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Comparison of interspecific competition and N use in pea–barley, faba bean–barley and lupin–barley intercrops grown at two temperate locations

M. TRYDEMAN KNUDSEN, H. HAUGGAARD-NIELSEN*, B. JØRNSGÅRD AND E. STEEN JENSEN

Organic Farming Unit, Department of Agricultural Sciences, The Royal Veterinary and Agricultural University, Højbakkegård Alle 10. DK-2630 Taastrup, Denmark

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SUMMARY

Mixed intercropping of spring barley (*Hordeum vulgare* L.) with field pea (*Pisum sativum* L.), faba bean (*Vicia faba* var. *minor* L.) or narrow-leafed lupin (*Lupinus angustifolius* L.) was compared with sole cropping in two field experiments at different locations, on a sandy loam soil and a sandy soil, in Denmark in 2001.

Grain legumes were dominant in intercrops on the sandy loam soil, except for lupin, whereas barley was dominant in intercrops on the sandy soil site. Combined intercrop grain yields were comparable to grain yields of the respective sole cropped grain legume or sole cropped, fertilized barley on each soil site. On the sandy loam soil, pea–barley and faba bean–barley intercrops increased the proportion of plant N derived from N_2 fixation in grain legumes and increased the barley grain N concentration (from 1·7 to 2·2 mg/g) compared with sole cropping. However, the later maturity of faba bean compared with barley caused problems at harvest. The grain N concentration of intercropped barley was increased where grain legumes were the dominant intercrops and not on the sandy soil site. Lupin-barley intercrops did not show intercropping advantages to the same degree as faba bean and pea, but lupin constituted a more stable yield proportion of the combined intercrop yield over locations.

Furthermore, the study indicated that the natural ^{15}N abundance at certain locations might not always be sufficient to ensure a reliable estimate of N_2 fixation using the ^{15}N natural abundance method.

INTRODUCTION

Grain legumes contribute to sustainable farming systems through their symbiotic N_2 fixation (SNF) and their effect as a break-crop on diseases in cereal-rich rotations (Herridge 1982). Furthermore, grain legumes are valuable protein and energy sources in food and fodder.

The predominant cultivation of grain legumes for mature seeds in temperate climates is sole cropping of field pea (*Pisum sativum* L.). A major concern for farmers growing peas is the high degree of yield variability (Jensen 1996) due to, for example, drought sensitivity (Heath & Hebblethwaite 1985), lodging and weak competitive ability towards weeds (Hauggaard-Nielsen *et al*. 2001 *a*). Faba bean (*Vicia faba* var. *minor* L.) and narrow-leafed lupin (*Lupinus angustifolius* L.) are well adapted to temperate growing conditions but are seldom grown mainly due to late maturity. Improved cultivars of faba bean and lupin might be alternative grain legumes to pea with a higher protein concentration in seeds and stronger stem strength compared with pea but having potentially some of the same problems as peas, such as weak competitive ability towards weeds (Hebblethwaite 1982).

Grain legume-cereal intercropping may provide yield advantages and greater yield stability over years compared with sole cropping of either grain legumes

* To whom all correspondence should be addressed. Present address: Risø National Laboratory, Plant Research Department, Building PRD-301, P.O. Box 49, Frederiksborgvej 399, DK-4000 Roskilde, Denmark.
Email: henrik.hauggaard-nielsen@risoe.dk

or cereals (Trenbath 1976; Willey 1979; Ofori & Stern 1987). Pea–barley intercropping compared with sole cropping has shown a more efficient use of environmental sources for plant growth, especially nitrogen (N) (Hauggaard-Nielsen *et al.* 2001 *a*; Jensen 1996), increased N concentration in intercropped barley grains compared with sole cropped barley (Jensen 1996), higher proportion N derived from fixation (Pfix) in intercropped pea compared with sole cropped pea (Izaurralde *et al.* 1992; Jensen 1996; Jensen 1998), greater yield stability than sole cropped pea (Jensen 1996) and increased competitive ability towards weeds compared with pea sole cropping (Hauggaard-Nielsen *et al.* 2001 *a*). Intercropping experiments with faba bean and cereals have shown similar advantages (Martin & Snaydon 1982; Jensen 1986; Danso *et al.* 1987; Bulson *et al.* 1997), but knowledge of the effect of intercropping lupin and cereals for maturity is limited (Pálmason *et al.* 1992).

Comparable studies with different grain legumes intercropped with cereals are also limited. In addition, most temperate intercropping studies with pea and faba bean have been carried out on more fertile soils (Martin & Snaydon 1982; Andersen *et al.* 1983; Jensen 1986; Danso *et al.* 1987; Izaurralde *et al.* 1992; Jensen 1996, 1998; Bulson *et al.* 1997; Hauggaard-Nielsen *et al.* 2001 *a*, *b*; Hauggaard-Nielsen *et al.* 2003). However, different locations might affect the intercropping systems and the competitive relation between the intercropping components differently.

Evaluating symbiotic N_2 fixation (SNF) by grain legumes is an important aspect when comparing performance of grain legumes. SNF can be evaluated using several methods (Unkovich *et al.* 1994; Herridge & Danso 1995; Jensen 1996; Peoples *et al.* 1997). The N-difference method and the ^{15}N natural abundance method are both low cost methods easy to use in established experiments or farmers' fields (provided a reference plant is present) (Unkovich & Pate 2000). The N-difference method is known to give rather precise estimations if available soil N is low (Herridge & Danso 1995) and Pfix is accordingly high. The natural abundance method is regarded as a potentially more precise method than the N-difference method (Unkovich *et al.* 1994). This method has further advantages compared with, for example, ^{15}N enrichment methodology due to its lower costs while maintaining similar precision (Peoples & Herridge 1990).

The main objectives of the present study were to compare the performance of three grain legume species (pea, faba bean and lupin), sole cropped or intercropped with barley at two different temperate locations, by evaluating competitive relations between intercrop components and their effects on grain quality and N use. The crops were grown for grain, not forage, and focus was on the harvested grain.

MATERIALS AND METHODS

Site, soil and climate

The experiments were carried out in 2001 at two different sites in Denmark: a sandy loam soil (The Experimental Farm of The Royal Veterinary and Agricultural University; 55°40′N, 12°18′E) and a sandy soil (Jyndevad Experimental Station; 54°54′N, 9°8′E). The sandy loam soil (USDA soil classification) had 8 mg/g clay, 32 mg/g silt, 48 mg/g fine sand and 13 mg/g coarse sand, a pH($CaCl_2$) of 6·8, 1·7 mg total carbon (C)/g soil and 0·12 mg total N/g soil in the 0–20 cm layer. The sandy soil had 4 mg clay/g soil, 4 mg silt/g soil, 17 mg fine sand/g soil and 73 mg coarse sand/g soil, a pH($CaCl_2$) of 5·5, 1·2 mg total C/g soil and 0·085 mg total N/g soil in the equivalent 0–20 cm layer. The soil in 0–20 cm contained 9·4 mg K/g soil and 3·6 mg P/g soil on the sandy loam soil and 3·8 mg K/g soil and 5·4 mg P/g soil on the sandy soil. The temperatures were comparable at the two sites, whereas the sandy soil site had a higher rainfall in June and in total during the growing season (Fig. 1). The soil has been cultivated for centuries and mainly cropped with cereals for the last four decades.

Species, cultivars and experimental design

Field pea (*Pisum sativum* L.), faba bean (*Vicia faba* var. *minor* L.) and narrow-leafed lupin (*Lupinus angustifolius* L.) were grown as sole crops and in a two species intercrop with spring barley (*Hordeum vulgare* L.). The cultivars used in field pea were cv. Agadir, a semi-leafless cultivar with tendrils, relatively tall with a weak tendency to lodging and cv. Bohatyr, with normal leaves and medium stem strength. The faba bean cv. Columbo has a low content of tannins and medium to early maturity. The lupin cv. Prima has relatively early and uniform ripening caused by a highly reduced branching structure, where the upper main stem branches are reduced to a single floret in the axil of the main stem leaves (Dracup & Thomson 2000). The two barley cultivars were cv. Lysiba, a low to medium yielding cultivar but with a high content of the amino acids lysine and threonine and cv. Otira, a high yielding cultivar with low protein content. Both barley cultivars have a weak tendency to lodge.

The experimental plots (15·4 m^2 on the sandy loam soil and 36 m^2 on the sandy soil) were laid out in a complete one-factorial randomized block design with 16 treatments of intercrops and sole crops and four replicates. The intercrop design was based on the replacement principle, with mixed grain legume and barley grain sown in the same rows 12·8 cm apart at relative frequencies of 0·5:0·5. The rationale of the replacement design is that the interactions between intercrop components are not confounded by alterations in the plant density in the intercrop compared

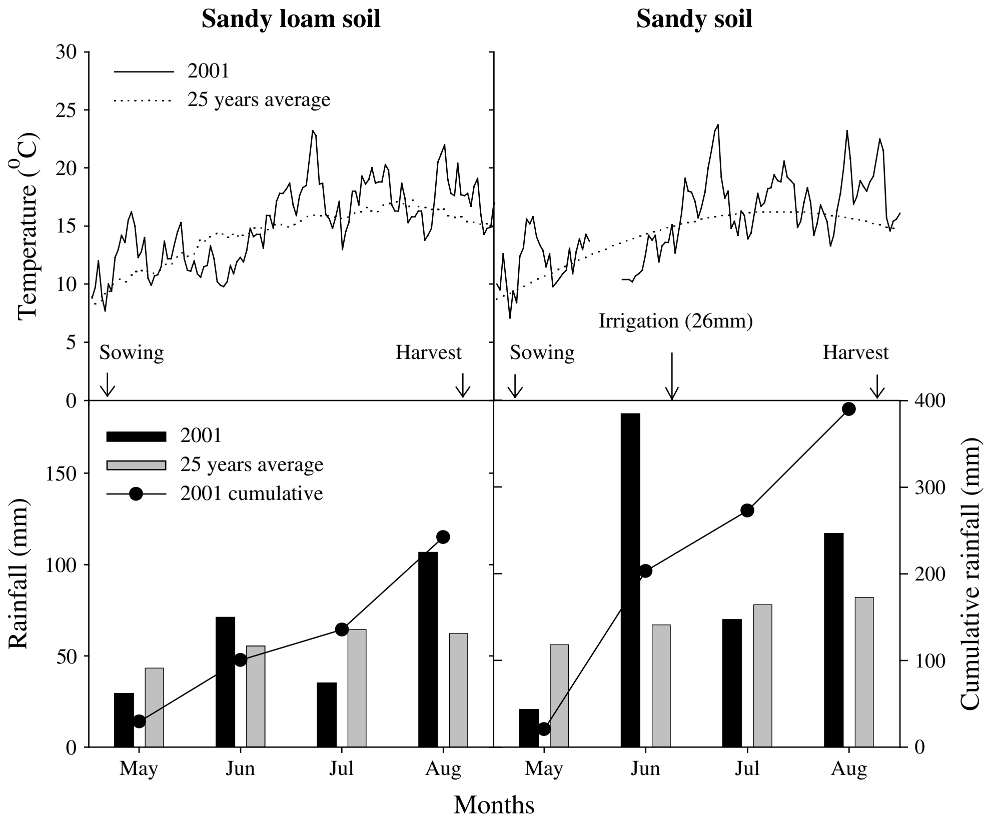

Fig. 1. Average daily temperatures, monthly rainfall and cumulative rainfall in the growing season 2001. Twenty-five years averages of monthly rainfall are shown. Major events during the growing season are plotted on the x-axis.

with the sole crops (De Wit & Van den Bergh 1965). Target plant population densities in sole crops were 300, 120, 90 and 40 plants/m² for sole crops of barley, lupin, pea and faba bean, respectively. The number of seedlings in four rows of length 1 m was counted 19 days after emergence. The intercrop plant ratio of 0·5:0·5 was successfully obtained at both locations (Table 1).

Management practices

Seeds were sown mixed in the rows in the same depth on 3 May 2001 on both locations (Fig. 1). The crops were grown according to organic agricultural management practice, except that the half of the barley sole crops were fertilized with 50 kg N/ha in urea. A false seedbed was established prior to sowing on both locations. Mechanical weeding was performed on the sandy soil.

Sampling and analytical methods

The crops were harvested at maturity on 21 August on the sandy loam soil and on 23 August on the sandy soil. A representative area of 1 m² was harvested manually and separated into three fractions, i.e. grain legume, barley and weeds. The samples were dried at 70 °C to constant weight and total dry matter production for each plot was determined separately for grain legumes, barley and weeds. After threshing the grain dry matter yield was determined. Total N and ^{15}N content were determined on 3–15 mg subsamples of finely ground material using an elemental analyser (EA 1110) coupled in continuous flow mode to an isotope ratio mass spectrometer (Finnigan MAT DeltaPlus).

Calculations and statistics

Combined intercrop yield is the sum of yields of both the components in the intercrop. The land equivalent ratio (*LER*) is defined as the relative land area growing sole crops (*SC*) that is required to produce the yields (*Y*) achieved when growing intercrops (*IC*) (Willey 1979).

$$L_A = \frac{Y_{A,IC}}{Y_{A,SC}} \quad L_B = \frac{Y_{B,IC}}{Y_{B,SC}} \tag{1}$$

Table 1. *Plant population densities (plants/m²) in sole crops and intercrops of grain legumes (GL) and barley 19 days after seedling emergence. All values are means*

Location	Crops	Sole crop GL	Sole crop Barley	Intercrop GL	Intercrop Barley	GL proportion in intercrop*
Sandy loam	Pea–barley	86	267	43	134	0·50
	Faba bean–barley	37		19		0·51
	Lupin–barley	109		55		0·50
Sand	Pea–barley	107	275	55	148	0·49
	Faba bean–barley	47		25		0·50
	Lupin–barley	135		79		0·52

* Calculation based on plant units, e.g. in pea–barley on the sandy loam soil, 1 unit = 1 pea plant or 267/86 = 3·1 barley plants.

LER for an intercrop of crop A and crop B is the sum of the partial *LER* values for crop A (L_A) and crop B (L_B) (Willey 1979).

$$LER = L_A + L_B \quad (2)$$

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

Grain legume symbiotic N_2 fixation (SNF) was estimated using the N-difference method (Herridge & Danso 1995),

$$N_2\ fixed_{legume\ SC} = N_{legume\ SC} - N_{barley\ SC,\ reference} \quad (3)$$

where the amounts of N_2 fixed in intercropped grain legumes were calculated as:

$$N_2\ fixed_{legume\ IC} = (N_{legume\ IC} + N_{barley\ IC}) - N_{barley\ SC,\ reference} \quad (4)$$

The ^{15}N natural abundance (NA) method was used as a supplement to the N-difference method to estimate SNF and calculated as the product of shoot N (grain legume biomass × mg/g N content) and the proportion of plant N derived from fixation (Pfix). Pfix was determined as (Peoples *et al.* 1997; Shearer & Kohl 1986):

$$Pfix = \frac{(\delta^{15}N_{reference\ plant} - \delta^{15}N_{legume})}{(\delta^{15}N_{reference\ plant} - B)} \times 100 \quad (5)$$

The B value is a measure of isotopic fractionation during N_2 fixation determined by analysis of the δ^{15}N of shoot N of nodulated legume grown in N-free media (Unkovich *et al.* 1994). The δ^{15}N values are the ^{15}N abundance relative to atmospheric N_2 expressed as parts per thousand, calculated for each sample of the legume and the reference plant (Shearer & Kohl 1986):

$$\delta^{15}N = \frac{(atom\%^{15}N_{sample} - atom\%^{15}N_{atmosphere})}{atom\%^{15}N_{atmosphere}} \times 1000 \quad (6)$$

The NA method relies on differences in natural ^{15}N enrichment in soil N compared with atmospheric N_2 and reflected in δ^{15}N value of the non-fixing reference plant (Peoples *et al.* 1997). Barley sole crop was used as the reference plant using an average of δ^{15}N of the two barley cultivars.

Statistical analyses by ANOVA were performed using SAS software, assuming the measured variables to be normally distributed. The significance of difference between treatments were estimated using the Tukey's Studentized range test with $P \leqslant 0{\cdot}05$ if a main effect or interaction was significant. Results of pea or barley cultivars are shown as an average for the species due to non-significant differences between cultivars.

Determination of B-values for pea, faba bean and lupin

The B values, used in the natural abundance technique, were estimated for each grain legume species by analysis of the δ^{15}N of shoot N of nodulated pea, faba bean and lupin grown in N-free media. The experimental layout was a one-factorial design with 20 replicate 5-litre pots for each species containing vermiculite placed in a temperature and light-controlled glasshouse (15 °C day, 14 h/12 °C night, 10 h). Four pre-germinated seeds of pea (cv. Agadir), faba bean (cv. Columbo) or lupin (cv. Prima) were sown in each pot. Inoculation was achieved by addition of a solution containing *Rhizobium leguminosarum* for faba bean and pea, while lupin was inoculated by *Bradyrhizobium lupini*. Plants were supplied with all nutrients (modified from Steinar 1984) except N throughout the experimental period. Four replicate pots were harvested on five separate occasions from early vegetative growth (44 days after sowing) until late pod filling (in average 95 days after sowing). At each harvest, the shoot material from each replicate pot was dried at 70 °C to constant weight. Total N and ^{15}N content were determined as described above.

Table 2. *Grain yield and grain nitrogen (N) yields of sole cropped (SC) grain legumes and sole cropped barley with (+N) or without 50 kg N/ha and combined intercrops (IC) of grain legumes and barley. Proportions of grain legumes (GL prop.) in combined intercrop grain yield are based on grain yields or grain N yields. All values are means*

		Sandy loam soil			Sandy soil		
		SC	IC	GL prop.	SC	IC	GL prop.
Grain yield (g/m²)	Pea	490	455	0·78	268	231	0·32
	Faba bean	347	394	0·63	132	207	0·70
	Lupin	416	337	0·44	269	220	0·29
	Barley	339			211		
	Barley+N	430			253		
	S.E. (D.F.=53)	29·5			20·6		
Grain N yield (g/m²)	Pea	16·2	14·1	0·86	12·7	6·4	0·56
	Faba bean	16·4	14·9	0·79	8·6	4·2	0·20
	Lupin	21·4	10·1	0·69	18·3	7·3	0·56
	Barley	5·6			3·4		
	Barley+N	7·5			4·4		
	S.E. (D.F.=53)	1·46			1·02		

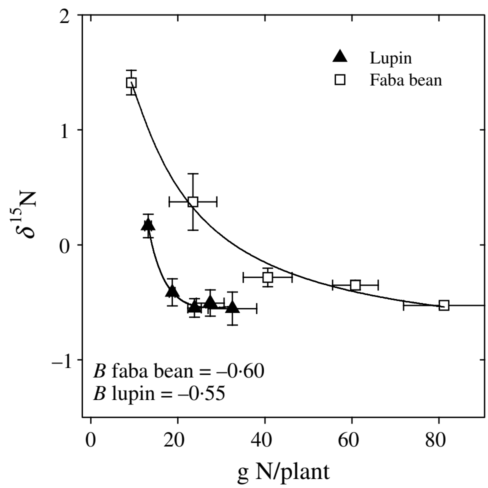

Fig. 2. δ^{15}N of faba bean cv. Columbo and lupin cv. Prima shoots as a function of inverse shoot N content per plant, representing five harvests from emergence to early pod filling. All values are means ± S.E.

The concentration of faba bean and lupin shoot δ^{15}Nitrogen (N) were high initially, presumably reflecting the δ^{15}N of cotyledonary reserves, but declined to an equilibrium value of δ^{15}N estimated as the *B* value. B was determined fitting a curve to changes during development in the δ^{15}N of the shoots when fully dependent upon SNF for growth (Fig. 2) giving δ^{15}N values at $-0·60$ for faba bean and $-0·55$ for lupin. Due to experimental errors the B value for pea was abandoned. A value of $B=-0·72$ for pea (cv. Bohatyr) was used in the calculations (Hauggaard-Nielsen *et al.* 2003).

RESULTS

Grain yields

Pea and barley crops matured at the same time, lupins 4 days later, and faba beans approximately 12 days later than pea and barley.

When grown as sole crops, the grain yields of barley were equivalent to those of the grain legumes at both locations (Table 2). The grain yields were on average 44% lower on the sandy soil than on the sandy loam soil. For individual crops the grain yields were 62% lower in faba beans and 35% lower in lupins at the sandy soil compared with the sandy loam soil (Table 2).

When grown as sole crops, the grain yields of peas were significantly larger than those of faba beans at both locations. The yields of lupins were intermediate on the sandy loam soil and comparable with pea yields on the sandy soil (Table 2). Sole-cropped lupin produced the highest yields of N in the grains at both locations, but the yields of faba bean were comparable on the sandy loam soil (Table 2).

Combined grain yields of the intercropped barley and legume were similar to grain yields of the sole-cropped grain legume or fertilized barley component, respectively, on each soil site – except that on the sandy soil site, the combined grain yields of intercropped faba bean–barley was significantly larger than that of sole-cropped faba bean (Table 2). The

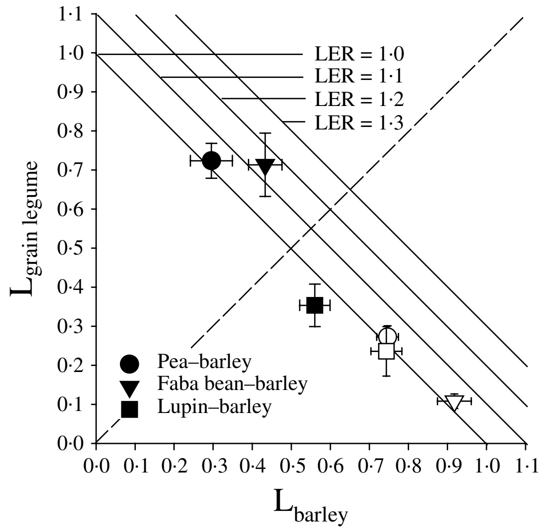

Fig. 3. Partial land equivalent ratio (LER) of barley (L_{barley}) and grain legume ($L_{grain\ legume}$) and the combined LER calculated from grain dry matter yields of intercrops on a sandy loam soil (closed symbols) and sandy soil (open symbols). The oblique lines show LER values. The diagonal line from (0,0) is the border of species dominance. All values are means ± S.E.

combined yields of N in the grains of the intercrops were significantly smaller than the corresponding yields of N in the grains of the sole cropped legumes, except that at the sandy loam soil, the combined yields of grain N from the intercropped pea–barley and faba bean–barley were comparable with the yields of grain N for the respective grain legumes grown as sole crops (Table 2).

The proportion of pea in the combined grain yield of the pea–barley intercrop was 0·78 on the sandy loam soil but only 0·32 on the sandy soil (Table 2). At the sandy loam soil, the faba bean proportion was 0·63 of the combined grain yield of the faba bean–barley intercrop but the contribution was almost absent on the sandy soil (Table 2). Lupin contributed more uniformly with a proportion of 0·29–0·44 of the combined grain yield of the lupin–barley intercrop at the locations (Table 2).

Competitive relations and utilization of growth resources

Barley was the dominant component in all the barley–legume intercrops on the sandy soil but only the dominant component in lupin–barley intercrops on the sandy loam soil (Fig. 3). In contrast, the peas and faba beans were the dominant component when intercropped with barley on the sandy loam soil (Fig. 3). When intercropped with barley, peas and faba bean achieved a proportion of 0·6–0·8 of the grain yields they produced when sole cropped on the sandy loam soil whereas on the sandy soil it was only 0·1–0·3 (Fig. 3). Intercropped lupins produced a proportion of 0·2–0·4 of the grain yields they produced when grown as sole crops on the locations (Fig. 3).

Land equivalent ratio (LER) values based on the grain yields for the pea–barley intercrops were approximately 1, indicating no advantage (or disadvantage) in grain yield from intercropping compared with sole cropping (Fig. 3).

On the sandy loam soil, intercropping faba bean and barley produced a LER that indicated that the intercrop was considerably more efficient than sole crops, but there was no advantage on the sandy soil (Fig. 3).

LER values indicated no advantage in intercropping lupins and barley on either soil type.

Table 3. *Grain N concentration (mg/g) in spring barley, sole cropped (SC) without or with application of 5 g N/m² or intercropped (IC) with pea, faba bean or lupin on the sandy loam soil and sandy soil. All values are means*

Cropping strategy		Sandy loam soil	Sandy soil
SC	Barley, 0 N	1·6	1·6
	Barley, 5 g N/m²	1·7	1·7
IC	Barley–pea	2·2	1·8
	Barley–faba bean	2·2	1·8
	Barley–lupin	1·7	1·8
S.E. (D.F. = 40)		0·12	0·09

Grain nitrogen concentration

Intercropping did not affect grain N concentration of the grain legumes (data not shown). On the sandy soil neither fertilization nor intercropping affected the grain N concentration of barley (Table 3). Applying N fertilizer to sole cropped barley did not significantly increase the concentration of N in the grain. However, intercropping significantly increased grain N concentrations of the barley from 1·7 mg/g when sole cropped to 2·2 mg/g in the intercrops with pea or faba bean on the sandy loam soil (Table 3). There was no effect of intercropping in barley with lupin on grain N concentration on the sandy loam soil (Table 3).

Symbiotic N_2 fixation

Using the N-difference method, it was estimated that peas and faba beans fixed similar amounts of N when sole cropped or intercropped with barley on the sandy

Table 4. *Nitrogen fixation in sole-cropped (SC) and intercropped (IC) pea, faba bean and lupin on the sandy loam soil and sandy soil. Calculations of proportion of N derived from fixation (Pfix) and amount of* N_2 *fixed (g N/m²) are based on shoot N and estimated by the N-difference method (see equation 3 and 4). All values are means.* N.D. *= not determined*

Cropping strategy		Sandy loam soil		Sandy soil	
		Pfix	g N/m²	Pfix	g N/m²
Pea	SC	0·65	12·9	0·71	13·2
	IC	0·73	10·3	0·99	4·9
Faba bean	SC	0·66	14·1	0·60	7·3
	IC	0·80	11·5	N.D.	1·7
Lupin	SC	0·69	16·9	0·79	18·2
	IC	0·56	5·1	0·98	6·2
S.E. (D.F. = 39)		0·064	1·85	0·102	1·41

Table 5. $\delta^{15}N$ *of shoot N in sole-cropped (SC) barley reference plants and in sole-cropped and intercropped (IC) pea, faba bean and lupin. All values are means ± standard error (D.F. = 47)*

Cropping strategy		Sandy loam soil	Sandy soil
Barley	SC	4·1 ± 0·28	1·4 ± 0·14
Pea	SC	1·1 ± 0·18	0·5 ± 0·06
	IC	0·2 ± 0·07	0·2 ± 0·03
Faba bean	SC	1·0 ± 0·05	0·3 ± 0·12
	IC	0·1 ± 0·05	0·1 ± 0·01
Lupin	SC	0·8 ± 0·07	−0·2 ± 0·06
	IC	0·3 ± 0·13	0·1 ± 0·16

loam soil but intercropped lupins fixed, on average, only a third of the N they fixed when sole cropped (Table 4). Similar responses were obtained on the soil using the natural abundance method (data not shown), which, however, showed that intercropped peas derived significantly more (0·80) of their shoot N from fixation (Pfix) than sole-cropped peas (0·62) (data not shown). Using the N-difference method, the difference in Pfix was found not to be significant (Table 4). The same was found for faba beans with 0·66 Pfix being obtained when sole cropped compared with 0·85 when intercropped using the natural abundance method. In lupins the difference was smaller but still significant, 0·71 Pfix (estimated by the natural abundance method) was obtained when sole cropped compared with 0·82 when intercropped with barley. On the sandy loam soil, the soil $\delta^{15}N$ abundance, reflected in the barley reference crop, was on average 4·1 (Table 5) indicating a high degree of precision in both soil N uptake and SNF estimations using the natural abundance method (Peoples *et al.* 1997; Unkovich *et al.* 1994).

On the sandy soil, intercropped grain legumes fixed significantly less nitrogen than when sole cropped using the N-difference method (Table 4). Using the N-difference method on the sandy soil Pfix in intercropped pea and lupin was not significantly different from Pfix by sole cropped pea and lupin, respectively, despite an obvious trend towards higher Pfix values when intercropped. Unfortunately the natural abundance method could not be used to supplement the N-difference method at the sandy soil site as the soil $\delta^{15}N$ abundance, reflected in the barley reference crop, was on average only 1·4 (Table 5) indicating non-reliable SNF estimates by the natural abundance method (Peoples *et al.* 1997; Unkovich *et al.* 1994).

Soil N uptake

Using the N-difference method, soil N uptake is by definition identical to the soil N uptake of sole-cropped barley. Thus, it is not possible to clarify soil N uptake differences comparing treatments on the sandy soil. In contrast, the natural abundance method could be used on the sandy loam soil showing that intercrops took up an equal amount of soil N as their respective sole crops. This method showed that intercropped barley obtained a greater proportion of soil N in the intercrops (from 0·52–0·75, Fig. 4) than the proportion barley comprised in the combined grain yields of the intercrops (from 0·19–0·30, Table 2).

DISCUSSION

Pea–barley intercropping

Combined grain yields of intercropped peas and barley was similar to those of peas or fertilized barley (Table 2) grown as sole crops, as also found by Jensen (1996). However, in contrast to findings by Jensen (1996), Hauggaard-Nielsen *et al.* (2001*a*) and Jensen (1998), the pea–barley intercrops in the present study did not show advantages from intercropping compared with sole cropping in terms of the use of environmental resources for plant growth (indicated by the LER) (Fig. 3). Ofori & Stern (1987) inferred that the trend of LER in legume-cereal intercrops were associated with the yields of the legumes. At the sandy loam site, however, peas intercropped with barley were the dominant component and decreased cereal yields and LER values, whilst faba beans intercropped with barley had less of an effect, causing the yields of the cereal component to be larger and thereby creating higher LER values (Table 2,

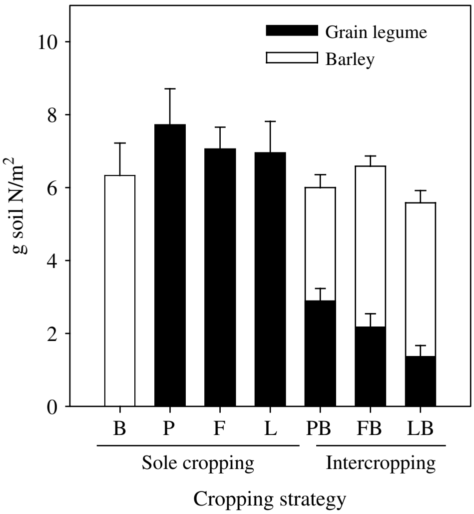

Fig. 4. Soil N uptake of shoot N in sole crops and intercrops of pea (P), faba bean (F) and lupin (L) with barley (B) on a sandy loam soil estimated by the ^{15}N natural abundance method. Sole cropped barley was applied with (B+) and without (B) 5 g N/m². All values are means ± S.E.

Fig. 3). This indicates that the weaker competitor – here barley – determines the yield efficiency of the system, in agreement with Harper (1977 cf. Ofori & Stern 1987).

In accordance with findings of Andersen *et al.* (1983), Hauggaard-Nielsen *et al.* (2001*a*) and Jensen (1996), barley obtained proportionately more of the soil N in intercropped pea and barley on the sandy loam soil (Fig. 4), indicating that barley has a greater competitive ability for inorganic N sources than peas. Hauggaard-Nielsen *et al.* (2001*b*) showed that barley roots had a faster growth rate and a deeper rooting system than peas.

As previously shown by Hauggaard-Nielsen *et al.* (2001*b*), Izaurralde *et al.* (1992), Jensen (1996) and Jensen (1998), intercropping peas with barley increased the proportion of N derived from fixation compared to sole cropped peas (Table 4). This is presumed to be associated mainly with a reduction in the soil inorganic N by a fast uptake by barley (Jensen 1996), due to the negative correlation between inorganic N and N_2 fixation (Sprent & Minchin 1985). Hauggaard-Nielsen *et al.* (2001*b*), Jensen (1996) and Jensen (1998) found that the amount of N_2 fixed by intercropped pea was lower than in sole cropped pea, in accordance with the results of the present study when barley was the dominant component (Table 4). However, the amount was not significantly lower when pea was the dominant component (Table 4), indicating that increased competitiveness of peas in the mixtures, increases the amount of N_2 fixed in accordance with Rauber *et al.* (2001).

On a sandy loam soil Jensen (1996) found an increase in barley grain N concentration due to intercropping with pea, which was larger than the increase due to N fertilization, as shown in the present study (Table 3). The increase in grain N concentration is presumed mainly to be associated with the higher competitive ability of barley for inorganic N sources, the lower number of barley plants in the intercrop and competition from pea for other growth factors than soil N (see also "Effect of location").

Faba bean–barley intercropping

On the sandy soil, late sowing, low rainfall and rather warm temperatures in May (Fig. 1), combined with low water-holding capacity, killed almost all the faba beans despite a successful germination (Table 1), as found by Hebblethwaite (1982). Despite outstanding intercropping advantages of faba bean-barley intercrops on the sandy loam soil (Fig. 4), the later maturity of faba bean might be a problem in relation to harvest.

Pea and faba bean performed similarly when intercropped with barley on the sandy loam soil, which is presumed mainly to be associated with similar shoot and root growth patterns (Bond *et al.* 1985; Hamblin & Hamblin 1985) and the equivalent complementary use of N sources (Trenbath 1976; Martin & Snaydon 1982). As found for pea, the amount of N_2 fixed was dependent on the proportion of faba bean in intercrops (Table 4). It is also supported by increased grain N concentration in barley intercropped with faba bean (Table 3), as observed in similar studies (Jensen 1986; Bulson *et al.* 1997).

Lupin–barley intercropping

Lupin showed an ability to obtain high grain N yields and more stable yield proportions in intercrops compared with pea and especially faba bean (Table 2). However, lupin did not benefit from intercropping to the same degree as faba bean and pea (Fig. 3).

The lack of effect on barley grain N concentration, when intercropping barley with lupins at the sandy loam soil (Table 3), is presumed to be mainly associated with a limited lupin aboveground competitive ability towards the dominant barley (Fig. 3), compared with pea–barley and faba bean–barley intercrops where grain legumes dominated the intercrops. The highly reduced branching structure of the present lupin cultivar might possibly be a major factor limiting lupin growth in intercrops. Limited ability to obtain sunlight by the shoots might translate into major competitive limitations (Midmore 1993) that strongly influence the interspecific competitive ability.

The lower amount of N_2 fixed by intercropped lupin than by sole-cropped lupin on both locations, contrary to intercropped pea and faba bean on the sandy loam soil (Table 4), indicates that the amount of N_2 fixed in the intercrop is positively correlated with the proportion of the grain legume in the final grain yield, as found by Rauber *et al.* (2001).

Effect of location

The yield stability of lupins, especially in contrast to faba beans on the sandy soil (Table 2) is possibly due to the deeper lupin root system (Bond *et al.* 1985; Hamblin & Hamblin 1985). The greater ability of barley to absorb limiting soil factors especially on sandy soil may increase the interspecific competition in the intercrop (Trenbath 1976).

The more stable intercrop yield proportion of the lupin cultivar over environments (Table 2) could be related to the highly reduced branching structure of the specific lupin cultivar, limiting lupin in dominating intercrops, and the deep growing taproot of lupin (Hamblin & Hamblin 1985) making lupin less susceptible to, for example, water stress compared to faba bean.

The lack of significant differences in the barley grain N concentration on the sandy soil as affected by intercropping with pea or faba bean (Table 3) may be caused by the low proportion of grain legumes lowering the interspecific competition for other growth factors than N in the intercrop. Bulson *et al.* (1997) likewise found that the grain N concentration in barley was increased when the density of faba beans in the intercrops were increased.

Evaluating methods for estimation of N_2 fixation

The N-difference method, used to estimate N_2 fixation (Table 4), is known to give rather precise estimations when having low concentrations of plant available N (Herridge & Danso 1995) as in sandy soils. Other modified N-difference methods such as those presented by Evans & Taylor (1987) and Stülpnagel (1982) taking soil mineral N at harvest into account were not found relevant for the present growing conditions. Additional inorganic N under legume crops at harvest compared with cereals may result from rapid mineralization of organic N derived from rhizodeposition rather than from a lower N use by the N_2 fixing legume (Unkovich *et al.* 1997) making it questionable to include soil N at harvest. Furthermore, Jensen (1996) has shown that the soil N uptake in sole-cropped pea and barley was not significantly different at harvest using ^{15}N enrichment technique, supported by Hauggaard-Nielsen *et al.* (2001 *a*) on a similar soil using the same methodology. In the present N-difference calculations it was assumed that the soil N uptake by the barley reference crop and the grain legumes were the same.

The N-difference method and the natural abundance method showed comparable results on the sandy loam soil. However, the natural abundance method has an advantage in its ability to estimate soil N uptake by each component of the intercrop (Fig. 4) shown to be an important factor when discussing interspecific competition. Reliability of the N-difference method at the sandy soil could not be tested via the natural abundance method due to the low natural enrichment of ^{15}N (Table 5).

The natural abundance method relies on the slight natural enrichment of ^{15}N in soils relative to atmospheric N_2 (Shearer & Kohl 1986), but as shown on the sandy soil this is not always the case (Table 5). Using the natural abundance method to estimate N_2 fixation, Unkovich *et al.* (1994) suggests a minimum of at least 2 in the $\delta^{15}N$ value of the reference crop with preferable concentrations up to 6 for optimum precision. The low natural ^{15}N abundance at the sandy soil site, reflected in the reference crop (Table 5), may be caused by a yearly deposition of N-difference around 18 kg/ha in 1987/88 diluting the soil ^{15}N abundance by the lighter ^{14}N isotope. Atmospheric deposition might even be increased by today due to a major increase in pig production in this area. Other factors might also have influenced the natural ^{15}N abundance like cultivation, fertilization, particle size, depth etc.

CONCLUSIONS

On a sandy loam soil pea–barley and faba bean–barley intercrops used N resources more efficiently by increasing the proportion of plant N derived from N_2 fixation and at the same time increasing the barley grain N concentration. However, the later maturity of faba bean compared with barley might be a problem in relation to harvest. Intercropped barley grain N concentration was increased where grain legumes were dominating intercrops, exposing barley to a higher interspecific competition for other growth factors than N, and consequently not increased at the sandy soil site. The amount of plant N derived from fixation in intercropped grain legumes seems positively correlated with the proportion of grain legumes in mixtures. Lupin had a more stable yield proportion in mixtures with barley over locations, but did not show intercropping advantages to the same degree as pea and faba bean. Furthermore the study indicates that the natural ^{15}N abundance at certain locations might not always be sufficient to ensure a reliable estimate of N_2 fixation.

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