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Width of clover strips and wheat rows influence grain yield in winter wheat/white clover intercropping

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Abstract

Cereal–legume intercropping offers potential benefits in low-input cropping systems, where nutrient inputs, in particular nitrogen (N), are limited. In the present study, winter wheat (*Triticum aestivum* L.) and white clover (*Trifolium repens* L.) were intercropped by sowing the wheat into rototilled strips in an established stand of white clover.

A field experiment was performed in two fields starting in two different years to explore the effects of width of the wheat rows and clover strips on the competition between the species and on wheat yields. The factors were intercropping (clover sole crop, wheat sole crop and wheat/clover intercropping), rototilled band width, sowing width and wheat density in a factorial experimental design that enabled some of the interactions between the factors to be estimated. The measurements included grain yield, ear density, grain weight, grain N concentration, dry matter and N in above-ground biomass of wheat, clover and weeds and profiles of photosynthetic active radiation (PAR) within the crop canopy.

Intercropping of winter wheat and clover resulted in wheat grain yield decreases of 10–25% compared with a wheat sole crop. The yield reductions were likely caused by interspecific competition for light and N during vegetative growth, and for soil water during grain filling. N uptake in the wheat intercrop increased during late season growth, resulting in only small differences in total N uptake between wheat intercrops and sole crops, but increased grain N concentrations in the intercrop. Interspecific competition during vegetative wheat growth was reduced by increasing width of the rototilled strips from 7 to 14 cm, resulting in higher grain yields and increased grain N uptake. Increasing the sowing width of the wheat crop from 3 to 6 cm increased interspecific interactions and reduced wheat intraspecific competition during the entire growing season, leading to improved grain yields and higher grain N uptake.

Keywords: Intercropping; Winter wheat; White clover; Competition; Crop management; Yield components; Nitrogen uptake

1. Introduction

The area farmed according to organic principles is increasing in many developed countries. The area farmed organically in Denmark thus constituted 6.3%

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of the agricultural area in 2003 (Plantedirektoratet, 2004). The major limits on crop production in organic farming in Denmark are the availability of soil nitrogen (N) and the control of weeds (Olesen et al., 2002). In this context, cereal–legume intercropping may offer some benefits through increased N supply from biological N fixation (BNF) and by improved weed control through a denser crop stand (Anil et al., 1998). There may be additional benefits of intercropping, including better control of pests and diseases (Trenbath, 1993) and reduced soil erosion.

Intercropping of cereals in a perennial stand of white clover has been proposed as a possible option for whole-crop silage production in low-input farming systems (Jones and Clements, 1993). However, it may also have some merits for grain production in organic farming (Clements and Donaldson, 1997; Thorsted et al., 2002). In this system, a cereal crop (e.g. winter wheat [*Triticum aestivum* L.]) is established in a stand of white clover (*Trifolium repens* L.). The clover should supply N to the system and thus to the cereal crop via BNF. The cereal crop may be established by direct drilling into the clover crop. Alternatively, the wheat may be sown into a rototilled band in the clover, which will reduce the competition between cereal and clover during establishment of the cereal crop.

The biomass growth of the cereal crop in a cereal:clover intercrop without high levels of N fertilisation appears to be dominated by below-ground competition, presumably for N (M.D. Thorsted, unpublished data). Below-ground competition may be influenced indirectly through the spatial structure of the cereal:legume intercrop. Factors such as rototilled band width, seed density and sowing width may affect competition and offer possibilities of increasing cereal yield and cereal grain quality. Such spatial factors may offer some of the best options to maximize complementarity of intercrops in low-input farming (Midmore, 1993). The cereal seed density has thus been found to significantly affect the competition between cereals and clover in cereal:clover intercrops (Ross et al., 2003).

The spatial arrangement of individual plants influence crop yields in several ways. A uniform arrangement of crop plants offers a greater chance of the single plant to obtain an equal share of the available resources (light, water and nutrients), resulting in a decreased intraspecific competition. A uniform spatial arrangement of crop plants also increase competitive ability to weeds, since a greater proportion of the weeds will be affected by competition from the crop (interspecific competition) (Weiner et al., 2001). Experiments have thus shown that the biomass of interrow weeds may increase by increased distance from nearest winter wheat row and nearest conspecific neighbours (von Wettberg and Weiner, 2004).

Plant competition below-ground seems to be size symmetric, i.e., plants obtain soil resources proportional to their size (von Wettberg and Weiner, 2003), but above-ground competition have often shown to be size asymmetric (Weiner, 1990). Thus, it may be possible to affect above-ground competition of a cereal:clover intercrop through changes in the spatial structure, and through effects on the above-ground biomass also to affect below-ground competition for water and nutrients.

The experiment presented here was designed to investigate the effects of several factors on the performance of wheat in a winter wheat:white clover intercrop. These include the width of rototilled strip in which the wheat is planted, the width of the sowing band within this strip, and the seed density of wheat. For comparison, treatments without clover or without wheat were included.

2. Materials and methods

The experiment was carried out during two years from 1999 to 2001 in two different fields on a sandy loam soil at Research Centre Foulum in Denmark (56°30′N, 9°35′E). The soil type is a typic hapludult according to the Soil Taxonomy System (Nielsen and Møberg, 1985). Monthly mean temperature, precipitation and potential evapotranspiration are shown for the two main growing seasons in Table 1.

2.1. Experimental design

The experiment was a fully randomised block design with four replicates. The plot size was 3 m × 18 m. The experiment had 4 factors, but only 10 factor combinations were tested, giving a total of 40 plots (Table 2). The first factor, rototilled strip width, consisted of two treatments, 7 and 14 cm. The second

Table 1
Monthly mean temperature and sums of precipitation and potential evapotranspiration at Foulum during the main growing season in 2000, 2001 and the mean for the years 1961–1990 (Olesen, 1991)

Month	Temperature (°C)			Precipitation (mm)			Potential evapotranspiration (mm)		
	1961–1990	2000	2001	1961–1990	2000	2001	1961–1990	2000	2001
April	5.5	7.9	5.3	35	34	66	54	53	45
May	10.5	12.1	10.8	45	55	34	86	59	99
June	14.2	13.0	12.0	52	38	61	103	85	92
July	15.4	14.4	16.8	67	61	28	98	88	115
August	15.1	14.4	16.3	66	56	70	83	69	79

factor, wheat sowing width, consisted of two treatments, 3 and 6 cm. The third factor, wheat plant density, consisted of two treatments, 250 and 400 plants m^{-2}. The fourth factor (intercropping) was either a winter wheat sole crop (no clover), a white clover sole crop (no wheat) or a wheat:clover intercrop. The white clover cultivar was Milo (DLF-Trifolium, Denmark), and the winter wheat cultivar was Stakado (Abed, Denmark).

The same experimental design was used in 2000 and 2001 in two different fields. To establish the white clover crop, white clover seeds were undersown in spring 1999 and 2000 in spring oats (*Avena sativa* L.) by evenly distributing 10 kg ha^{-1} seeds in 40 plots in 1999 and in 24 plots in 2000. The oat crop was harvested and grain and straw removed on 3 September in 1999 and on 25 August in 2000. In 1999, the clover was cut at a height of 4 cm and the cuttings removed on 20 September. On the same date, clover and the upper 2 cm soil layer was removed in the plots, where there should not be clover. In 2000, no clover was seeded in the plots, where there should not be clover. In the plots with clover, the clover was cut at a height of 4 cm and the cuttings removed just before sowing the wheat. Strips, either 7 or 14 cm wide, were rototilled in the clover sward with a Maschio rotary cultivator. The 7 cm strip was rototilled with straight blades and the 14 cm strip with helicoidal blades. Winter wheat was sown in the strips on 8 October 1999 and on 20 September 2000 with a Nordsten disc coulter sowing machine mounted on the rotary cultivator. The sowing width was either 3 or 6 cm and was regulated by placing one or two coulters, respectively, in the rototilled rows. The row distance was 25 cm, and the direction of the rows was East–West. Inorganic fertiliser (70 kg N ha^{-1}, 17 kg P ha^{-1} and 52 kg K ha^{-1}) was applied by even distribution on the surface on 10 April 2000 and on 26 April 2001.

2.2. Measurements

Grain yields were determined by harvesting a 1.5 m × 9.15 m area in each plot. The area outside the harvest plot was used for sampling of above-ground

Table 2
Combinations of five treatment factors in the experiment

Treatment	Rototilled width (cm)	Sowing width (cm)	Plant density (plants m^{-2})	Presence of *Trifolium repens*	Presence of *Triticum aestivum*
a	7	3	400	+	+
b	7	3	250	+	+
c	14	3	400	+	+
d	14	6	400	+	+
e	7	3	400	−	+
f	7	3	250	−	+
g	14	3	400	−	+
h	14	6	400	−	+
i	7	–	–	+	−
j	14	–	–	+	−

Table 3
Occurrence of selected growth stages of wheat according to the BBCH scale (Lancashire et al., 1991)

Growth stage	1999/2000	2000/2001
Plant emergence (GS 09)	25 October	5 October
Flag leaf emerged (GS 39)	19 May	1 June
Anthesis (GS 65)	15 June	25 June
Yellow ripeness (GS 87)	1 August	6 August
Harvest	15 August	23 August

biomass. The number of wheat ears was taken as the average of five counts of ears in 0.1 m^2 rings randomly placed in each plot on 14 June 2000 and on 21 June 2001. The plots were harvested at maturity using a combine harvester. Grain weight was determined by weighing 600 dried grains per plot. The occurrence of selected growth stages in wheat and the harvest dates were recorded (Table 3).

Wheat, clover and weed above-ground biomass production was determined by sampling above-ground biomass in two 50 cm × 50 cm quadrants per plot. Sampling of above-ground plant material was done on four dates from 11 June to 9 August 2000, and on three dates from 5 May to 1 August 2001. The dry weight of grains and all plant samples were determined after oven drying at 80 °C for 24 h. Total N in the wheat biomass and grain was determined by the Dumas method on finely milled samples from each plot (Hansen, 1989).

The interception of photosynthetic active radiation (PAR, 400–700 nm) by the crop canopy was measured before each plant sampling in 2000 in treatments a, c–e, g and i (Table 2). The measurements were taken with a line quantum sensor (LI-191SA, LI-COR Inc., Lincoln, NE, USA) at heights 0, 10, 20 and 40 cm above the ground. The line quantum sensor was held perpendicular to the wheat row direction, and simultaneous measurements of PAR were taken above the crop canopy. Each recorded PAR measurement was an average of three measurements taken in each plot.

2.3. Calculations and statistical analysis

The yield and biomass data were subjected to analyses of variance using the MIXED procedure of the SAS statistical analysis system (SAS Institute, 1999). To balance the data with respect to factors tested, the data were split into subgroups. When the rototilled width was analysed the treatments a, c, e and g were used (Table 2). When the sowing width was analysed the treatments c, d, g and h were used, and when the plant density was analysed the treatments a, b, e and f were used. Yield data was analysed for each year separately with block as a random variable. The biomass data were analysed for both years using year and block as random variables and using the repeated measurements analysis. To obtain variance homogeneity wheat, clover and weed above-ground biomass and accumulated N in wheat biomass were log-transformed.

The harvest index was calculated as the ratio of dry matter grain yield to wheat above-ground dry matter at the last sampling date in the respective year.

3. Results

3.1. Wheat biomass and grain yield

Presence of clover led to reductions in wheat grain yields by 12 and 25% in 2000 and 2001, respectively, compared to the corresponding wheat sole crops (Tables 4 and 5). Increasing the sowing width from 3 to 6 cm led to increased grain yields in both years. When clover was present the increase was 5% in 2000 and 17% in 2001 and in wheat monoculture the increase was 6% in 2000 and 9% in 2001. An increase in rototilled width from 7 to 14 cm had no effect on grain yield in the wheat sole crop, but increased grain yield in the intercrop (Table 4). However, this effect was only significant in 2000.

The above-ground biomass of wheat was greater in the wheat sole crop than in intercropped wheat in both years ($P = 0.003$, Fig. 1a and b). There was an increase in wheat biomass with increased plant density ($P = 0.03$, data not shown), and there was a tendency in 2000 for wheat biomass to increase with increased rototilled width ($P = 0.06$, data not shown).

3.2. Nitrogen uptake and concentrations

The wheat grain N concentration was increased in the intercropped compared with sole wheat crops in both years (Tables 4 and 5). However, this increase occurred as a result of the reduced grain dry matter yield in the intercrop, because the total grain N content

Table 4
Grain yield, yield components, harvest index (HI) and grain N in winter wheat

Factors	Clover	2000 Grain yield (Mg ha^{-1})	2000 Grain mass (mg)	2000 HI	2000 Ears (m^{-2})	2000 N in grain (%)	2000 N in grain (kg ha^{-1})	2001 Grain yield (Mg ha^{-1})	2001 Grain mass (mg)	2001 HI	2001 Ears (m^{-2})	2001 N in grain (%)	2001 N in grain (kg ha^{-1})
Clover intercrop													
	–	4.70	55.1	0.47	263	1.41	67	4.38	57.5	0.40	308	1.38	60
	+	4.14	54.9	0.44	308	1.64	68	3.27	55.5	0.38	322	1.62	53
S.E.		0.082	0.38	0.012	11	0.021	1.7	0.115	0.35	0.018	18	0.018	1.7
Rototilled width (RW) (cm)													
7	–	4.70	54.7	0.46	275	1.42	67	4.34	56.9	0.37	351	1.39	60
7	+	3.82	55.1	0.41	328	1.68	64	2.97	55.0	0.36	348	1.69	50
14	–	4.61	55.1	0.49	269	1.40	65	4.39	56.9	0.39	325	1.38	61
14	+	4.34	54.3	0.42	356	1.56	68	3.30	54.8	0.33	372	1.60	53
S.E.		0.066	0.87	0.016	10	0.024	1.8	0.117	0.47	0.021	14	0.015	1.8
Sowing width (SW) (cm)													
3	–	4.61	55.1	0.48	269	1.40	65	4.39	56.9	0.39	325	1.38	61
3	+	4.34	54.3	0.42	356	1.55	68	3.30	54.8	0.33	372	1.60	52
6	–	4.87	56.2	0.45	279	1.39	68	4.77	57.6	0.45	358	1.36	65
6	+	4.58	53.8	0.46	325	1.56	71	3.87	55.4	0.42	348	1.54	59
S.E.		0.075	0.34	0.017	7	0.019	1.6	0.116	0.35	0.030	9	0.021	1.9
Plant density (PD) (plants m^{-2})													
250	–	4.63	54.5	0.49	231	1.45	67	4.04	58.4	0.47	198	1.39	56
250	+	3.82	56.3	0.46	222	1.75	67	2.95	56.9	0.43	219	1.66	49
400	–	4.70	54.7	0.46	275	1.42	67	4.34	56.9	0.37	351	1.39	60
400	+	3.82	55.1	0.41	328	1.68	64	2.97	55.0	0.36	348	1.69	50
S.E.		0.073	0.63	0.016	9	0.020	1.7	0.116	0.56	0.017	16	0.013	1.7

Grain yields, grain mass, N concentration and N content in grain are shown on at dry matter basis.

was unaffected by intercropping in 2000 and slightly reduced by intercropping in 2001 (Table 4). The grain N concentration was reduced in both years when rototilled width was increased from 7 to 14 cm, and this was due to a change in grain dry matter yield rather than grain N uptake. Increasing sowing width caused an increase in grain N uptake in both years (Tables 4 and 5). In 2000, grain N concentration was

Table 5
Probability values for the statistical tests of the factors clover (CL), rototilled width (RW), sowing width (SW), plant density (PD) and interactions between CL and the RW, SW and PD factors from analyses of variances for the different variables from Table 4

Factors	2000 Grain yield (Mg ha^{-1})	2000 Grain mass (mg)	2000 HI	2000 Ears (m^{-2})	2000 N in grain (%)	2000 N in grain (kg ha^{-1})	2001 Grain yield (Mg ha^{-1})	2001 Grain mass (mg)	2001 HI	2001 Ears (m^{-2})	2001 N in grain (%)	2001 N in grain (kg ha^{-1})
Clover intercrop (CL)	<0.0001	NS	<0.05	<0.01	<0.0001	NS	<0.0001	<0.001	NS	NS	<0.0001	<0.0001
Rototilled width (RW)	<0.05	NS	NS	NS	<0.001	NS	NS	NS	NS	NS	<0.01	NS
Sowing width (SW)	<0.01	NS	NS	NS	0.083	<0.01	<0.01	0.23	<0.05	NS	<0.05	< 0.05
Plant density (PD)	NS	NS	0.10	<0.001	<0.05	NS	NS	0.05	NS	<0.0001	NS	NS
Interactions												
CL × RW	<0.01	NS	NS	NS	<0.01	0.08	NS	NS	NS	NS	0.05	NS
CL × SW	NS	0.09	<0.05	0.08	NS	NS	NS	NS	NS	<0.05	NS	NS
CL × PD	NS	NS	0.56	<0.05	NS	NS	NS	NS	NS	NS	NS	NS

NS: $P > 0.10$.

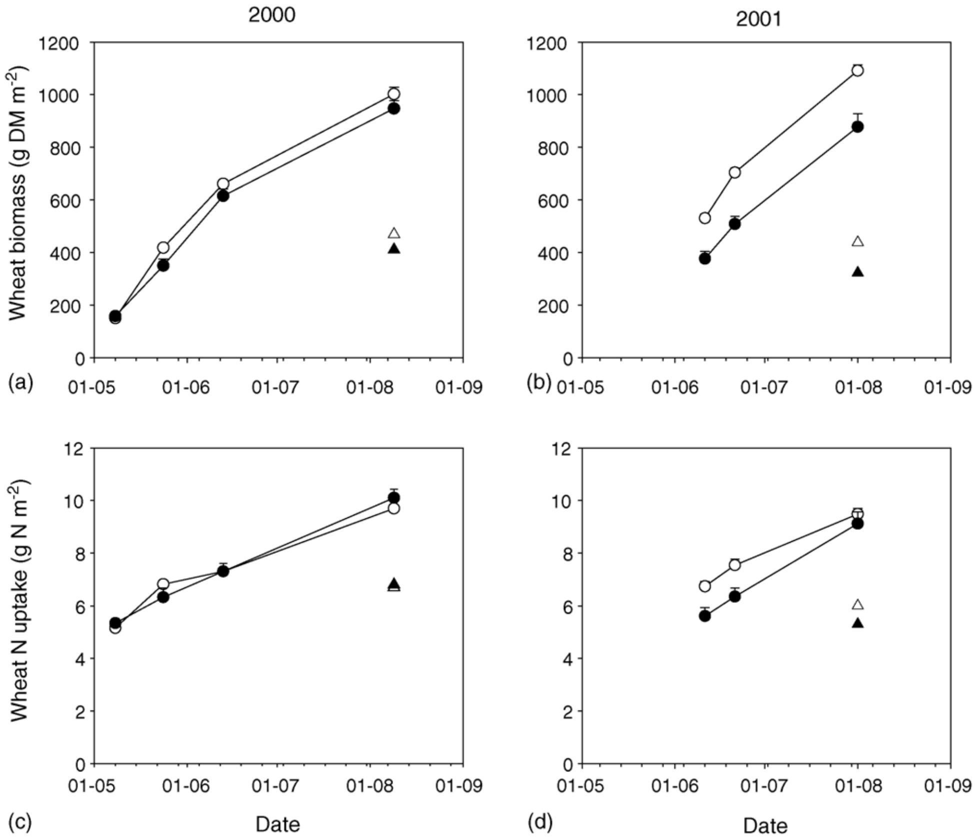

Fig. 1. Development of above-ground dry matter in wheat in 2000 (a) and 2001 (b), and N in above-ground biomass in 2000 (c) and 2001 (d). Symbols indicate wheat sole crop (○) and wheat intercropped with clover (●). Means of treatments a–h (Table 2). Triangles indicate dry matter grain yield (a and b) and grain N yields (c and d), wheat sole crop (△) and wheat intercropped (▲). The bars show the standard error.

higher at the low plant density than at the high plant density. However, grain N uptake was unaffected by plant density (Table 5).

The total N in wheat biomass was lower for the intercropped wheat compared to wheat in monoculture in 2001 ($P = 0.0003$, Fig. 1d). The above-ground total N at a plant density of 250 plants m^{-2} was reduced by 0.86 g N m^{-2} on average compared to a plant density of 400 plants m^{-2} ($P < 0.001$, data not shown). The N uptake rate in above-ground wheat biomass estimated by linear regression over all samplings in 2000 was 0.045 and 0.051 g N m^{-2} d^{-1} for wheat sole crop and wheat/clover intercrop, respectively. The corresponding values in 2001 were 0.051 and 0.067 g N m^{-2} d^{-1}. However, this difference in N uptake rate was not significant in either year.

3.3. Wheat grain weight and ear density

The wheat grain weight was lower when wheat was intercropped with clover than in the wheat sole crop in 2001 (Tables 4 and 5). There was a tendency towards decreased grain weight with increased plant density in 2001.

Wheat ear density was greater in 2000 in the intercropped wheat compared to wheat in monoculture (Tables 4 and 5). Ear density increased with increasing plant density in both years (Table 5). In 2000, the ear density was increased in the intercropped wheat at the high plant density, but not at the low plant density (Table 4). In 2001, the ear density was increased at the greater sowing width in the wheat sole crop, whereas ear density decreased at the greater sowing width in the wheat/clover intercrop. The tendency was the same in 2000 (Table 4).

The overall effects of the changes in ear density, grain yield and grain weight was a reduction in number of grains per ear of 25–26% in both years in the intercropped wheat compared with the wheat sole crop. This reduction was highest at low sowing width (28–31%) and smaller at the greater sowing width (13–16%). The rototilled width did not influence the effect of intercropping on number of grains per ear.

3.4. Harvest index

The mean harvest index was lower in 2001 (0.39) than in 2000 (0.45). The harvest index of wheat was reduced by intercropping in both years, but the difference was only significant in 2000 (Tables 4 and 5). In 2001, there was an increase in harvest index when sowing width was increased. This effect was seen to a lesser extent in 2000, but only in the wheat/clover intercrop.

3.5. White clover and weed biomass

Intercropping of wheat and clover led to a reduction in clover biomass compared with a clover sole crop under the same management (Fig. 2a and b). An increase in rototilled width reduced the amount of clover in both years ($P < 0.001$, data not shown). This effect was obtained during spring, whereas there was no difference in the amount of clover from mid June and onwards. There was a tendency for a reduction in clover biomass at higher plant density ($P = 0.07$, data not shown).

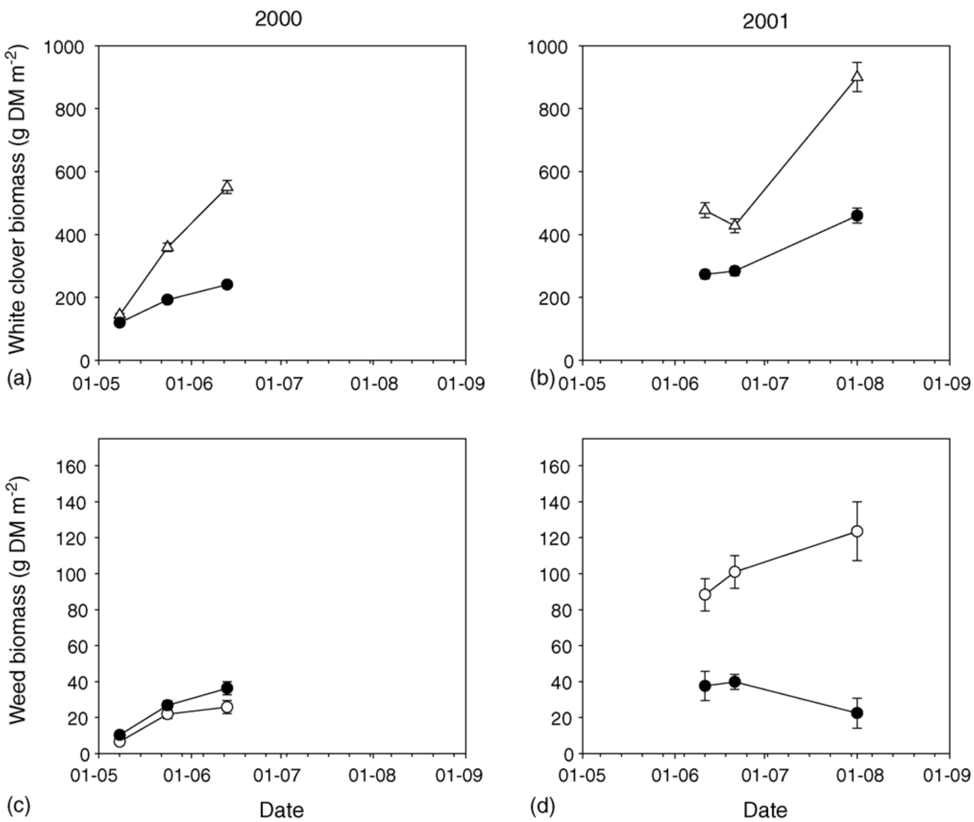

Fig. 2. Development of above-ground dry matter in white clover in 2000 (a) and 2001 (b), and above-ground weed dry matter in 2000 (c) and 2001 (d). Symbols in (a and b) indicate white clover sole crop (△) and clover intercropped with wheat (●). Symbols in (c and d) indicate weeds in wheat sole crop (○) and weeds in wheat/clover intercrop (●); (a and b) are means of treatments a–d and (c and d) are means of treatments a–h (Table 2). The bars show the standard error.

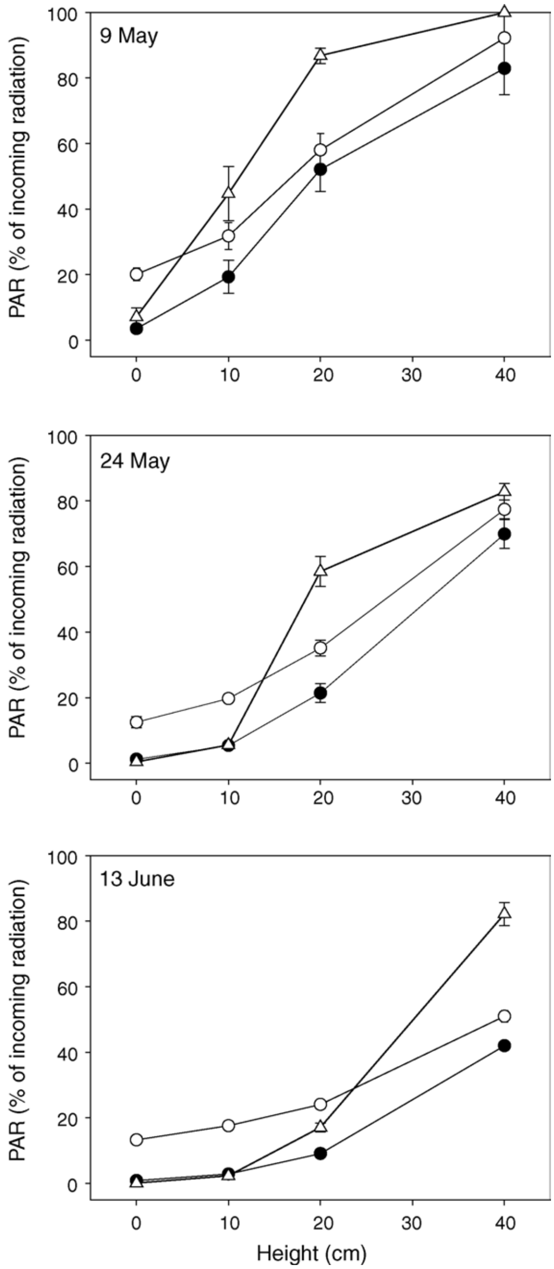

Fig. 3. Proportion of photosynthetic active radiation (PAR) at different depth in the crop canopy on three dates in 2000. Symbols indicate wheat sole crop (○), white clover sole crop (△) and wheat/clover intercrop (●). Means of treatments a, c, e, g and i (Table 2). The bars show the standard error.

The presence of clover caused a slight increase in the weed biomass in 2000 ($P < 0.05$), whereas the weed biomass was reduced in 2001 in the intercrop compared with the wheat sole crop ($P < 0.0001$) (Fig. 2c and d).

3.6. Interception of PAR

The presence of clover in combination with wheat reduced PAR for all heights and at all sampling dates compared to the wheat sole crop (Fig. 3). Except for the two last dates at the two lowest heights, intercropping also reduced PAR compared with the clover sole crop. When all dates and heights were included in the analysis, PAR was increased at increased rototilled width in the sole crop ($P < 0.005$, data not shown). When the first sampling date was excluded from the analysis there was a tendency ($P = 0.06$) for increased PAR with increasing rototilled width in the intercrop treatment (data not shown). When the first sampling date was excluded from the analysis, there was a higher reduction in PAR in the clover treatments compared to wheat monoculture at the lower heights (0, 10 and 20 cm above the soil surface) than for the higher canopy layer (40 cm above soil surface) ($P < 0.05$).

4. Discussion

4.1. Competition for water

Both total dry matter and grain yield of the wheat was reduced when intercropping wheat and clover (Table 4 and Fig. 1). However, the effect on grain yield was higher than on above-ground biomass, resulting in a reduced harvest index (HI) in the intercropped wheat. A lower HI can be an indicator of a reduced assimilation during the grain filling period, because total above-ground biomass is a function of dry matter accumulation during the whole growing season, whereas a large fraction of grain yield is determined by assimilation after anthesis (Olesen et al., 2000b). A reduction in HI of winter wheat sole crops with increasing disease attack from about 0.50 in healthy crops to about 0.40 in moderately diseased crops has been observed, and this effect was attributed to a reduction in photosynthesis during grain filling in the diseased crops (Olesen et al., 2000a). In the present case, the reduction in HI was not due to disease but other factors reducing growth during the grain filling period. There were no major differences in overall N uptake between the wheat sole crop and the wheat intercrop, so it is unlike that this could have affected HI. Alternatively, the reduction in wheat HI due to the presence of clover could be an effect of wheat plant size (Weiner, 2004).

White clover contributed 30–40% of total above-ground biomass during June in both years, and its share of the green leaf area index may have been even higher. Thus, although wheat has it leaves located higher in the canopy, clover will contribute a large proportion of the total crop transpiration. The larger total leaf area of the intercrop has most likely led to a higher transpiration from the intercrop compared with the wheat monoculture, and during the summer this then may have resulted in a higher soil water deficit in the intercrop. Drought stress can be an important factor in reducing HI in wheat (Xiao-Yun et al., 2003).

The hypothesis that HI was reduced by drought stress is supported by the fact that HI was substantially lower in 2001 compared with 2000, and the potential water deficit (potential evapotranspiration minus precipitation) during April to July was 97 mm in 2000 and 162 mm in 2001 (Table 1). The soil at Foulum has a capacity for available water of approximately 193 mm in the upper 100 cm of the soil profile (Djurhuus and Olesen, 2000), and the crop would therefore have used up almost all available water in 2001. In addition, increasing plant density could have contributed to drought stress, because high plant density leads to high leaf area index and consequently high evapotranspiration in early season. The normal potential soil water deficit at Foulum is 142 mm, and it is therefore likely that the higher evapotranspiration from the intercrop will reduce HI and grain yield in many years.

An increase in the sowing width from 3 to 6 cm increased the harvest index in the wheat/clover intercrop. Such an increase in sowing width increases the interspecific competition and reduces the intraspecific competition (Weiner et al., 2001). It is possible that the higher interspecific competition for soil water has improved the water uptake of the wheat crop by improving the exploration of the soil volume by the wheat roots. A similar effect was not seen by increased rototilled width in the intercrop, which did not affect clover amount from mid June and onwards. Thus, the increase in rototilled width probably did not affect the competition for soil water.

4.2. Competition for light

Competition for light played an important role in the interspecific competition, in particular below a height of 20 cm, where the clover dominated the light interception (Fig. 3). During June and July this competition for light probably had a larger effect on the clover than on the wheat, such that clover only grew very slowly during this period (Fig. 2), whereas the growth rate of wheat biomass was similar in the wheat sole crop and in the intercropped wheat (Fig. 1).

During early development of the wheat crop, however, competition for light probably also affected the growth of the wheat crop. Increasing the width of the rototilled strip reduced this early competition for light by leaving a narrower band of clover prior to sowing the wheat. The increase in rototilled width increased wheat above-ground biomass, ear density and grain yield, whereas the grain weight was slightly reduced. This points to the influence of rototilled width on early competition for light, since ear density is affected by factors during vegetative growth, whereas grain weight is primarily affected by factors during grain filling (Gooding et al., 2000).

The clover soil cover may have reduced the emergence and growth of weeds in the wheat/clover intercrop and could explain the significantly reduced weed biomass of the intercrop in 2001 (Fig. 2). Intercrops generally provide a better competition against weeds by offering a better soil coverage and a more effective light interception due to an increase in overall biomass density (Hauggaard-Nielsen et al., 2001). These effects are then complemented by effects of crop density, plant geometry, species and cultivars on light interception and thus weed suppressive ability (Champion et al., 1998). In 2000, the weed density was low in both intercropped and sole cropped plots. The difference in the two years may have been due to the removal of the top surface soil layer in the wheat sole crop in the first year, which may have removed many germinating weed seeds.

4.3. Nitrogen supply

Total N harvested in grains varied between 53 and 68 kg N ha^{-1} in both years and indicate that similar amounts of N were available to the wheat sole crop and the wheat intercrop. This is also indicated by the measured N uptake in the above-ground biomass (Fig. 1). However, the wheat in the intercrop had a lower N uptake during spring compared with the wheat sole crop, especially in 2001. This may have been due to competition for the spring-applied mineral N fertiliser, which was evenly spread on the ground. Because of the clover ground cover, some of this fertiliser would have been taken up by clover in the intercrop and thus not made available to the wheat.

On the other hand, release of N from the clover biomass in the intercrop may increase the general level of soil mineral N (Bergkvist, 2003) and thus improve the wheat N supply. This effect was seen as a higher rate of N uptake during June and July in the wheat intercrop (Fig. 2). However, this N uptake occurred too late to improve grain yields and the result was an increase in grain protein concentration. Much of the increase in grain protein concentration can also be attributed to the yield reduction caused by increased competition for water in the intercrop as described above. Similar effects of cereal/clover intercrops resulting in higher grain N concentration have been found in other studies (Thorsted et al., 2002; Bergkvist, 2003), in some cases resulting from increased N uptake in the intercropped cereal and in other cases from dilution of the N uptake in a higher dry matter yield in the sole crop.

Grain N uptake was increased in both years by increasing the sowing width from 3 to 6 cm. As with competition for water described above, the greater sowing width increased the interspecific competition and reduced the intraspecific competition in wheat for soil N thus resulting in an overall larger N uptake in the wheat crop.

One of the more surprising effects of the intercropping was an increase in the ear density in the intercropped wheat. This effect was particularly large at the greater rototilled width, which indicates that temporal patterns in N supply may have affected tiller production and/or tiller survival. The reduced yields and higher ear density in the intercropped wheat gave substantially fewer grains per ear, and this may have contributed to the lower harvest index of the intercropped wheat. This is supported by the fact that the reduction in HI from intercropping was particularly large at the low sowing width, where the reduction in number of ears per grain was greatest.

4.4. Perspectives

The results show that it is possible under conditions of good water supply to obtain grain yields in intercropped wheat and white clover that are similar to yields of wheat sole crops, but with a higher grain N concentration. A wide seeding width of the wheat in a wide rototilled band in the clover is required. Intercropping of wheat and white clover should be avoided where there is a large risk of summer droughts as the transpiration from the clover will reduce the soil moisture available for the wheat crop. There may, however, be possibilities through control of the clover to reduce transpiration during the growing season (Thorsted et al., 2002), so that the moisture limitations of the intercropped wheat are reduced. The system also offers potential benefits for longer term improvements in soil fertility by increasing soil carbon and nitrogen inputs.

5. Conclusions

Intercropping of winter wheat and clover resulted in wheat grain yield decreases of 10–25% compared with a wheat sole crop. The yield reductions were probably caused by interspecific competition for light and N during vegetative growth and interspecific competition for soil water during grain filling. Release of N from the clover may have increased the N uptake in the wheat intercrop during late growth, resulting in only small differences between wheat intercrops and sole crops in total N uptake and in higher grain N concentrations in the wheat intercrops.

Increasing the rototilled width from 7 to 14 cm resulted in higher grain yields and increased grain N uptake presumably due to reduced interspecific competition for light and N during wheat vegetative growth. Increasing the sowing width of the wheat crop from 3 to 6 cm resulted in improved grain yields and higher grain N uptake, probably due to increased interspecific competition and reduced wheat intraspecific competition for water, N and light during the entire growing season.

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References

Anil, L., Park, R.H., Phipps, R.H., Miller, F.A., 1998. Temperate intercropping of cereals of cereals for forage: a review of the potential for growth and utilization with particular reference to the UK. Grass Forage Sci. 53, 301–317.

Bergkvist, G., 2003. Effect of white clover and nitrogen availability on the grain yield of winter wheat in a three-season intercropping system. Acta Agric. Scand., Sect. B 53, 97–109.

Champion, G.T., Froud-Williams, R.J., Holland, J.M., 1998. Interactions between wheat (*Triticum aestivum* L.) cultivar, row spacing and density and the effect on weed suppression and crop yield. Ann. Appl. Biol. 133, 443–453.

Clements, R.O., Donaldson, G., 1997. Clover and cereal: low input bi-cropping. Farming Conserv. 3, 12–14.

Djurhuus, J., Olesen, J.E., 2000. Characterisation of Four sites in Denmark for Long-Term Experiments on Crop Rotations in Organic Farming. DIAS Report No. 22. Danish Institute of Agricultural Sciences, Tjele, Denmark.

Gooding, M.J., Dimmock, J.P.R.E., France, J., Jones, S.A., 2000. Green area decline of wheat flag leaves: the influence of fungicides and relationships with mean grain weight and grain yield. Ann. Appl. Biol. 136, 77–84.

Hansen, B., 1989. Determination of nitrogen as elementary N, an alternative to Kjeldahl. Acta Agric. Scand. 39, 113–118.

Hauggaard-Nielsen, H., Ambus, P., Jensen, E.S., 2001. Interspecific competition N use and interference with weeds in pea-barley intercropping. Field Crops Res. 70, 101–109.

Jones, L., Clements, R.O., 1993. Development of a low-input system for growing wheat (*Triticum vulgare*) in a permanent understorey of white clover (*Trifolium repens*). Ann. Appl. Biol. 123, 109–119.

Lancashire, P.D., Bleiholder, H., van den Boom, T., Langelüddeke, P., Strauss, R., Weber, E., Witzenberger, A., 1991. A uniform decimal code for the growth stages of crops and weeds. Ann. Appl. Biol. 119, 561–601.

Midmore, D.J., 1993. Resource use and intercrop productivity. Field Crops Res. 34, 357–380.

Nielsen, J.D., Møberg, J.P., 1985. Klassificering af jordprofiler fra forsøgsstationer i Danmark. Tidsskr. Planteavl 89, 157–168.

Olesen, J.E., 1991. Jordbrugsmeteorologisk årsoversigt 1990. Tidsskr Planteavl Specialserie S2130, Danish Institute of Agricultural Sciences, Tjele, Denmark.

Olesen, J.E., Mortensen, J.V., Jørgensen, L.N., Andersen, M.N., 2000a. Irrigation strategy, nitrogen application and fungicide control in winter wheat on a sandy soil. I. Yield, yield components and nitrogen uptake. J. Agric. Sci., Camb. 134, 1–11.

Olesen, J.E., Jørgensen, L.N., Mortensen, J.V., 2000b. Irrigation strategy, nitrogen application and fungicide control in winter wheat on a sandy soil. II. Radiation interception and conversion. J. Agric. Sci., Camb. 134, 13–23.

Olesen, J.E., Rasmussen, I.A., Askegaard, M., Kristensen, K., 2002. Whole-rotation dry matter and nitrogen grain yields from the first course of an organic farming crop rotation experiment. J. Agric. Sci., Camb. 139, 361–370.

Plantedirektoratet, 2004. Økologiske jordbrugsbedrifter 2003. Autorisation, Produktion. Plantedirektoratet, Lyngby, Denmark.

Ross, S.M., King, J.R., O'Donovan, J.T., Izaurralde, R.C., 2003. Seeding rate effects in oat-berseem clover intercrops. Can. J. Plant Sci. 83, 769–778.

SAS Institute, 1999. SAS/STAT User's Guide, The SAS System for Windows, Version 8. SAS Institute, Cary, NC.

Thorsted, M.D., Koefoed, N., Olesen, J.E., 2002. Intercropping of oats (*Avena sativa* L.) with different white clover (*Trifolium repens* L.) cultivars. Effects on biomass development and oat yield. J. Agric. Sci., Camb. 138, 261–267.

Trenbath, B.R., 1993. Intercropping for the management of pests and diseases. Field Crops Res. 34, 381–405.

von Wettberg, E.J., Weiner, J., 2003. Larger *Triticum aestivum* plants do not preempt nutrient-rich patches in a glasshouse experiment. Plant Ecol. 169, 85–92.

von Wettberg, E.J., Weiner, J., 2004. Effects of distance to crop rows and to conspecific neighbours on the size of *Brassica napus* and *Veronica persica* weeds. Basic Appl. Ecol. 5, 35–41.

Weiner, J., 1990. Asymmetric competition in plant populations. Trends Ecol. Evol. 5, 360–364.

Weiner, J., 2004. Allocation, plasticity and allometry in plants. Perspect. Plant Ecol. Evol. Syst. 6, 207–215.

Weiner, J., Griepentrog, H.-W., Kristensen, L., 2001. Suppression of weeds by spring wheat (*Triticum aestivum*) increases with crop density and spatial uniformity. J. Appl. Ecol. 38, 784–790.

Xiao-Yun, P., Gen-Xuan, W., Hui-Min, Y., Xiao-Ping, W., 2003. Effect of water deficits on within-plot variability in growth and grain yield of spring wheat in northwest China. Field Crops Res. 80, 195–205.