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Interspecific competition, N use and interference with weeds in pea–barley intercropping

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Abstract

Field pea (*Pisum sativum* L.) and spring barley (*Hordeum vulgare* L.) were intercropped and sole cropped to compare the effects of crop diversity on productivity and use of N sources on a soil with a high weed pressure. ^{15}N enrichment techniques were used to determine the pea–barley–weed-N dynamics. The pea–barley intercrop yielded 4.6 t grain ha^{-1}, which was significantly greater than the yields of pea and barley in sole cropping. Calculation of land equivalent ratios showed that plant growth factors were used from 25 to 38% more efficiently by the intercrop than by the sole crops. Barley sole crops accumulated 65 kg soil N ha^{-1} in aboveground plant parts, which was similar to 73 kg soil N ha^{-1} in the pea–barley intercrop and significantly greater than 15 kg soil N ha^{-1} in the pea sole crop. The weeds accumulated 57 kg soil N ha^{-1} in aboveground plant parts during the growing season in the pea sole crops. Intercropped barley accumulated 71 kg N ha^{-1}. Pea relied on N_2 fixation with 90–95% of aboveground N accumulation derived from N_2 fixation independent of cropping system. Pea grown in intercrop with barley instead of sole crop had greater competitive ability towards weeds and soil inorganic N was consequently used for barley grain production instead of weed biomass. There was no indication of a greater inorganic N content after pea compared to barley or pea–barley. However, 46 days after emergence there was about 30 kg N ha^{-1} inorganic N more under the pea sole crop than under the other two crops. Such greater inorganic N levels during early growth phases was assumed to induce aggressive weed populations and interspecific competition. Pea–barley intercropping seems to be a promising practice of protein production in cropping systems with high weed pressures and low levels of available N.

Keywords: Land equivalent ratio; Nitrogen fixation; ^{15}N isotope dilution principle; Field pea; Barley; Weed management

1. Introduction

Light, water and nutrients may be more completely absorbed and converted to crop biomass by intercropping, which is the simultaneous growing of two or more crop species in the same field. This is a result of differences in competitive ability for growth factors between intercrop components (e.g. Anil et al., 1998; Ofori and Stern, 1987; Willey, 1979). In terms of competition this means that the components are not competing for the same ecological niches and that interspecies competition is weaker than intraspecific competition for a given factor (Vandermeer, 1989).

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Efficient utilisation of available growth resources is fundamental in achieving sustainable systems of agricultural production. However, during the last 50 years agricultural intensification in terms of plant breeding, mechanisation, fertiliser and pesticide use, intercropping has disappeared from many farming systems.

Symbiotic dinitrogen (N_2) fixation is an important element in the development of sustainable food production and long-term crop productivity (van Kessel and Hartley, 2000). Legume–cereal intercropping offers a potential method to reduce inputs, such as fertilisers. Cropping legumes as sole crops can be considered an inefficient way of utilising the soil N sources, since the legumes can cover major part of the N requirement by N_2 fixation. Earlier studies show a complementary use of N sources in legume–cereal intercrops where the legume is forced to rely on N_2 fixation because the cereal is more competitive for soil inorganic N (Anil et al., 1998; Carr et al., 1998; Carruthers et al., 2000; Jensen, 1996a). According to Jensen (1996a), pea–barley intercropping offers an opportunity to increase the input of fixed N_2 into agro-ecosystems without compromising cereal N use, yield level and stability.

The main values of grain legumes in cropping systems are their ability to fix atmospheric N, produce high protein grain and act as break crops in cereal-rich rotations. However, a major concern for farmers growing grain legumes in low-input agricultural systems is the weak competitive ability towards weeds (Liebman and Dyck, 1993). Grain legume–cereal intercropping may provide an ecological method, utilising competition and natural regulation mechanisms reduce the need for fertiliser, and to manage weeds with less use of herbicides.

Few studies have focused on intercropping systems in temperate agro-ecosystems probably because researchers and many farmers consider these systems only relevant to low-input farming, and due to the complexity of intercropping systems. However, understanding key parameters determining the entire crop species complementarity in filling ecological niches would enhance agro-ecosystem performance, including weed management (Liebman and Dyck, 1993), and possibly facilitate the finding of means to reduce fertiliser and herbicide dependence, while maintaining crop yield.

The aims of the present study were to determine the productivity and use of N sources by pea–barley intercrops compared to sole crops and to measure the N_2 fixation ability of pea in sole crops compared to pea–barley intercrops on a soil with high weed pressure.

2. Materials and methods

2.1. Site and soil

The experiment was carried out in 1998 at Risø National Laboratory, Denmark (55°41′N, 12°05′E). The 25-year mean annual rainfall at Risø is 550 mm, mean annual air temperature is 8°C with maximum and minimum daily air temperature of 16°C (July) and −1°C (February). Soil temperature, air temperature and rainfall during the experimental period are shown in Fig. 1. The day before sowing, the soil was sampled from the 0 to 25, 25 to 50 and 50 to 100 cm soil layers. In the topsoil (0–25 cm) water content at field capacity (−10 kPa) was 28 ± 0.7%

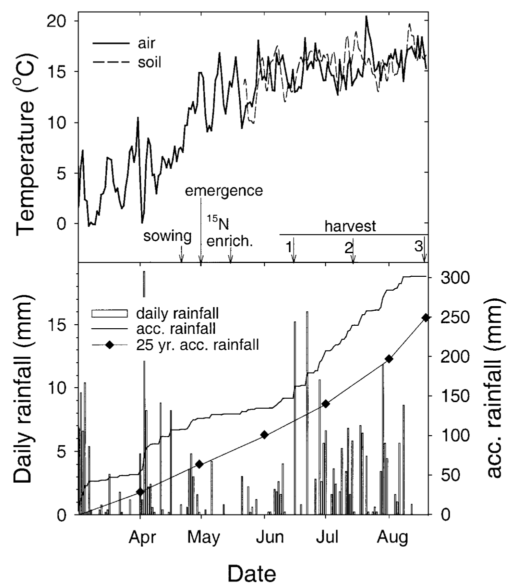

Fig. 1. Average daily soil and air temperatures, daily and accumulated (acc.) rainfall (mm) at Risø National Laboratory, Denmark, during the growth season 1998. The 25-year average acc. rainfall is also included. Major events during the experimental period are plotted on the *x*-axis.

Table 1
Soil characteristics measured before crop establishment. Values are the mean ($n = 4$) $\pm$ S.E.

Soil depth (cm)	Percentage of total C	Percentage of total N	pH in water
0–25	1.20 ± 0.08	0.13 ± 0.01	6.8 ± 0.12
25–50	0.92 ± 0.03	0.10 ± 0.01	7.2 ± 0.12
50–100	0.36 ± 0.04	0.04 ± 0.01	7.8 ± 0.15

(v/v) and the soil bulk density was $1.6 \pm 0.02\,\mathrm{Mg\,m^{-3}}$ (values are mean $\pm$ S.E., $n = 4$). The topsoil was a sandy loam (Typic Hapludalf) with 11% clay, 14% silt, 49% fine sand and 25% coarse sand. Other measured soil characteristics are shown in Table 1. The experimental site has been cultivated with a pea–wheat–barley–oilseed rape rotation. Oilseed rape (*Brassica napus* L.) was grown in 1997 growing season. The soil contained efficient populations of native *Rhizobium leguminosarum* bv. *vicia*.

2.2. Experimental set-up

Field pea (*Pisum sativum* L. cv. Focus), a medium early, semi-leafless with tendrils, dwarf and determinate cultivar and spring barley (*Hordeum vulgare* L. cv. Otira), a medium early, medium short cultivar with high tillering ability and stem strength were grown as sole crops (SC) and intercrop (IC).

The experimental plots ($6.0\,\mathrm{m} \times 3.4\,\mathrm{m}$) were laid out in a complete one-factorial randomised design with pea SC, barley SC and pea–barley IC as treatments with eight replicates. Seeds were sown on 23 April. The number of seedlings in four rows of length 1 m was counted 3 weeks after seedling emergence, which occurred on 1 May. Actual plant densities were 70 field pea and 300 barley plants $\mathrm{m^{-2}}$ in the sole cropping plots, which was slightly lower than the target densities of 80 pea and 350 barley plants $\mathrm{m^{-2}}$. The intercrop design was based on the replacement principle, with mixed pea and barley grain sown in the same rows 15 cm apart in 0.5:0.5 ratios. The rationale of this design is that the interactions between intercrop components are not confounded by alterations in the plant density in the intercrop compared to sole cropping (De Wit and Van den Bergh, 1965). For both field pea and barley we achieved an intercrop plant ratio of 0.45 compared to the sole crop, which was 10% lower than the target ratio of 0.50. The actual relative pea–barley intercrop ratio was 0.54:0.46.

Each experimental plot was subdivided into four subplots ($3.0\,\mathrm{m} \times 1.7\,\mathrm{m}$). Of the four subplots one was labelled with 10 kg N $\mathrm{ha^{-1}}$ as KNO_3 of 10 atom% ^{15}N ($2.0\,\mathrm{m} \times 1.7\,\mathrm{m}$) and the remaining three subplots received equivalent unlabelled KNO_3. The uptake of inorganic N and fixation of N_2 were studied by the ^{15}N isotope dilution principle. Fertiliser was given 10 days after seedling emergence, and the crops did not receive other fertiliser applications.

2.3. Management practice

The site was managed according to organic agriculture guidelines with no use of herbicides and with mechanical weeding three times during emergence and early tillering. Different scarecrows were used at different times from sowing until around flowering in order to limit damage from birds, and the site were fenced to avoid hares.

2.4. Sampling and analytical methods

Three harvests were carried out during the experimental period (Fig. 1) by cutting the plants 2 cm above the soil surface. The first harvest was taken at the tillering stage in barley (stage 30–32, in accordance with Tottmann (1987)) and the pre-flowering stage in pea (stage 103, in accordance with Knott (1987)) 46 days after emergence. The second harvest (74 days after emergence) was taken at the end of the elongation stage in barley (stage 53–59) corresponding to post-flowering in pea (stage 205–206). The third harvest was taken at maturity, 111 days after emergence. At each harvest 2.2 $\mathrm{m^2}$ were harvested inside the 5.1 $\mathrm{m^2}$ subplot, at the same time two rows of 30 cm was harvested in the labelled subplot. The harvested plant biomass was separated in three fractions, i.e. pea, barley and weeds. At the final harvest, grain dry matter yield was determined separately for both pea and barley after threshing. Samples were dried at 70°C to constant weight and total dry matter production determined. Total N and ^{15}N content were determined on 5–10 mg sub-samples of finely ground material using an elemental analyser (EA 1110) coupled in continuous flow mode to an isotope ratio mass spectrometer (Finnigan MAT DeltaPlus).

Inside the harvested area, soil samples were taken to 100 cm depth the day after harvest. Each sample was taken with a manual soil corer (diameter 2.5 cm) in three successive depth intervals, i.e. 0–25, 25–50 and 50–100 cm. From each plot four soil cores (two samples in and two samples between rows) were sampled, bulked and mixed thoroughly. All soil samples were kept at <5°C before extraction. Soil inorganic N was extracted in 2 M KCl (10 g soil to 100 ml extractant, rotary shaken for 60 min and filtered). The KCl extracts were frozen (−18°C) prior to analyses. Nitrate and ammonium were determined in the extracts by standard colorimetric methods using a segmented flow injection autoanalyser (Technicon Autoanalyser II). The ammonium content was always less than 5% of the total soil inorganic N content and, consequently, the sum of ammonium and nitrate is given as inorganic N.

2.5. Soil water content

Soil water content in the 0–25 and 25–50 cm soil layers was measured using time domain reflectometry (TDR). The apparent soil dielectric constant was measured by TDR using wave-guides of two parallel 0.65 cm steel rods placed 5.1 cm apart. In each main plot the pairs of steel rods were installed vertically to the target depth just after sowing. Dual sets of rods for each depth were installed in each plot.

2.6. Calculations and statistics

Nitrogen in crops derived from ^{15}N labelled fertiliser N, soil N and N_2 fixation in pea was calculated using conventional ^{15}N isotope dilution equations (Chalk, 1998). Barley SC was used as the reference crop for calculating N_2 fixation in pea SC and IC.

The land equivalent ratio (LER) is defined as the relative land area growing sole crops that is required to produce the yields achieved when growing intercrops (Willey, 1979). LER for a pea–barley intercrop is the sum of the partial LER values for barley (L_B) and pea (L_P), in accordance with De Wit and Van den Bergh (1965):

$$L_B = \frac{Y_{\text{barley IC}}}{Y_{\text{barley SC}}} \quad (1)$$

$$L_P = \frac{Y_{\text{pea IC}}}{Y_{\text{pea SC}}} \quad (2)$$

$$\text{LER} = L_B + L_P \quad (3)$$

LER values >1 indicate an advantage from intercropping in terms of the use of environmental resources for plant growth. When LER < 1 resources are used more efficiently by sole crops than by intercrops.

All measured variables were assumed to be normally distributed and statistical analyses by ANOVA were performed using SAS software (SAS, 1990). The significance of difference between treatments were estimated using the Tukey's Studentised range test with $\alpha = 0.05$ if a main effect or interaction was significant.

3. Results

3.1. Climatic conditions and soil water content

Rainfall in the early spring of 1998 was unusually high with an accumulated rainfall through March and April of 122 mm, which was equivalent to about 25% of the total annual rainfall (Fig. 1). In the 0–25 cm soil layer soil water content was relatively close to the field capacity from the beginning of the experiment until the final harvest (Fig. 2). There was no significant difference between treatments in the 0–25 cm soil layer although pea SC tended to have greatest soil water content before the first harvest but the lowest later in the growth season. In the 25–50 cm soil layer

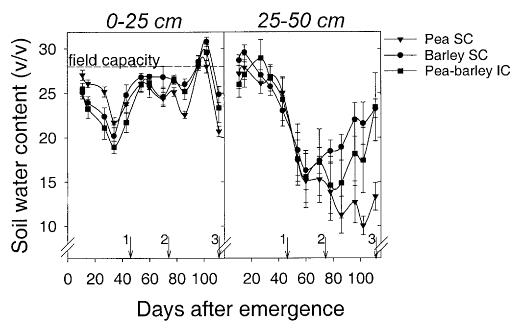

Fig. 2. Volumetric water content in sole crops (SC) and intercrops (IC) of pea and barley in the 0–25 and 25–50 cm soil layers determined by TDR during the experimental period. The arrows on the x-axis indicate the three harvests times. Values are the mean ($n = 8$) ± S.E.

there was slightly greater soil water content before the first harvest compared to the 0–25 cm soil layer. However, after the first harvest soil water content was lower in the 25–50 cm soil layer compared to the 0–25 cm soil layer throughout the experimental period. The pea SC plots also tended to have lower soil water content than the other two treatments in the 25–50 cm soil layer.

3.2. Grain yield and nitrogen content

The barley grain dry matter (DM) and N yield in both SC and IC was equivalent, whereas pea IC showed a considerable decline (Table 2). The total intercrop grain yield was significantly greater than sole crop yields. The proportion of pea N in the total intercrop grain yield was greater than the proportion of pea in the grain DM yield (Table 2).

The average N concentration in pea and barley SC grains were 3.72 and 1.15% N, respectively, whereas pea and barley IC grains contained 3.81 and 1.28% N, respectively. The increase in barley grain N concentration due to intercropping was significant.

3.3. Aboveground dry matter production and N accumulation in crops

Total aboveground DM accumulation was significantly greater in all three harvests in the intercrop plots than in the sole crop plots. Barley SC yield was always significantly greater than pea SC (Fig. 3). Weed DM accumulation was significantly greater in pea SC compared to barley SC and pea–barley IC, independent of harvest time.

The aboveground accumulation of soil N in barley increased steadily during the growth season compared to pea, in which there was no significant difference in accumulated soil N between harvests two and three, for both intercropping and sole cropping (Fig. 4). There was significant greater total aboveground plant soil N uptake in barley SC and pea–barley IC compared to pea SC plots. Barley accumulated similar amounts of aboveground N when grown as sole crop and intercrop, independent of harvest time, whereas the total aboveground N acquired by pea in the intercrop was much lower than in the sole crop (Fig. 4).

Table 2
DM production and nitrogen (N) accumulation in harvested grain. Values are the mean $(n = 8) \pm$ S.E.

	Crop	Sole crop	Intercrop	Total intercrop
DM (kg DM ha^{-1})	Barley	3927±239	3974±438	
	Pea	2630±191	604±74	4577±358
N (kg N ha^{-1})	Barley	49±3.2	54±4.5	
	Pea	104±7.5	25±2.8	78±4.9

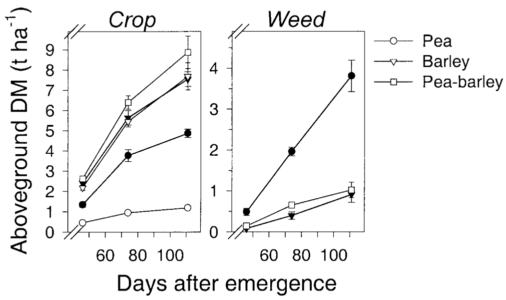

Fig. 3. Total aboveground DM production in SC and IC of pea and barley partitioned in weeds, pea and barley. Values are the mean $(n = 8) \pm$ S.E. Each specific pattern in the bar plot is associated to the single S.E. error bar.

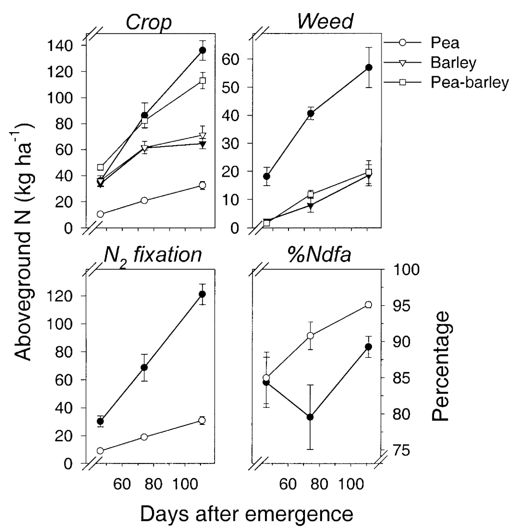

Fig. 4. Total aboveground nitrogen (N) accumulation in SC and IC of pea and barley partitioned in crop soil N, weed soil N, pea N_2 fixation and percentage of N accumulated in aboveground pea originated from fixation (%N dfa). Values are the mean $(n = 8) \pm$ S.E.

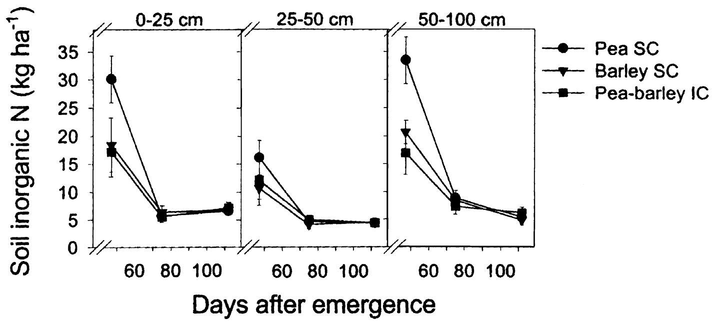

Fig. 5. Soil inorganic N in 0–25, 25–50 and 50–100 cm soil depth after harvest of SC and IC of pea and barley. Values are the mean ($n = 8$) ± S.E.

The total amount of N_2 fixed was 120 and 30 kg N ha^{-1} in pea SC and pea IC, respectively (Fig. 4), corresponding to 90 and 95% of the total N accumulated in pea. There was a tendency for the amount of N_2 fixed to increase as the crop advanced toward maturity (data not shown).

A lower ^{15}N enrichment of intercropped than sole cropped barley may be an indication of N transfer from pea to barley. The ^{15}N enrichment of intercropped and sole cropped barley grain was 0.97 and 1.08% ^{15}N, respectively. For the straw the values were 1.01 and 1.06% ^{15}N in intercropped and sole cropped barley, respectively. However, the ^{15}N enrichments were not statistically significant among plant components or treatments ($p > 0.19$).

3.4. Estimated weed pressure

In all three harvests weed aboveground DM production and aboveground N accumulation was significant greater in the pea SC compared to barley SC and pea–barley IC (Figs. 3 and 4). In pea–barley IC and barley SC weed aboveground soil N uptake was on average 5–10% of total aboveground soil N accumulation, whereas it was 70–80% of total aboveground soil N accumulation in pea SC independent of harvest time (Fig. 4).

3.5. Soil inorganic N

At sowing the soil contained 30 kg extractable inorganic N per hectare in the 0–100 cm soil depth of which 27% was present in the topsoil. At 47 days after emergence 30–35 kg inorganic N ha^{-1} was present in two soil layers: 0–25 and 50–100 cm with pea SC, which was significantly more than the total 15–20 kg inorganic N ha^{-1} measured in these depths in barley SC and pea–barley IC (Fig. 5). There was no significant difference between the sole crops and intercrops in the 25–50 cm soil layer with an average content of about 10–15 kg inorganic N ha^{-1}. At day 74 and 111 after emergence there was no significant difference among treatments with an average inorganic N content about 5 kg N per layer ha^{-1}.

3.6. Utilisation of plant growth factors

The pea partial LER (L_P) declined during growth, whereas the barley partial LER (L_B) increased for both DM production and N accumulation (Fig. 6). Early

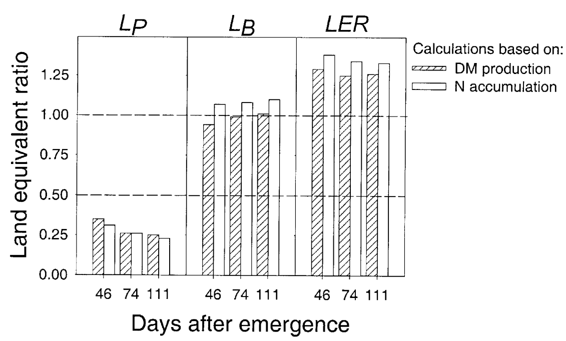

Fig. 6. Pea and barley partial LER (L_P and L_B, respectively) and LER. The calculations were based on total harvested aboveground DM production and N accumulation. The horizontal 0.5 and 1.0 line indicate expected L_P and L_B values and LER values, respectively, according to sole crop yields. Values are the mean ($n = 8$) ± S.E.

interspecific competition was indicated by L_P and L_B 46 days after emergence with values lower and greater, respectively, than the expected 0.5 planned when sowing and counted 3 weeks after emergence. In all three harvests the L_B values were greater than 0.9, while the L_P values varied between 0.35 and 0.23 indicating that barley was the dominant component in the intercrop.

The LER $(L_P + L_B)$ based on aboveground DM accumulation varied between 1.25 and 1.29 comparing the three harvests. The LER values based on total N accumulation indicated that N was used 33–38% more efficiently in intercrops than sole crops (Fig. 6).

4. Discussion

4.1. Interspecific competition and intercrop advantages

When plant species are intercropped it is likely that yield advantages occur as a result of complementarity in the use of resources by the component crops. Soil water is probably one of the environmental plant growth factors most often limiting N_2 fixation in pea in temperate soils (Schubert, 1995). In the present study there was no indication of drought or soil waterlogging conditions and it was assumed that water did not cause any major limitation to crop growth at any time in the experimental period (Fig. 2). At day 46 after emergence it was observed that pea growth in the sole crop was less than in the intercrop, which indicates that water availability was probably not a factor decreasing the initial outcome of competition.

In the present study barley was the dominant component in the intercrop showing a high degree of plasticity, when the sowing density was reduced by about 50% (Fig. 6). LERs were greater than 1, which indicates a better utilisation of plant growth factors by the intercrop compared to the sole crops. Jensen (1996a, 1998) report similar findings growing pea and barley intercrops in several years on the same locality. This advantage is probably due to different above- and below-ground growth habits and morphological characteristics of intercrop components causing a greater efficiency in the utilisation of plant growth resources, i.e. water, nutrients and radiation energy (Fukai and Trenbath, 1993; Ofori and Stern, 1987; Willey, 1979).

Legume–cereal intercropping advantages are often presumed to be associated with the complementary use of N sources by components (Trenbath, 1976; Ofori and Stern, 1987). In the present study pea IC covered their N requirement by N_2 fixation and soil inorganic N was utilised by barley IC and weeds (Fig. 4). However, Jensen (1996a) showed that LER values did not correlate well with initial concentration of soil inorganic N, indicating that other factors might also influence intercropping performances such as root system dynamics, canopy structure and competitive ability towards weeds.

4.2. Pea growth and N_2 fixation

In the present study up to 95% of total pea IC N accumulation was derived from N_2 fixation at maturity (Fig. 4). However, the total amount of N fixed per unit area in the intercrop was lower than in the sole crop due to decreased pea growth caused by interspecific competition. Jensen (1996a) showed a significantly greater percentage N derived from fixation in pea IC compared to pea SC. This was not observed in the present study probably because weed competition for soil inorganic N in the pea sole crops was similar to barley and weeds in the intercrop (Fig. 5). Weeds were controlled with appropriate herbicides in the study of Jensen (1996a). In the present study, independent of cropping strategy, pea percentage N derived from fixation varied between 90 and 95% compared to other field studies with values around 60–81% (Peoples et al., 1995) indicating strong competition for soil inorganic N between plant species.

4.3. Soil inorganic N and crop performance

Variable competitive abilities for utilising soil inorganic N between grain legumes and cereals causing a higher soil inorganic N content after grain legumes than after cereals is termed ‘spared N’ (Chalk, 1998). Evans et al. (1989, 1991) found less soil N was taken up by lupin than adjacent cereal crops, and Herridge et al. (1995) measured an apparent N-sparing effect comparing chickpea and wheat. This is contrary to the present study which showed no spared N effect (Fig. 5). However, there was significantly greater soil inorganic N content in the pea SC plots compared to the barley SC and pea–barley IC plots 46 days after emergence. Such levels of inorganic N and a slow uptake by the crop during early growth may induce aggressive weed populations and interspecific competition, as seen in the present study (Figs. 3 and 4).

Unkovich et al. (1997) argued that the concept of spared N needs to be reconsidered. The authors state that additional inorganic N under legume crops compared with cereals may result from rapid mineralisation of organic N derived from rhizodeposition rather than from lower N use by the N_2-fixing legume. N mineralisation from rhizodeposition may contribute to the N nutrition of an associated plant (Jensen, 1996c). Field pea rhizodeposition in the present study may be a significant source of N to intercropped barley or the weed component in the pea sole crops, as shown by Jensen (1996b), and of special interest in low-input agricultural systems with low rates of N application. However, N transfer from pea to barley could not be detected using the ^{15}N enrichment technique due to a large variability in ^{15}N enrichment between replicate plots. However, barley IC N accumulation did not respond to the additional soil N availability 46 days after emergence (Fig. 5). This suggests that crop growth was limited by factors other than N, as stated above.

4.4. Crop management in soils with high weed pressure

Any part of the soil surface that is not occupied by crop plants is potentially subject to invasion by weedy species. Independent of sole cropping or intercropping barley canopy structure showed a more vigorous growth than pea providing quicker, greater and more extensive soil coverage. A faster established pea crop than the one used in the present study may result in an increased DM accumulation and thus an increased competitive ability towards weeds, increased N demand and thereby a stronger sink in the host plant increasing N_2 fixation (van Kessel and Hartley, 2000).

When growing pea and barley in intercrops instead of sole crops, there was an increased efficiency in utilising environmental sources for plant growth (Fig. 6), a better competitive ability towards weeds of the intercrop compared to pea SC and the soil inorganic N was consequently used for barley grain production (Table 2) instead of weed biomass (Fig. 3).

This study showed that a popular pea cultivar for conventional sole cropping, like the present cv. Focus, may not be suited for sole cropping in environments with relative fertile soils and aggressive weed populations using organic agriculture management standards.

5. Conclusion

Grain yield was significantly greater in the pea–barley intercrop than in the sole crops. LER values showed that plant growth factors were used from 25 to 38% more efficiently by the intercrop than by the sole crops.

There was a significantly greater crop soil N uptake in barley sole cropping and pea–barley intercropping compared to pea sole cropping. Sole cropped and intercropped pea were forced to rely on N_2-fixation because weeds and barley, respectively, were more competitive for soil inorganic N. When growing pea in intercrop with barley instead of sole crop there was a better competitive ability towards weeds and the soil inorganic N was consequently used for barley grain production instead of weed biomass.

There was no indication of spared-N effects in the present study after the final harvest. Pea sole cropping showed temporary enhanced soil inorganic N availability, but there was no indication of increased N accumulation in intercropped barley. This suggests that crop growth was limited by factors other than N, like root system dynamics, canopy structure and competitive ability towards weeds.

Pea–barley intercropping seems very promising in the development of sustainable food production with a limited use of external inputs. However, there is a lack of knowledge about complementarity in mixed crop communities.

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