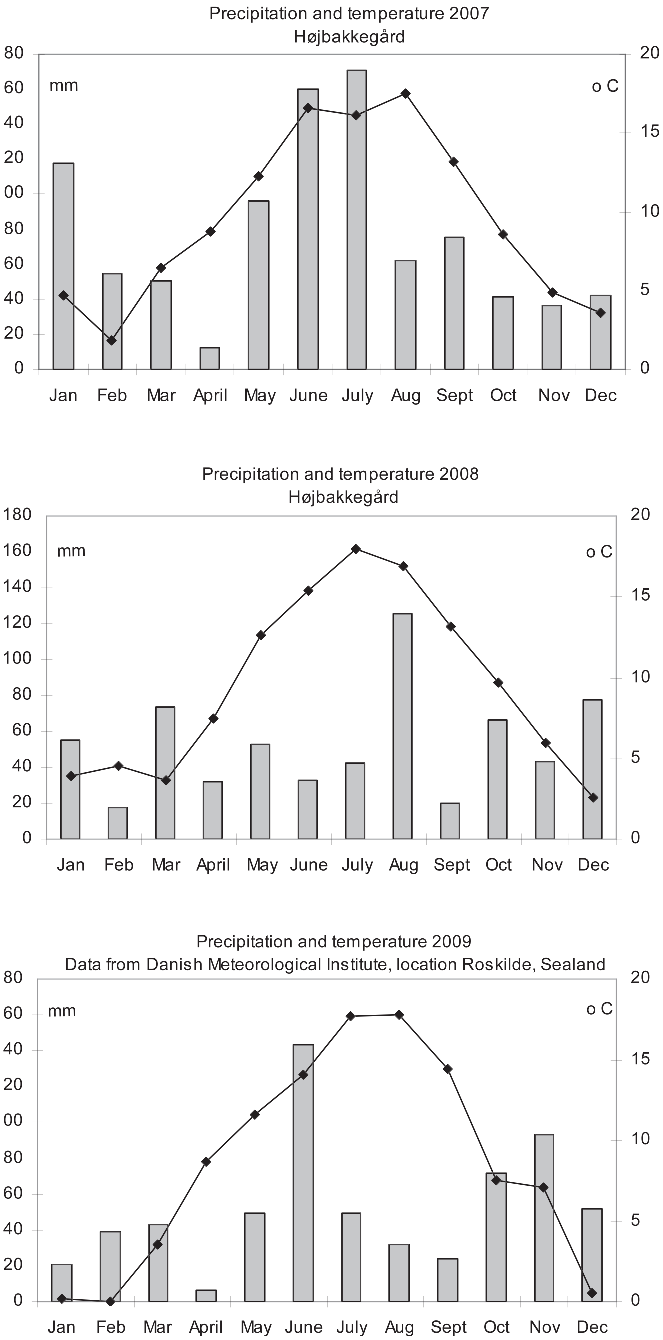


Figure 2. Precipitation (bars) and temperature (curves) for 2007–2009. Data from 2007 and 2008 are measured at the farm Højbakkegård in Taastrup at the Faculty of Life Science, University of Copenhagen. The data for 2009 are from the Danish Meteorological Institute measurements in Roskilde (near Højbakkegård). Note that the experiment was watered with 10 L m^{-2} in April, 2007 and with 10 L m^{-2} in May and a total of 20 L m^{-2} in June, 2008 (not shown in the figure).

ladysthumb (*Polygonum persicaria* L.), and Persian speedwell (*Veronica persica* Poir.). The experiments were fertilized at a rate of 80 kg N ha^{-1} on May 9, 2007, 96 kg N ha^{-1} on April 15, 2008, and 80 kg N ha^{-1} on April 6, 2009. In 2007 the experiment was watered with 10 L m^{-2} on April 27. In 2008 the experiment was watered with 10 L m^{-2} on May 13, June 3, and June 9. Weed and crop plants were counted 3 to 4 wk after sowing in a 50 by 50–cm quadrat in the center of each plot.

Two to three weeks after sowing, photographs were taken with a digital camera mounted on a camera stand in a fixed position 90 cm aboveground, pointing directly downwards and centered over a 50 by 50–cm frame. The pictures were digitized and referenced with the use of the program Surfer© Version 8.0 (Golden Software, Golden, CO), giving the (*x, y*) point-referenced data for each crop plant (Figure 1). The point-referenced (*x, y*) data were used to calculate the Morisita's index of dispersion (I_δ), after the total plot area is divided into 100 5 by 5–cm quadrats within the 0.25-m^2 sampling area (Kristensen et al. 2006). At the time of maximum weed biomass (late June in all 3 yr) the biomass of weed and crop was measured by harvesting, drying, and weighing all aboveground biomass within a centrally placed 0.25-m^2 quadrat in each plot. Data were analyzed with the use of PROC MIXED and GLM in SAS version 9.1 (SAS Institute, Cary, NC 27513). PROC MIXED is based on likelihood principles, with block as a random variable. In the mixed model (PROC MIXED) crop density was treated as a categorical variable with three levels. In the general linear model (GLM) density was treated as a covariate. The differences between these two analyses were very small and did not affect inferences, so we present only results with density as categorical variable. Because of large variation between weed biomass between the first and the two last years, as well as some experimental changes over the 3 yr, the results for each year were analyzed separately. The procedure SATTERTH was used to calculate DDF (denominator degrees of freedom) in *F*- and *t*-tests. To achieve homogeneity of variance weed biomass was log transformed. Data are presented as untransformed mean values. Differences between treatments were evaluated by the pdiff LSMEANS option in the PROC MIXED procedure.

Results and Discussion

The weather conditions during April to June were very different over the 3 yr (Figure 2). In all 3 yr the mean temperature was higher than the 30-yr mean, and hours with sunshine from April to June was higher than the 30-yr mean. From April to June hours of sunshine were 694, 822, and 826 in 2007, 2008, and 2009, respectively, compared to the 30-yr mean of 580 h of sunshine (from April to June). In 2007 the temperature was 3.1 C higher and precipitation 70% lower than the 30-yr mean in April. In May, June, and July the temperature was 1.5, 2.3, and 0.6 C higher, and precipitation was 100%, 192%, and 158% higher, respectively, than the 30-yr mean. In 2008 the temperature was 1.8, 1.9, and 1.1 C higher than the 30-yr mean in April, May, and June, respectively, and precipitation was 22% lower, 10% higher, and 40% lower than the 30-yr mean. In 2009 the temperature was 3 and 0.8 C higher than the 30-yr mean in April and May and 0.2 C lower in June than the 30-yr mean. Precipitation in 2009 was 85% lower in April and 2% and 160% higher than the 30-yr mean in May and June, respectively. On June 11, 2009 there was a heavy fall of rain, with 88% of the total precipitation for the month. During one night 119 mm of rain fell, more than twice the 30-yr mean rainfall in June. The remainder of the month was dry and the month had 280 h of sunshine compared to the 30-yr mean of 209 h.

In 2007 wheat plants germinated 10 d after sowing and weed plants started to germinate approximately 14 d after sowing. Twenty days after sowing the germinated weed plants

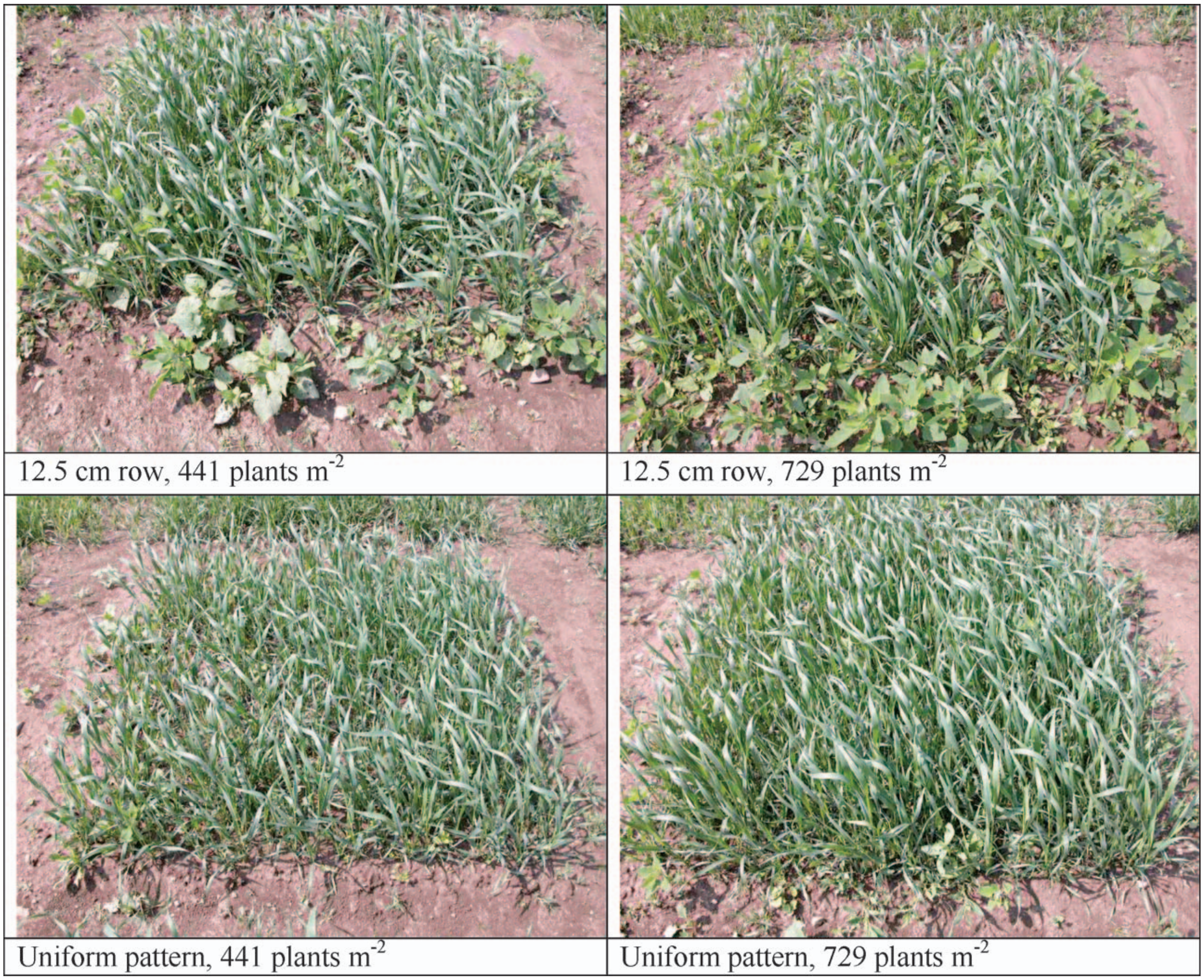


Figure 3. Photographs of row and uniform patterns (441 and 729 seeds m^{-2}), 42 d after sowing (May 29, 2007).

were small and had at most two to three foliage leaves, whereas wheat plants had two to three leaves and were on average 10 cm high. Visual inspections during the growing season did show differences in height of the weed plants among the different crop patterns (Figure 3). In 2008 and 2009 crop plants also germinated earlier than weed plants. In some of the crop spatial patterns weed plants reached the same height as the crop plants in 2007, but this was not the case in 2008 and 2009. The wheat emergence rate was 66% of the planned density in 2007, 65% in 2008, and 90% in 2009. The number of weed plants was 106 plants m^{-2} on May 11, 2007, 306 plants m^{-2}, on May 15, 2008, and 143 plants m^{-2} on May 7, 2009.

Effects of Crop Density and Crop Pattern on Weed and Crop Biomass. Weed biomass averaged 160 g m^{-2} in 2007, 49 g m^{-2} in 2008, and 72 g m^{-2} in 2009, and crop biomass averaged 642 g m^{-2} in 2007, 732 g m^{-2} in 2008, and 756 g m^{-2} in 2009. In all 3 yr higher crop density resulted in reduced weed biomass and increased crop biomass (Figures 4

Table 1. Test of fixed effects on weed biomass per square meter, crop biomass per square meter, and Morisita's index (I_δ) in 2007, 2008, and 2009. Weed biomass was log transformed in all 3 yr. Crop biomass and Morisita's index were untransformed.

Factor		Weed biomass		Crop biomass		Morisita's index (I_δ)	
2007	df	*F*	P	*F*	P	*F*	P
Density	2	32.9	< 0.0001	16.2	< 0.0001	3.5	0.0493
Pattern	3	12.5	< 0.0001	7.0	0.0018	98.3	< 0.0001
Density × pattern	6	1.4	0.2601	1.4	0.2449	4.4	0.0051
2008							
Density	2	17.6	< 0.0001	8.7	0.0012	9.3	0.0008
Pattern	4	0.4	0.8272	0.6	0.6570	67.0	< 0.0001
Density × pattern	8	0.3	0.9639	1.3	0.2698	3.1	0.0118
2009							
Density	2	41.9	< 0.0001	5.3	0.0113	0.1	0.9338
Pattern	4	0.4	0.8355	1.8	0.1516	59.1	< 0.0001
Density × pattern	8	0.6	0.7458	1.6	0.1776	2.1	0.0655

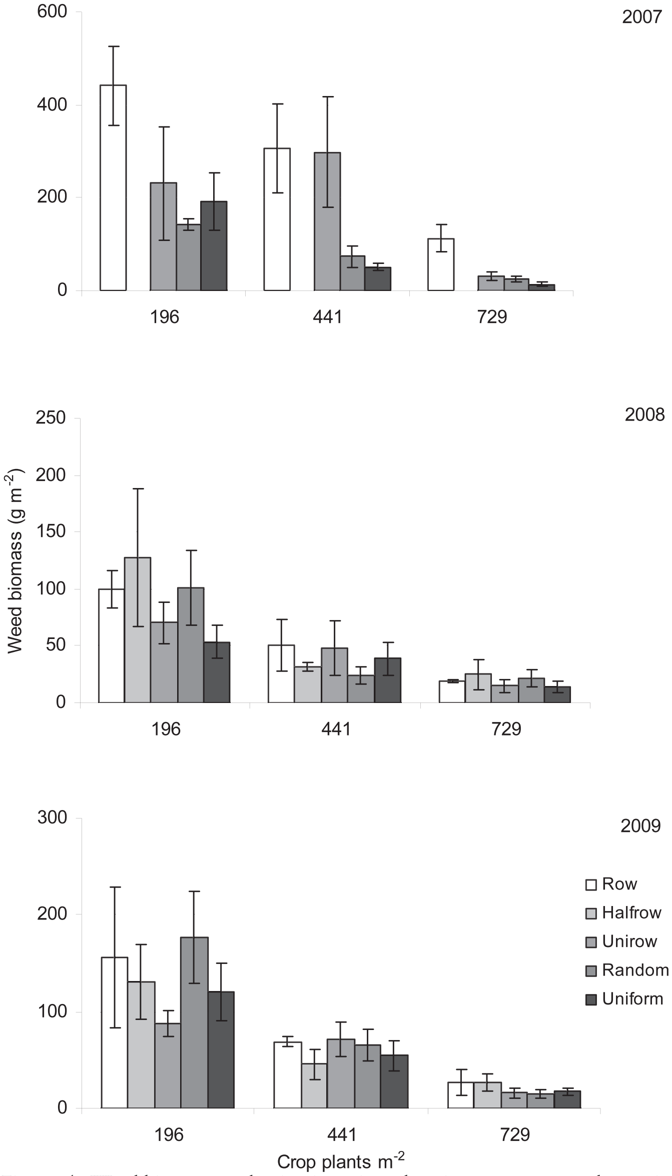


Figure 4. Weed biomass production in spring wheat in 2007, 2008, and 2009 in relation to three crop densities (196, 441, and 729 plants m^{-2}) and five crop-sowing patterns (row: 12.5-cm row distance, distance between seeds within the row is random; half row: 6.25-cm row distance, distance between seeds within the row is random; unirow: row distance is the same as the uniform pattern, distance between seeds within the row is random; random: random crop pattern; and uniform: row distance and distance between the seeds within the row is the same). The patterns have been ordered in increasing degree of uniformity. Note that the half-row spacing was not used in 2007 and that the scale is different in the 3 yr. Bars represent ± 1 standard error.

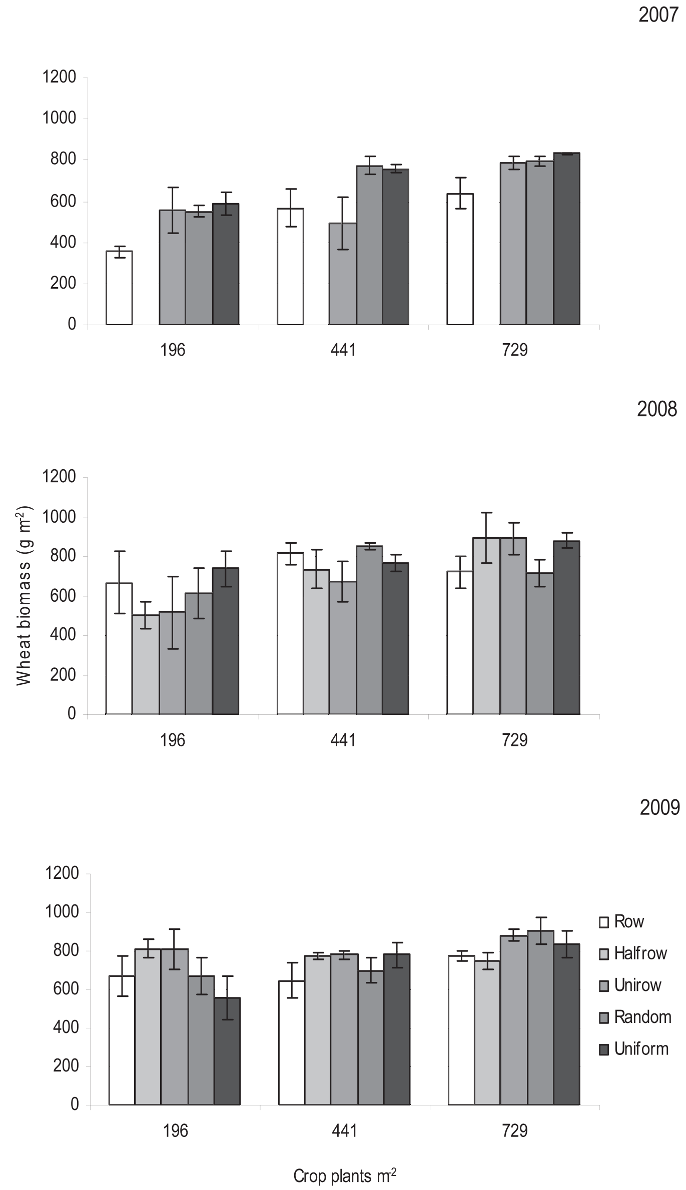


Figure 5. Crop biomass production in spring wheat in 2007, 2008, and 2009 in relation to three crop densities (196, 441, and 729 plants m^{-2}) and five crop-sowing patterns (row: 12.5-cm row distance, distance between seeds within the row is random; half row: 6.25-cm row distance, distance between seeds within the row is random; unirow: row distance is the same as the uniform pattern, distance between seeds within the row is random; random: random crop pattern; and uniform: row distance and distance between the seeds within the row are the same). The patterns have been ordered in increasing degree of uniformity. Note that the half-row spacing was not used in 2007. Bars represent ± 1 standard error.

Table 2. Least-squares means comparisons of different patterns for weed biomass, crop biomass, and Morisita's index. Comparisons with $P > 0.1$ are marked as nonsignificant (NS) in the table.

	Weed biomass			Crop biomass			Morisita's index		
Pattern	2007	2008	2009	2007	2008	2009	2007	2008	2009
Uniform vs. random	NS	NS	NS	NS	NS	NS	< 0.0001	< 0.0001	< 0.0001
Uniform vs. unirow	0.0130	NS	NS	0.0541	NS	0.0642	< 0.0001	< 0.0001	< 0.0001
Uniform vs. row	< 0.0001	NS	NS	0.0006	NS	NS	< 0.0001	< 0.0001	< 0.0001
Random vs. unirow	0.0743	NS	NS	NS	NS	NS	NS	NS	NS
Random vs. row	< 0.0001	NS	NS	0.0017	NS	NS	< 0.0001	< 0.0001	< 0.0001
Unirow vs. row	0.0116	NS	NS	0.0760	NS	0.0200	< 0.0001	< 0.0001	< 0.0001
Half row vs. uniform	–	NS	NS	–	NS	NS	–	< 0.0001	< 0.0001
Half row vs. random	–	NS	NS	–	NS	NS	–	NS	NS
Half row vs. unirow	–	NS	NS	–	NS	NS	–	NS	NS
Half row vs. row	–	NS	NS	–	NS	NS	–	< 0.0001	< 0.0001

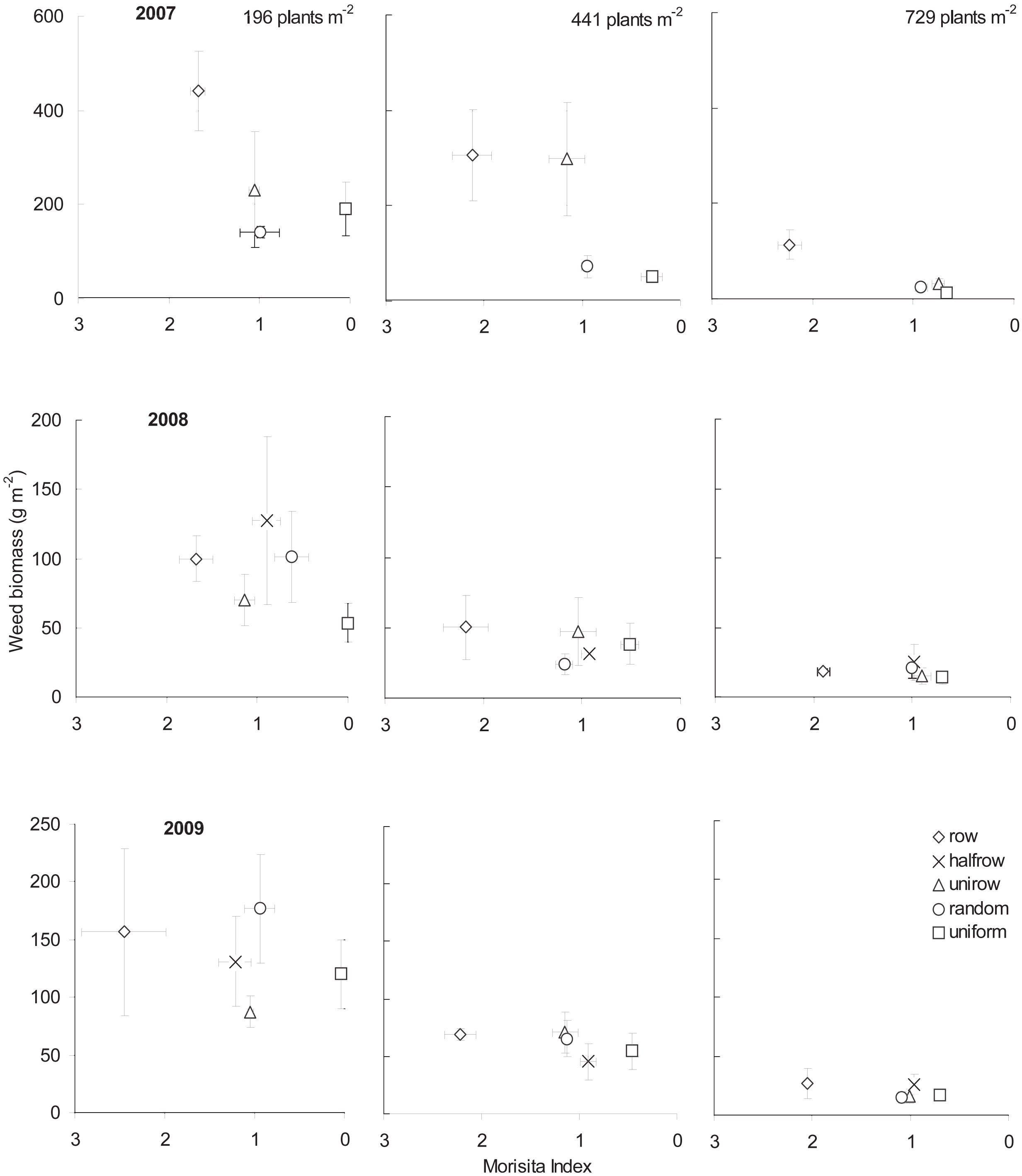


Figure 6. Relationship between Morisita's index at 5 × 5–cm square size at 196, 441, and 729 crop plants m^{-2} and weed biomass (late June) in spring wheat in 2007, 2008, and 2009 (in 2007: $y_{441} = 128.8x + 36.1$ [P = 0.0668] and $y_{729} = 56.6x - 20$ [P = 0.0011]). Note that the scale for weed biomass is different in the 3 years and that the scale for Morisita's index is ranked by increasing uniformity in the crop pattern.

to 7, Table 1). There was a strong effect of crop pattern on weed and crop biomass in the first year, but no significant effect in the following 2 yr (Table 1). Earlier experiments (Olsen et al. 2005a,b; Weiner et al. 2001) have shown that not only increasing crop density but also increasing uniformity in crop pattern had a negative effect on weed biomass. Weed biomass in 2007 was on average 70% lower in the most regular (uniform) pattern compared to standard practice (12.5-cm row distance) and crop biomass was on average 28% higher. Pairwise tests of the patterns for weed biomass showed that all patterns were different in 2007, except uniform and random, and that none of the patterns differed significantly from the others in 2008 and 2009 (Table 2). Pairwise tests on the effect of sowing patterns for crop biomass showed that in 2007 the patterns were different, except comparisons of uniform vs. random pattern and random vs. unirow pattern; in 2008 no differences between the patterns were found and in 2009 only uniform vs. unirow pattern and unirow vs. row pattern were significantly different (Table 2). Spring 2008 and 2009 were dry and warm and the

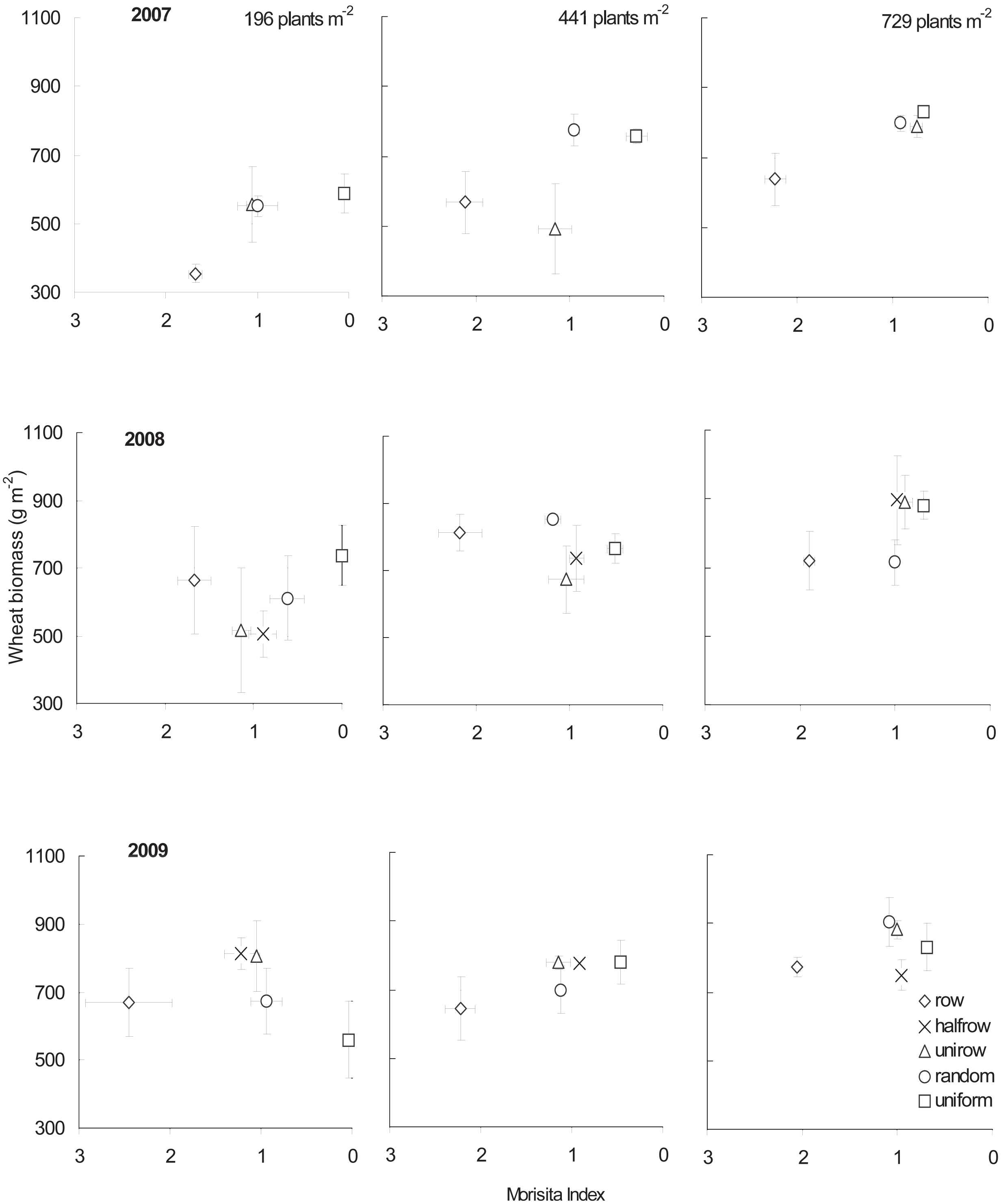


Figure 7. Relationship between Morisita's index at 5 × 5–cm square size at 196, 441, and 729 crop plants m^{-2} and crop biomass (late June) in spring wheat in 2007, 2008, and 2009 (in 2007: $y_{729} = -109.3x + 890.1$ (P = 0.0046). In 2009: $y_{441} = -76.9x + 852.9$ (P = 0.0890). Note that the scale for Morisita's index is ranked by increasing uniformity in the crop pattern.

plants were drought stressed early in the growing season, but the total biomass production (crop + weed) was similar in all 3 yr.

The results indicate that water availability is a very important factor for the interaction between weed and crop growth. Water deficiency had a more negative influence on weed growth than it had on crop growth, which resulted in a lower weed biomass production. Even though crop plants seemed to suffer from water deficiency at the beginning of the growing season, crop plants achieved a higher biomass production than in 2007. This may have been due to the much lower weed biomass in 2008 and 2009. Competition for light is size asymmetric (larger plants have a disproportionate advantage in competition with smaller plants, suppressing the growth of their smaller neighbors), whereas competition for water and nutrients is thought to be more

Table 3. Analysis of variance (type 1 fixed effects) of density and Morisita's index (spatial aggregation) on log of weed biomass and wheat biomass in 2007, 2008, and 2009.[a,b]

		Weed biomass				Wheat biomass		
Year	Source	DF	SS	P value	r^2	SS	P value	r^2
2007					0.6818			0.5478
	Block	2	0.1149	0.5545		44,459	0.2291	
	Density	2	4.0699	< 0.0001		311,931	0.0003	
	Morisita	1	1.7445	0.0002		147,047	0.0033	
2008					0.5296			0.4368
	Block	2	0.1386	0.4771		281,202	0.0041	
	Density	2	3.8804	< 0.0001		370,983	0.0009	
	Morisita	1	0.0148	0.6906		18,292	0.3692	
2009					0.7222			0.3187
	Block	2	0.1129	0.3803		131,842	0.0161	
	Density	2	5.5722	< 0.0001		124,340	0.0199	
	Morisita	1	0.0935	0.2078		5,159	0.5520	

[a] Abbreviations: DF, degrees of freedom; SS, sum of squares.

symmetric (Schwinning and Weiner 1998; Weiner 1990). Water deficiency in 2008 and 2009 may have resulted in a more size-symmetric competition, and this could explain that the effect of crop pattern on weed and crop biomass was only clearly observed in 2007. Weed biomass production was low in the two dry years and could be an alternative explanation for the absence of an effect of crop pattern on biomass production.

Morisita's Index. Quantifying the spatial aggregation with Morisita's index showed a clear distinction among the different sowing patterns in all 3 yr (Table 1), but pairwise tests did not detect differences in Morisita's index between random and unirow pattern, random and half-row pattern, and unirow and half-row pattern (Table 2). Models including Morisita's index showed that it had a highly significant effect on both weed and crop biomass in 2007, but not in 2008 and 2009, whereas crop density had a highly significant effect on both weed and crop biomass in all 3 yr (Table 3). The correlation between Morisita's index for the crop's spatial pattern and weed biomass was positive in 9 out of 9 cases ($P < 0.002$; Figure 6) and negative between crop spatial pattern and wheat biomass in 7 out of the 9 cases ($P = 0.09$; Figure 7), although most of the correlations themselves are not significant. Despite large variation in the data, the correlation between Morisita's index for the crop's spatial pattern and weed biomass was positive in all cases (Figure 6). This is strong evidence that weed suppression increases with spatial uniformity in cereal crops, even though the strength of this effect varies from year to year, presumably due to weather conditions. The effect of crop density on weed suppression has been well documented in previous studies (Blackshaw 1993; Boyd et al. 2009; Lemerle et al. 2004; Olsen et al. 2005b; Tanji et al. 1997) and confirmed in the present study (Table 3, Figure 4). Increased crop density and spatial uniformity can play a role in weed management. A combination of increased crop density and spatial uniformity means that both an improvement in weed suppression can be achieved to a degree that the technology and costs permit and a reduction in the use of herbicides can be obtained. The effect of density on crop biomass when there is high weed pressure is also very clear from our data and from previous studies, but the evidence for a positive effect of crop uniformity on crop biomass is less strong. This may be because weed biomass is only one of several factors influencing crop biomass. If weeds are not limiting crop biomass, the improved weed suppression will not necessarily result in increased crop biomass (and, by implication, yield).

Conclusions

The results confirm that increased crop density has a negative effect on weed biomass production and, when weed pressure is high, a positive effect on crop biomass production. Increased uniformity also had a negative effect on weed biomass, but not in all cases. Under spring drought conditions, which occurred in 2 of the 3 yr, the effect of spatial uniformity was smaller, or even nonexistent, than under nondrought conditions.

In general, increased cereal crop density can reduce weeds via two mechanisms:

1. A proportion effect (Mohler 2001). If crop density is increased, the crop population is a larger fraction of the total crop + weed community, so it will also be a larger fraction of the total biomass.
2. Size-asymmetric competition (Schwinning and Weiner 1998; Weiner et al. 2001). When a cereal crop has an initial size advantage over weeds, as is the case with annual weeds, this advantage increases with density, producing an overproportional effect of increased crop density.

Mechanism 1 always occurs when weeds are present, but its potential for weed suppression is limited. Mechanism 2 has more potential, but it depends on (1) initial crop size advantage and (2) environmental conditions leading to intense competition for light. We hypothesize that crop pattern effects on weeds occur only through size-asymmetric competition, so an effect of pattern is dependent on an initial size advantage and resource levels that produce size-asymmetric competition. The weather conditions that favor size-asymmetric competition are usually, but not always, present in cool mesic climates like in Denmark. In the present study the weather conditions resulted in size-asymmetric competition in 2007, but not in 2008 and 2009.

In previous studies (Olsen et al. 2005a,b; Weiner et al. 2001) weed biomass was reduced by 25 to 30% when the crop was sown in a highly uniform pattern, and an even stronger effect was observed in the first year of the present study. But water limitation early in the growing season in 2008 and 2009 resulted in only weak effects of crop spatial pattern on weed biomass.

Increased crop density can be used to improve weed suppression as observed in other experiments (Auškalnienė et al. 2010; Boyd et al. 2009; Lemerle et al. 2004; Wilson et al. 1995). Increased crop spatial uniformity maximized the effect of density on weed suppression when abiotic stress (e.g., drought) did not limit total biomass production, so improvement in the spatial uniformity of crop plants can play a role in weed management in mesic environments. A weed management strategy in cereal crops based on increasing crop density and spatial uniformity, as well as the development of varieties for such a strategy (Weiner et al. 2010) offers an environmentally friendly alternative to herbicides or mechanical weed control.

Acknowledgments

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