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Effects of density and spatial pattern of winter wheat on suppression of different weed species

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Field experiments on suppression of three species (scentless chamomile, field poppy, and canola) by winter wheat sown in two different spatial patterns (normal 12.8-cm rows and a uniform, grid-like pattern) and three densities (204, 449, and 721 plants m^{-2}) in two growing seasons were performed. The effects of crop-sowing density and pattern when weeds were controlled by herbicide were also investigated in one season. Weed and crop biomass were measured when weed biomass was at its maximum (late June/early July), and grain was harvested in August. Weed biomass comprised on average 30% of the total (crop + weed) biomass in the first year and only 5% in the second year. Weed biomass decreased and grain yield increased with increasing sowing density. Weed biomass was on average 23% lower and grain yield 14% higher in the uniform pattern than in rows. Weed biomass decreased 27% and 38% in the row pattern and 36% and 50% in the uniform pattern by increasing sowing density from low to medium and from low to high density, respectively. When weeds were controlled with herbicide, increasing sowing density had no influence on grain yield, but grain yield was 7% higher in the uniform pattern. Field poppy was the weed with the largest biomass and the largest impact on yield, whereas canola had the lowest biomass and the least impact on yield.

Nomenclature: Field poppy, *Papaver rhoeas* L. PAPRH; scentless chamomile, *Matricaria perforata* Mérat MATIN; canola, *Brassica napus* L. 'Karola'; winter wheat, *Triticum aestivum* L. 'Terra'.

Key words: Crop–weed competition, sowing density, spatial uniformity.

Late sowing with preemergence (PRE) and postemergence (POST) harrowing in winter crops can be a useful method for controlling weeds in autumn-sown cereals, but harrowing in the wet and cold weather conditions during autumn and winter in Denmark and other northern countries can result in crop damage and yield loss (Cirujeda et al. 2003; Melander et al. 2003; Rasmussen 1998). Interrow hoeing to control weeds is less sensitive to treatment timing but requires an accurate steering of the machinery to avoid crop damage and increased row spacing (Melander et al. 2003). Increased row spacing in winter cereals can result in increased (Hashem et al. 1998), decreased (Koscelny et al. 1991; Solie et al. 1991), or unaltered (Justice et al. 1994; Vander Vorst et al. 1983) yield. Some experiments show no effect of row spacing at a constant seeding rate on yield, but yield sometimes increases with narrower rows at high-seeding rates (Blackshaw et al. 1999; Teich et al. 1993). The contradictory results for decreased row spacing are probably because of different experimental designs, height and growth habit of crop and weeds, and nutrient management (Mohler 2001). Results generally indicate that a strategy combining increased sowing density and narrow row spacing can decrease weed biomass and increase yield. In one study, increased winter wheat density improved suppression of naturally occurring weeds for some, but not all, varieties investigated, and the authors concluded that sowing density was more important than cultivar selection for improved weed suppression (Korres and Froud-Williams 2002).

Increased sowing density and a more uniformly distributed crop pattern can contribute to suppression of weeds by spring wheat (Weiner et al. 2001). The question here is whether the advantage of sowing the crop in a more uniform spatial pattern and at increased density also occurs in winter wheat. If so, such a strategy could represent an alternative to herbicides or mechanical weed control for controlling weeds in winter wheat.

Materials and Methods

The experiments were performed in 2001–2002 and repeated in the following year 2002–2003. The treatments were (1) three crop-sowing densities (204, 449, and 721 seeds m^{-2}) of winter wheat cv. Terra; (2) two spatial patterns (normal 12.8-cm rows and a uniform, grid-like pattern); and (3) three weed species with various growth forms (canola cv. Karola, scentless chamomile, and field poppy). A precision seed drill[1] was modified to sow wheat in a uniform grid-like pattern by having very narrow row spacings in which the spacing between rows was as close as possible to the precision spacing within the rows for each sowing density (Weiner et al. 2001). Interrow distance (row width) was 7.0, 4.2, and 4.2 cm, and intrarow seeding distance was 7.0, 5.5, and 3.3 cm for the low, medium, and high densities, respectively. A standard Hege research seed drill[2] with 12.8-cm row spacing was used to sow the normal row pattern.

The experiment was sown on October 10, 2001 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 14.4 C in June and a mean annual precipitation of 594 mm (Anonymous 2004). Precipitation in both research periods (Period 1: October 1, 2001, to August 31, 2002; Period 2: October 1, 2002, to August 31, 2003) was higher than normal. In the first research period, precipitation in January, February, and June to August, and in the second research period in October, May, and July was higher than normal. During autumn and winter, temperature was higher in the first growth season than normal, whereas it was lower than normal in February in the second research period.

Plots were 1.31 by 8.0 m, and there were four replicated blocks in which each block was a single row of 18 plots in a random order. There was 0.5 m between adjacent plots and 4 m between the rows of plots. After sowing the wheat, the soil was rolled, and the individual weed species were sown at random in high densities to obtain high weed pressures (canola, 400 seeds m^{-2}; scentless chamomile, 1,500 seeds m^{-2}; and field poppy, 3,000 seeds m^{-2}). The seeds of the small-seeded weed species, scentless chamomile and field poppy, were mixed with coarse-ground flour before sowing. The number of wheat plants and the number of weeds of all species were counted within a single randomly placed 0.25-m^2 quadrat in each plot in three blocks on October 26, although there may have been some additional germination of weeds later. At that time, the average densities of the sown weeds were canola, 110 m^{-2}; scentless chamomile, 615 m^{-2}; and field poppy, 617 m^{-2}. The experiment was fertilized at a rate of 80 kg nitrogen (N) ha^{-1} on April 4, 2002. The biomass of sown weeds, wheat, and naturally occurring weeds on July 3, 2002 was measured by harvesting, drying, and weighing all aboveground biomass within a single randomly placed 0.25-m^2 quadrat in each plot. The crop was harvested (7.3 m^2) at maturity in late August and grain yield determined after cleaning.

The experiment was repeated in the following year (wheat sown October 2, 2002, weeds sown October 4, 2002) using the same procedures. Wheat plants in a 0.25-m^2 quadrat were counted in three of the four blocks on October 21. The crop and canola germinated in autumn, but canola died during the winter, and the plots with that species were sprayed twice with tribenuron plus Agropol adjuvant[3] applied on April 30 (4 g ai ha^{-1}) and May 27, 2003 (7.5 g ai ha^{-1}) to create weed-free control plots. Field poppy never germinated, and in those plots, all naturally occurring weeds (predominantly chickweed, *Stellaria media*; ladysthumb, *Polygonum persicaria*; scentless chamomile; and Persian speedwell, *Veronica persica*, most of which germinated in March 2002) were harvested instead. Scentless chamomile also germinated in March. Weeds were not counted. The experiment was fertilized at a rate of 80 kg N ha^{-1} on April 30, 2003. The biomass of sown weeds (in plots with scentless chamomile), wheat, and naturally occurring weeds was measured in the same way as the previous year on June 23, 2003. In herbicide-treated plots, only wheat was harvested. At maturity in early August, the crop was harvested and grain yield determined after cleaning.

All data were analyzed using PROC MIXED in SAS (1996), based on likelihood principles with sowing pattern, weed species, and sowing density as categorical variables and block as a random factor. Because weed biomass and grain yield and their variances differed greatly between the years, each year was analyzed separately. To achieve homogeneity of variance, weed biomass data were square root transformed

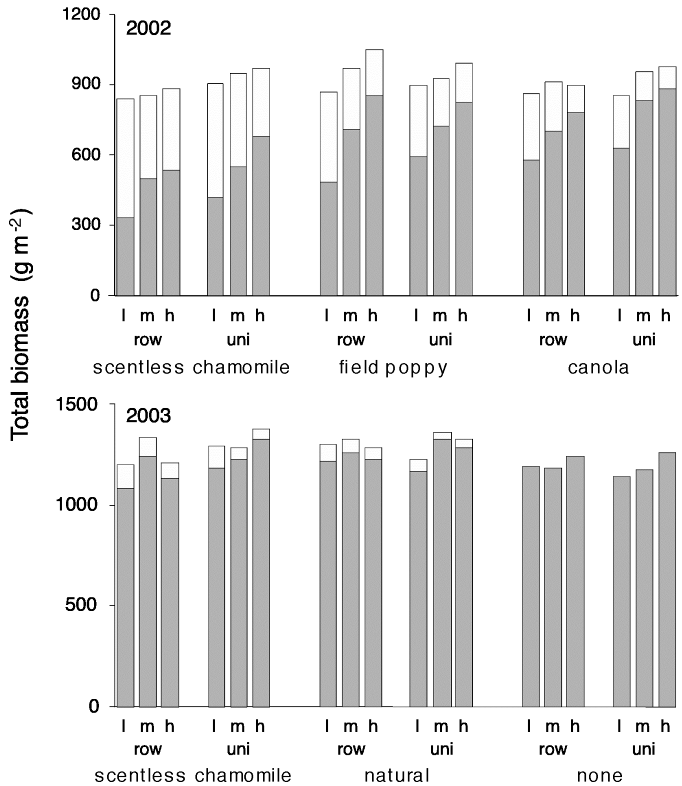

FIGURE 1. Total biomass of wheat (grey) and weed species (white), scentless chamomile, field poppy, canola, naturally occurring weeds, and no weeds, sown in combination with winter wheat, sown in two patterns (row, uni = uniform) at three densities (l = 204, m = 449, h = 721 plants m^{-2}) in 2001–2002 and 2002–2003. Note that the scale is different in the two years.

in 2002–2003. Data are presented as untransformed means with corresponding standard error (SE) given as a simple measure of variability. Differences between treatments were evaluated by the pdiff LSMEANS option in the PROC MIXED procedure.

Results and Discussion

The number of wheat plants that emerged was 5.5% and 7% higher in the uniform pattern than in rows in the two years, respectively, which could be because of a higher seeding rate or better germination in the uniform pattern.

A visual inspection early in the spring in both years showed that lower leaves of wheat in uniform pattern were more horizontally oriented than leaves of wheat sown in rows. Later in spring, this difference in leaf orientation was no longer observed.

2001–2002

Weed and Wheat Biomass

Weed biomass decreased with increasing sowing density in both patterns (Figure 1). There were strong effects of weed species ($P < 0.0001$), sowing density ($P < 0.0001$), and sowing pattern ($P = 0.0107$) on weed biomass (Table 1). On average, the percentage decrease in weed biomass by increasing sowing density was similar in row and uniform patterns. An increase from low to medium density resulted in 30% less weed biomass, and the increase from low to

Table 1. Test of fixed effects on total aboveground weed weight in 2001–2002 and 2002–2003. Interactions with P > 0.1 are removed from the analyses.

Source	Num DF[a]	Den DF	*F* value	P value
2001–2002				
Weed species	2	63	71.26	< 0.0001
Crop density	2	63	39.25	< 0.0001
Crop pattern	1	63	6.92	0.0107
2002–2003				
Weed species	1	40	19.35	< 0.0001
Crop density	2	40	11.31	0.0001
Crop pattern	1	40	16.80	0.0001

[a] Abbreviations: Den DF, denominator degrees of freedom; Num DF, numerator degrees of freedom.

Table 2. Test of fixed effects on wheat biomass in 2001–2002 and 2002–2003. Interactions with P > 0.1 are removed from the analyses.

Source	Num DF[a]	Den DF	*F* value	P value
2001–2002				
Weed species	2	66	38.24	< 0.0001
Crop density	2	66	41.25	< 0.0001
Crop pattern	1	66	10.25	0.0021
2002–2003				
Weed species	2	63	1.64	0.2014
Crop density	2	63	4.30	0.0178
Crop pattern	1	63	2.17	0.1459

[a] Abbreviations: Den DF, denominator degrees of freedom; Num DF, numerator degrees of freedom.

high density resulted in 45% less weed biomass. The proportion of weed biomass of the total biomass differed between the three weed species. On average, field poppy comprised 45% of the total biomass, scentless chamomile comprised 27%, and canola 20% of the total biomass. In all combinations of sowing density and spatial pattern, biomass of field poppy was significantly different from scentless chamomile and canola, whereas biomass of scentless chamomile and canola was only significantly different in the low-sowing density row pattern (P = 0.039). Weed biomass was 4, 10, and 25% lower in uniform pattern than in rows for field poppy, scentless chamomile, and canola, respectively.

There were strong effects of weed species (P < 0.0001), sowing density (P < 0.0001), and crop pattern (P = 0.0021) on wheat biomass (Table 2). In post hoc tests, wheat biomass in the presence of field poppy was significantly lower than with scentless chamomile and canola in all comparisons of sowing density and spatial patterns, whereas there were no significant differences in wheat biomass between scentless chamomile and canola.

Grain Yield

Grain yield increased with sowing density in both patterns (Figure 2). There were effects of weed species (P = 0.0019), sowing density (P < 0.0001), and crop pattern (P < 0.0001) on grain yield. Grain yield was negatively correlated with weed biomass (Figure 3) and significantly different between plots sown with canola and those sown with field poppy. For canola and scentless chamomile, grain yield was different in uniform pattern and low-density row pattern (P = 0.022), whereas grain yield was only slightly different in medium (P = 0.047) and high-density (P = 0.049) in the row pattern in plots sown with scentless chamomile and field poppy (Figure 2).

Weed biomass was, on average, 14% lower, wheat biomass 12% higher, and grain yield 14% higher in uniform pattern than in rows. Comparisons of high-sowing density and uniform pattern with normal-sowing practice (rows and medium density) resulted in 33% lower weed biomass, 25% higher wheat biomass, and 23% higher grain yield.

2002–2003

Weed and Wheat Biomass

Weed biomass was much lower in the second year than the first year. During the winter, canola died, and the plots in which this species was sown were sprayed with tribenuron to obtain weed-free plots. Field poppy never germinated, and in these plots, all naturally occurring weed species were harvested instead. On average, weed biomass of scentless chamomile and naturally occurring weeds comprised 6.6% and 4% of the total biomass, respectively. Despite differences from the previous year, including higher crop biomass and lower weed biomass, the observed trends were similar.

Weed biomass decreased with increasing sowing density in both patterns, except biomass of naturally occurring weeds when sowing density was increased from medium to

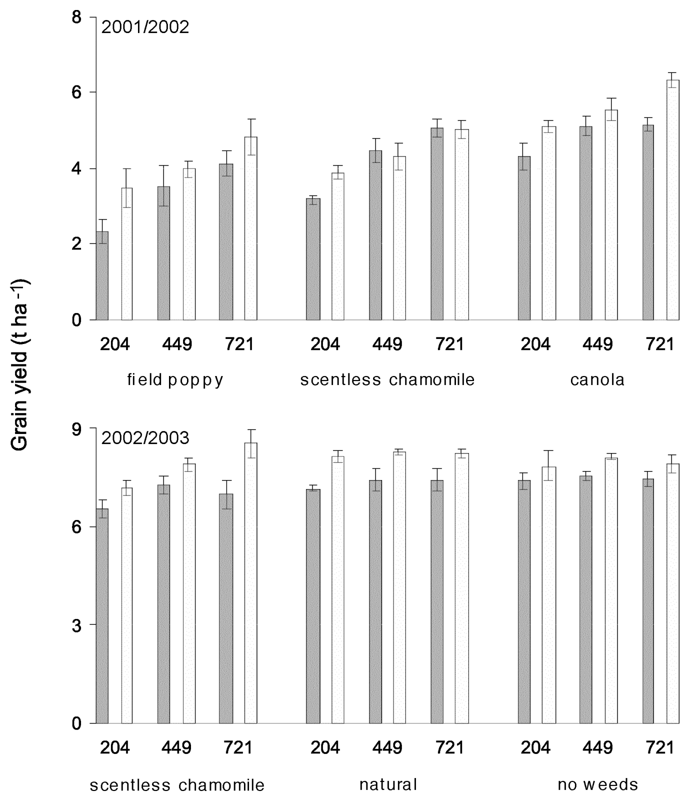

Figure 2. Grain yield of winter wheat sown in two spatial patterns (row, uniform) at three densities (204, 449, 721 plants m^{-2}) in 2001–2002 and 2002–2003 in combination with three different weed species (2001–2002: field poppy, scentless chamomile, canola; 2002–2003: scentless chamomile, naturally occurring weeds, no weeds). Gray column are rows, open columns are uniform pattern. Error bars represent ± 1 standard error (SE). Note that the scale is different in the two years.

TABLE 3. Test of fixed effects on grain yield in 2001–2002 and 2002–2003. Interactions with P > 0.1 are removed from the analyses.

Source	Num DF[a]	Den DF	*F* value	P value
2001–2002				
Weed species	2	9	13.57	0.0019
Crop density	2	55	37.96	< 0.0001
Crop pattern	1	55	19.81	< 0.0001
Species by pattern	2	55	2.62	0.0821
2002–2003				
Weed species	2	59	4.40	0.0165
Crop density	2	59	5.51	0.0085
Crop pattern	1	59	52.51	< 0.0001
Species by density	4	59	2.13	0.0884

[a] Abbreviations: Den DF, denominator degrees of freedom; Num DF, numerator degrees of freedom.

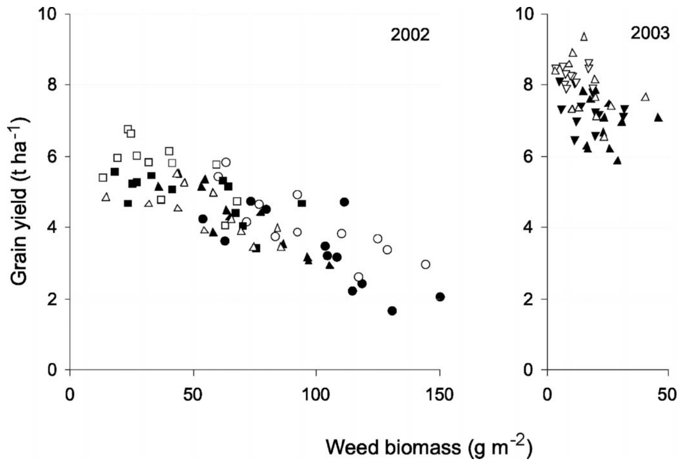

FIGURE 3. Grain yield in 2002 and 2003 in relation to weed biomass (scentless chamomile [triangles]; *Field poppy* [circles, 2002]; *Canola* [squares, 2002]; and naturally occurring weeds [inverted triangles, 2003]). Filled symbols row pattern (R), open symbols uniform pattern (U).

high in row pattern (Figure 1). There were strong and significant effects of weed species (P < 0.0001), sowing density (P = 0.0001), and crop pattern (P = 0.0001) on weed biomass (Table 1). An increase from low- to medium-sowing density resulted in 27 and 36% less weed biomass in row and uniform patterns, respectively, and an increase from low to high density resulted in 38% less weed biomass in row pattern and 50% less weed biomass in uniform pattern. Weed biomass was 26 and 38% lower in uniform pattern than in rows for plots with scentless chamomile and those with naturally occurring weeds, respectively. There was an effect of sowing density (P = 0.0178), but not spatial pattern, on wheat biomass (Table 2).

The total (weed + crop) biomass was higher in the second year, and weed biomass comprised, on average, 30% of the total biomass in the first year and only 5% in the second year. In the first year, all weed species germinated in the autumn, but in the second year, scentless chamomile, the only species that grew vigorously in both years, germinated in spring. This species comprised a much higher proportion of the total biomass in the first year than in the second year, demonstrating that the timing of weed emergence has major effects on crop–weed competition. The strong effects of sowing density and spatial pattern on weed biomass and yield loss appear to be mediated by the crop's size advantage (Weiner et al. 2001). This advantage is very sensitive to the relative germination time of crop and weed plants.

Grain Yield

There were effects of weed species (P = 0.0165), sowing density (P = 0.0085), and crop pattern (P < 0.0001) on grain yield (Table 3, Figure 2). Grain yield was negatively correlated with weed biomass in most cases, except for the plots with a uniform pattern and naturally occurring weeds (Figure 3), where weeds contributed only 3% of the total biomass. Grain yield in plots with scentless chamomile and plots without weeds was significantly different at low-sowing density in both patterns. There was no difference in grain yield between plots with naturally occurring weeds and plots without weeds (Figure 2).

Biomass of scentless chamomile and naturally occurring weeds was, on average, 31% lower, wheat biomass 5% higher, and grain yield 13% higher in uniform pattern than in rows. Comparisons of high-sowing density and uniform pattern with the treatments closest to normal sowing practice resulted in 49% lower weed biomass, 5% higher wheat biomass, and 15% higher grain yield.

Effects on yield in 2002–2003, although strong and highly significant, were still weaker than in the first year, because weeds did not limit yield in this season. Although only a small proportion of the total biomass consisted of weeds in 2002–2003, increased sowing density and a more uniformly distributed pattern resulted in lower weed biomass and a higher yield than normal sowing practice.

The results from the herbicide-treated plots are interesting because they indicate that when weeds are absent, increased sowing density in any of the two patterns had no influence on wheat biomass or grain yield in the range of crop densities chosen for this experiment. This supports the hypothesis that the advantage of increased sowing density occurs only when weeds are present. When weeds are absent or well controlled, the advantage of a uniform pattern is marginal, and there is no advantage of increased sowing density (Weiner et al. 2001). Although the uniform pattern did not have a significant effect on crop biomass, grain yield was 7% higher in the uniform pattern than in rows (P < 0.0108). This suggests that there are positive agronomic effects of a uniform spatial distribution of the crop in addition to those due to increased weed suppression.

Despite differences in biomass production and grain yield between the two years, the results for both years support previous findings and demonstrate that a combination of increased sowing density and a more uniformly distributed pattern can increase weed suppression in winter- as well as spring-sown wheat (Weiner et al. 2001). A significant reduction of weed reproductive structures at higher crop densities for different winter wheat cultivars has been observed in other studies (Korres and Froud-Williams 2002).

Our results suggest that a weed management strategy based on increased sowing density and a more uniformly distributed pattern can be used in conventional agriculture as a way to reduce herbicide application levels, but it is incompatible with POST mechanical weed control in winter wheat. One potential problem with increased sowing density is the risk of an increase in fungal pathogens, especially in row pattern, but this has not been observed in this or in other experiments (Olsen et al. 2005; Weiner et al. 2001). The gains in weed suppression and yield through increased crop density and spatial uniformity, without chemical or mechanical weed control, may be achievable in production if the appropriate technology is developed, and if farmers are willing to pay the additional cost of seed. In addition to reduced herbicide application, this weed management strategy may have other positive environmental effects, including less traffic on the field and, therefore, reduced soil compaction, fuel consumption, and carbon dioxide (CO_2) production.

Sources of Materials

[1] Seed drill, Kverneland Accord Corporation, Coesterweg 42, D-59494 Soest, Germany.

[2] Seed drill, Hege Machine Corporation, Kollmering 10, D-94535 Eging am See, Germany.

[3] Agropol adjuvant, DuPont Agro Denmark, Skojtevej 26, DK-2770 Kastrup, Denmark.

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