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The influence of *Triticum aestivum* density, sowing pattern and nitrogen fertilization on leaf area index and its spatial variation

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Summary

We investigated leaf area index (LAI) and its spatial variation early in the growing season in *Triticum aestivum* (spring wheat) sown in two spatial patterns (standard rows and a uniform pattern), at three densities (204, 449 and 721 seeds m^{-2}), and two nitrogen fertilization levels (0 and 80 kg nitrogen ha^{-1}). Our main hypothesis was that a more uniform distribution of individual plants does not affect overall LAI but reduces its spatial variation. We used the number of leaves touching a vertical pin (LAI*) as a measure of LAI. LAI* increased with sowing density, nitrogen fertilization and, contrary to our hypothesis, spatial uniformity. The coefficient of variation of LAI* was higher (1) at lower sowing density, (2) without nitrogen fertilizer and (3) in the row pattern. Both the increase in LAI and the decrease in its variation in more spatially uniform crops may contribute to increased weed suppression and increased yield.

Zusammenfassung

Wir untersuchten den Blattflächenindex (LAI) und seine räumliche Variation früh in der Wachstumssaison von *Triticum aestivum* (Sommerweizen), der in zwei räumlichen Mustern (Standardreihen und ein gleichförmiges Muster), in drei Dichten (204, 449 und 721 Samen m^{-2}) und bei zwei Stickstoffdüngerleveln (0 und 80 kg Stickstoff ha^{-1}) gesät wurde. Unsere Haupthypothese war, dass eine stärker uniforme Verteilung der individuellen Pflanzen den gesamten LAI nicht beeinflusst, aber seine räumliche Variation reduziert. Wir nutzen die Anzahl der Blätter, die eine vertikale Nadel berührten (LAI*), als ein Maß für den LAI. Der LAI* nahm mit der Saatdichte, der Stickstoffdüngung und im Widerspruch zu unserer Hypothese mit der räumlichen Uniformität zu. Der Variationskoeffizient des LAI* war größer bei (1)

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geringerer Saatdichte, (2) ohne Stickstoffdünger und (3) beim Reihenmuster. Beides, die Zunahme des LAI und die Abnahme seiner Variation in räumlich stärker uniformen Beständen, könnte zu einer zunehmenden Unterdrückung von Unkräutern und einer zunehmenden Ernte führen.

Introduction

High leaf area index (LAI) of crops early in the growing season is associated with high yield (Bullock, Khan, & Rayburn, 1998; Loomis & Connor, 1992; Thornley, 2000) and LAI has been used to predict crop losses due to weeds (Kropff & van Laar, 1993; Kropff et al., 1995). There are also many advantages of increased spatial uniformity in LAI, including reduced self-shading and therefore more efficient light interception. These advantages are especially important for crop–weed competition. Recent research has shown that increased uniformity in spatial distribution of crop plants can increase suppression of weeds (Kristensen, Olsen, Weiner, Griepentrog, & Nørremark, 2006; Olsen, Kristensen, & Weiner, 2005; Olsen, Kristensen, Weiner, & Griepentrog, 2005; Weiner, Griepentrog, & Kristensen, 2001). The mechanisms causing this effect are not clear (von Wettberg & Weiner, 2004), and we have hypothesized that reduced spatial variation in LAI is the most important. For a given LAI, the amount of light intercepted by the crop will be maximized, and therefore the amount of light reaching the soil surface will be minimized, when the spatial distribution of leaves is uniform. This also means that canopy closure will occur sooner if LAI is more uniform in space. Here we investigate the effect of sowing density, sowing pattern and nitrogen fertilization on a crop's LAI and its spatial variation.

Our hypotheses are that (1) overall LAI is not affected by the crop's spatial pattern but (2) spatial variation in LAI will be higher in the row pattern than in the uniform pattern (Weiner et al., 2001). While an increase in LAI with increasing crop density and nitrogen fertilization is to be expected, there is no obvious expectation concerning the effects of these two factors on spatial variation in LAI. We hypothesize that spatial variation in LAI will increase (3) with crop density and (4) with nitrogen availability. These hypotheses are based on the observation that competition among individual plants usually increases variation among individuals. Competition increases with density and increased nitrogen will increase mean size and therefore competition for other resources, although it is not clear that increased variation in individual size will result in increased spatial variation in LAI. To test the hypotheses we measured the effects of two crop sowing patterns, three crop densities, and two nitrogen-fertilization levels on LAI of *Triticum aestivum* L (spring wheat).

Materials and methods

We conducted a field study at the Royal Veterinary and Agricultural University's research farm in Taastrup, Denmark (55°40′N, 12°18′E), as part of an experiment investigating the effects of density, spatial uniformity and fertility level on weed suppression by spring wheat (Kristensen, Olsen, & Weiner, submitted). 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.

There were three sowing densities (204, 449 and 721 seeds m^{-2}) of spring wheat (*Triticum aestivum* L. cv. Leguan), two spatial patterns (normal rows and a uniform pattern) and two nitrogen fertilization levels (0 and 80 kg N ha^{-1}). A precision seed drill (Kverneland Accord Corporation, Soest, Germany) was modified to sow wheat in a highly uniform pattern (Weiner et al., 2001). The uniform pattern was achieved through a combination of narrow row spacing and individual placement of seeds within rows. The ratio of inter to intra row distance in the uniform pattern was 1:1 for the low density, 4:5 for the medium density and 5:4 for the high density. We used a standard Hege research seed drill (Hege, Waldenburg, Germany) with 12.8 cm row spacing to sow the normal row pattern.

The experiment was sown on 9 April 2002. Plots were 1.31×8.0 m and there were three replicate blocks. After sowing the wheat, the soil was rolled. Nitrogen fertilization was applied at a rate of 80 kg ha^{-1} 2 weeks after sowing. Plots were sprayed with the herbicide clorpyralid/fluoroxypyr/ioxynil (30/100/120 g a.i. l^{-1}) in an Ariane Super® formulation at a rate of 0.75 l ha^{-1} on May 15.

LAI was estimated using a 3 mm diameter metal pin with a level mounted on top to ensure that the pin was perfectly vertical during measurements.

The pin was lowered through the vegetation to the soil surface, and the number of leaves touching the pin was recorded. While a pin inclination angle of 32.5° in varying directions is considered a better measure of absolute LAI in complex vegetation because of variation in leaf angles (Bréda, 2003; Warren Wilson, 1963), we used a vertical pin because the use of an inclined pin in varying directions would be problematic for estimating spatial variation in LAI. Since (1) the vegetation here consists of only a single gramineous species, (2) there was no evidence of an effect of the treatments on leaf angles, and (3) our primary interest is in changes and variation in LAI, not its absolute value, the use of a vertical pin is reasonable for our purposes. Because we used a vertical pin, we refer to our estimate of LAI as LAI*. Thirty randomly placed measurements were made in each plot performed on May 23 and again on 27 May, when the wind was light. The data consist of the number of leaf contacts per pin within a plot. The LAI* of a plot is defined as the mean number of leaf contacts. The spatial variation in LAI* is defined as the coefficient of variance (CV) of the number of leaf contacts:

$$CV = \frac{S}{\bar{X}},$$

where S is the standard deviation and $\bar{X}$ the mean number of contacts. Biomass of wheat was measured on May 23 by harvesting, drying and weighing all aboveground biomass within a single randomly placed 0.25 m^2 quadrat in each plot.

Mean number of leaf contacts and the CV of leaf contacts were analyzed using PROC MIXED in SAS® version 8.2. (SAS Institute) which is based on likelihood principles (SAS, 1996), with block as a random effect. Analyses were carried out as successive tests, successively removing interactions with $P>0.1$ from the analysis. Data are presented as untransformed means. Mean number of leaf contacts and crop biomass are square root transformed in the analyses to achieve homogeneity of variance. The data were also analyzed as repeated measures over the two dates. The *F*- and *P*-values were almost identical in both analyses.

Results

LAI*

LAI* increased with sowing density and was higher in the uniform pattern than in rows at both fertilization levels (Fig. 1). LAI* increased over time and was largest at the high fertilization level (data not shown). There were strong and significant effects of fertilization level, sowing pattern, density ($P<0.0001$) and day of measurement ($P=0.001$) on LAI* (Table 1). LAI* was 33% higher in the uniform pattern than in rows in the absence of nitrogen fertilization and 37% higher with fertilization.

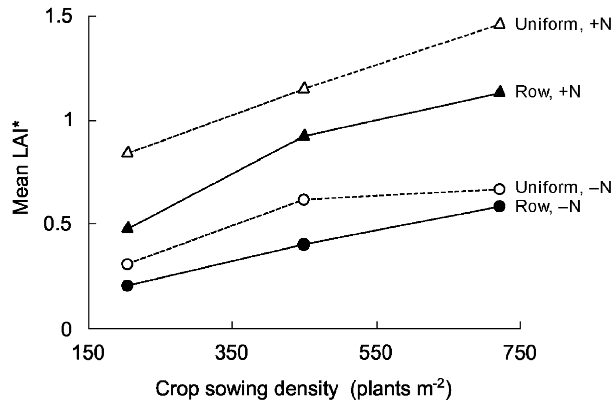

Figure 1. Estimate of leaf area index (LAI*, mean number of leaf contacts) of spring wheat (*Triticum aestivum*) sown in two patterns (row and uniform), at three densities (204, 449 and 721 plants m^{-2}) and at two nitrogen levels (0 and 80 kg nitrogen ha^{-1}). Mean of May 23 and 27.

Table 1. Test of fixed effects of nitrogen fertilization, sowing pattern, density and day on an estimate of leaf area index (LAI*, mean number of leaf contacts)

Effect	Num DF	*F*-value	*P*-value
Fertilization	1	209.98	<0.0001
Pattern	1	40.27	<0.0001
Density	2	66.70	<0.0001
Day	1	11.62	0.0011

Interactions with $P>0.1$ are removed from the analysis. Data are square root transformed. (Num DF: Numerator degrees of freedom; denominator degrees of freedom: 64).

Spatial variation in LAI*

CV of LAI* was higher without than with nitrogen addition in both patterns and it decreased with increasing density (Fig. 2). There were significant effects of sowing pattern, density, nitrogen (all $P<0.0001$) and day ($P=0.001$) on CV of LAI* (Table 2). CV of LAI* was 30% higher in rows than in the uniform pattern without nitrogen fertilization, and 32% higher when nitrogen was added.

Biomass

Biomass of *T. aestivum* increased with density in both patterns and fertilization levels (Fig. 3). There

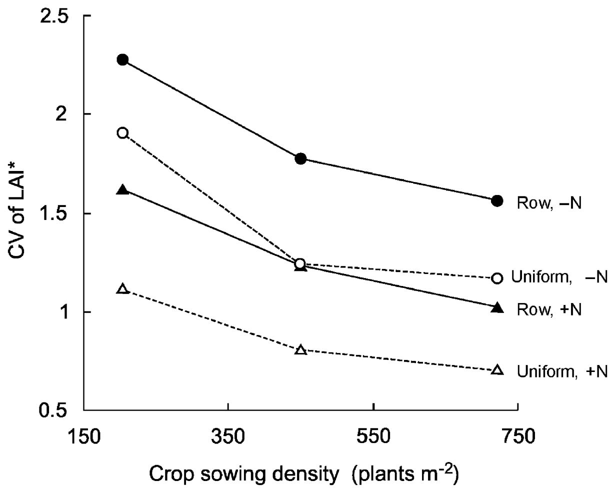

Figure 2. Coefficient of Variation (CV) of leaf area index of spring wheat (*Triticum aestivum*), sown in two spatial patterns (row and uniform), at three densities (204, 449 and 721 plants m^{-2}) and two nitrogen levels (0 and 80 kg nitrogen ha^{-1}). Mean of May 23 and 27.

Table 2. Test of fixed effects of nitrogen fertilization, sowing pattern, density and day on spatial variation in an estimate of leaf area index (coefficient of variation of number of leaf contacts)

Effect	Num DF	*F*-value	*P*-value
Fertilization	1	101.93	<0.0001
Pattern	1	56.49	<0.0001
Density	2	43.72	<0.0001
Day	1	11.87	0.0010

Interactions with $P>0.1$ are removed from the analysis. (Num DF: Numerator degrees of freedom; denominator degrees of freedom: 64).

were strong and significant effects of fertilization level ($P<0.0001$), sowing pattern ($P=0.0009$) and density ($P<0.0001$) on biomass (Table 3). There were highly significant interactions between fertilization and sowing pattern ($P=0.0060$), and between fertilization level and density ($P=0.0008$). Biomass was significantly higher in the uniform pattern than in the row pattern with nitrogen addition ($P<0.0001$), but not without.

Discussion

Not only was variation in LAI* lower when *T. aestivum* was sown in a uniform pattern rather than rows, as expected, but total LAI* was higher. The effect of sowing pattern on LAI* may be important for crop development and crop–weed interactions, because it implies an increase in the overall level of light interception by the crop (Hashem, Radosevish, & Roush, 1998; Norris, Elmore, Rejmanek, & Akey, 2001). The decrease in variation in LAI* in the more uniform pattern reduces self-shading and therefore increases light absorption by the canopy (Konno, 2001; Weiner et al., 2001).

As expected LAI* increased significantly with both density and nitrogen fertilization, but contrary to our hypotheses, the spatial variability in LAI* decreased with both density and nitrogen fertilization. This suggests that both crop density and nitrogen fertility can contribute to spatial uniformity in the field, which can be advantageous for crop growth and weed suppression.

Biomass was not significantly different between the two sowing patterns in the absence of nitrogen fertilization. While LAI* was higher in the uniform pattern than in rows without nitrogen addition, this higher LAI* was not reflected in higher biomass. This may be because the low growth rate without fertilization reduced any potential difference,

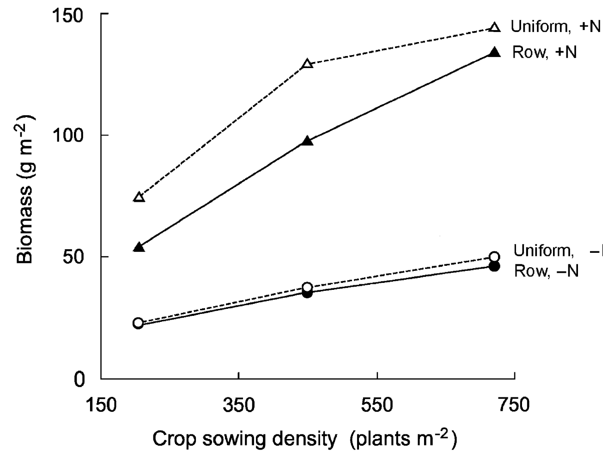

Figure 3. Biomass of spring wheat (*Triticum aestivum*), sown in two spatial patterns (row and uniform), at three densities (204, 449 and 721 plants m^{-2}) and two nitrogen levels (0 and 80 kg nitrogen ha^{-1}), harvested May 23.

Table 3. Test of fixed effects of nitrogen fertilization, sowing pattern, density and day on *T. aestivum* biomass

Effect	Num DF	*F*-value	*P*-value
Fertilization	1	693.72	<0.0001
Pattern	1	13.96	0.0009
Density	2	117.97	<0.0001
Fert × Pattern	1	8.97	0.0060
Fert × Dens	2	9.51	0.0008

Interactions with $P>0.1$ are removed from the analysis. Data are square root transformed. (Num DF: Numerator degrees of freedom; denominator degrees of freedom: 26).

whereas the growth rate was higher with nitrogen fertilization. At the higher nitrogen level there was 21% higher biomass in the uniform pattern than in rows. Later in the growing season there was no difference in biomass between the two sowing patterns with or without fertilization (data not shown). Under weed-free conditions, as here, the effect of a uniform pattern on biomass is expected to be small because the plasticity of growth allows plants to grow towards areas of high resource levels (Ballaré, Scopel, Jordan, & Vierstra, 1994; Hutchings & de Kroon, 1994) and use all available resources. The results suggest that plasticity cannot quickly compensate for the increase in local density in the row pattern.

The results indicate that LAI is influenced by the sowing pattern, and that the spatial variation in the distribution of LAI is reduced in a uniform pattern. These observations indicate that the uniform pattern performs better in covering the soil early in the growing season, and that this effect increases with increasing density and with fertilization. If weeds are present but their seedlings are initially smaller than crop seedlings, a uniform sowing pattern is competitively superior to rows (Olsen, Kristensen, & Weiner, 2005; Olsen, Kristensen, Weiner, & Griepentrog, 2005; Weiner et al., 2001). Our results suggest that the ground is covered more quickly in the uniform pattern both because there is higher LAI and because self-shading is reduced. Increased crop density and nitrogen availability can contribute to these positive effects.

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