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Temporal and spatial distribution of roots and competition for nitrogen in pea-barley intercrops – a field study employing ^{32}P technique

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Abstract

Root system dynamics, productivity and N use were studied in inter- and sole crops of field pea (*Pisum sativum* L.) and spring barley (*Hordeum vulgare* L.) on a temperate sandy loam. A ^{32}P tracer placed at a depth of 12.5, 37.5, 62.5 or 87.5 cm was employed to determine root system dynamics by sampling crop leaves at 0, 15, 30 and 45 cm lateral distance. ^{15}N addition was used to estimate N_2 fixation by pea, using sole cropped barley as reference crop. The Land Equivalent Ratio (LER), which is defined as the relative land area under sole crops that is required to produce the yields achieved in intercropping, were used to compare the crop growth in intercrops relative to the respective sole crops.

The ^{32}P appearance in leaves revealed that the barley root system grows faster than that of pea. P uptake by the barley root system during early growth stages was approximately 10 days ahead of that of the pea root system in root depth and lateral root distribution. More than 90% of the P uptake by the pea root system was confined to the top 12.5 cm of soil, whereas barley had about 25–30% of tracer P uptake in the 12.5 – 62.5 cm soil layer. Judging from this P uptake, intercropping caused the barley root system to grow deeper and faster lateral root development of both species was observed. Barley accumulated similar amounts of aboveground N when grown as inter- and sole crop, whereas the total aboveground N acquired by pea in the intercrop was only 16% of that acquired in the pea sole crop. The percentage of total aboveground N derived from N_2 fixation in sole cropped pea increased from 40% to 80% during the growth period, whereas it was almost constant at 85% in intercropped pea. The total amounts of N_2 fixed were 95 and 15 kg N ha^{-1} in sole cropped and intercropped pea, respectively. Barley was the dominant component of the pea-barley intercrop, obtaining 90% of its sole crop yield, while pea produced only 15% of the grains of a sole crop pea. Intercropping of pea and barley improved the utilization of plant growth resources (LER $>$ 1) as compared to sole crops. Root system distribution in time and space can partly explain interspecific competition. The ^{32}P methodology proved to be a valuable tool for determining root dynamics in intercropping systems.

Introduction

Legume-cereal intercropping can force the legume component to rely on N_2 fixation because the cereal is more competitive for soil inorganic N (e.g. Anil et al., 1998; Carr et al., 1998; Carruthers et al., 2000). This complementarity of N use between grain legumes and cereals offers an opportunity to increase the input of fixed nitrogen into agroecosystems without compromising cereal N use, yield level and stability (Jensen, 1996).

A number of mechanisms exist by which intercrops utilize plant growth resources such as light, water and nutrients more efficiently than the equiva-

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lent sole crops (Anil et al., 1998; Carr et al., 1998; Hauggaard-Nielsen et al., 2001; Jensen, 1996). This occurs if the intercrop components are not competing for exactly the same ecological niches in time and space (Ofori and Stern, 1987) and if interspecific competition is weaker than the intraspecific competition for a given factor (Vandermeer, 1989; Willey, 1979). Jensen (1996) showed that the uptake of soil N takes place earlier in sole cropped barley than sole cropped pea.

In order to adapt to different habitats and to survive in a plant community, species have evolved different phenologies and rooting patterns to acquire and utilize nutrients in the soil volume. Jakobsen and Nielsen (1983) found that the root density of barley was on average 6 cm cm^{-3} at heading in the 0–20 cm soil layer whereas root densities of dwarf and determinate pea cultivars of 1.4 – 3 cm cm^{-3} have been reported (Jensen, 1985). Root system morphology and fine root distribution are believed to be key factors in determining the magnitude of below-ground interspecific competition in intercropping systems (George et al., 1996).

The root growth dynamics of intercropped plants may differ from those of sole cropped plants, as a result of different degrees of root interactions and competition (Snaydon and Harris, 1981; Willey, 1979). This may have consequences for the way nutrients and water are utilized. Thus, improved knowledge of the spatial distribution and activity of roots is required for enhancing the efficiency of soil nutrient resources in intercropping systems (Ito et al., 1993).

Root studies should preferably be carried out under field conditions at normal population densities; in small plots or pot experiments, the influence of plant height and boundary effects can not be eliminated and the restrictions on root growth due to a limited volume of the soil may modify results (Snaydon and Harris, 1981).

Radioisotope techniques have been developed to investigate root activity and dynamics (Abbott and Fraley, 1991). One of the most commonly used isotopes is ^{32}P (i.e. George et al., 1996; Jacobs et al., 1970; Lai and Lawton, 1962) because its half-life of 14.3 days enables activity measurements over several months without long-term concerns for increased radiation levels.

The aim of the present work was to determine: (1) the temporal and spatial root development in pea-barley intercrops compared to sole crops and (2) the productivity and use of N sources by pea-barley intercrops compared to sole crops in relation to root dynamics using ^{15}N dilution technique. We used a method developed for field root studies (Jacobs et al., 1970) involving laboratory preparation of the radioactive ^{32}P solution in cooled gelatine capsules. Accurate amounts of radioactive tracers are precisely placed at specific soil depths and, due to encapsulation, contamination of soil layers around the deposition are minimised. The hypothesis we tested was: (1) barley has a faster growing root system than pea, (2) barley is better at utilizing water and nutrients in deeper soil layers compared to pea, and (3) interspecific competition induce a more vigorous root system distribution improving the crops search for nutrient sources.

Materials and methods

Site and soil

The experiment was carried out in 1999 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 Figure 1. The day before sowing, the soil was sampled in four successive soil depths, i.e. 0–25, 25–50, 50–75 and 75–100 cm. In the topsoil (0–25 cm), water content at field capacity (–10 kPa) was 28 $\pm$ 0.7% (v/v) and the soil bulk density was 1.6 Mg m^{-3} (Blake, 1965). 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 for centuries and NPK fertilisers used for the last four decades. It was assumed that due to considerable P application during the years applied ^{32}P-phosphorous would not be fully immobilized in the soil. In recent years, the experimental site has been cultivated with a pea – wheat – barley – oilseed rape rotation. Oilseed rape (*Brassica napus* L.) was grown in 1998.

Experimental set-up

The cultivars used were 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

Table 1. Soil characteristics measured before crop establishment. Values are the mean ($n = 4$) ± SE

Soil depth (cm)	% total C	% total N	pH in water[a]
0–25	1.5 ± 0.14	0.13 ± 0.012	7.2 ± 0.38
25–50	1.2 ± 0.66	0.05 ± 0.006	7.7 ± 0.30
50–75	0.9 ± 0.52	0.03 ± 0.006	7.9 ± 0.15
75–100	1.4 ± 0.54	0.01 ± 0.003	8.2 ± 0.12

[a] Ratio of soil:water are 1:2.5.

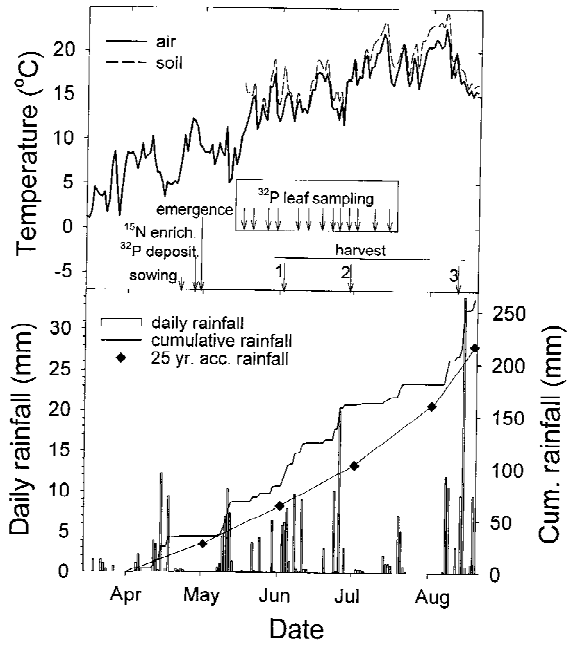

Figure 1. Average daily soil and air temperatures, daily and cumulative (Cum.) rainfall (mm) at Risø National Laboratory, Denmark, during the growth season 1999. The 25-year average accumulated rainfall is also included. Major events during the experimental period are plotted on the x-axis.

and stem strength. Typically these cultivars are grown as mixed pea-barley intercrops (IC) for silage and as sole crops (SC) for grain production in conventional cropping systems.

The experimental plots (6.0 × 3.4 m) were laid out in a complete one-factorial randomised design with pea SC, barley SC and pea-barley IC as treatments with three replicates. Seeds were sown on 21 April. The numbers of seedlings in four rows of 1 m length were counted three weeks after seedling emergence (28 April). The actual plant densities were 90 field pea and 290 barley plants m^{-2} in the sole cropping plots, which was lower than the target densities of 100 pea plants and 350 barley plants m^{-2}. Employing a replacement design pea and barley grains were mixed and sown in 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 relative total plant density in the intercrop compared to sole crops (De Wit and van der Bergh, 1965). Actual crop development confirmed the target intercrop plant frequency of 0.50.

Each experimental plot was subdivided into six subplots (2.0 × 1.7 m) of which four subplots were used for ^{32}P deposition and the remaining two for estimating biomass production. The ^{32}P tracer placed at a depth of 12.5, 37.5, 62.5 or 87.5 cm was employed to determine root system dynamics by sampling crop leaves at 0, 15, 30 and 45 cm lateral distance The use of N resources and the influence of intercropping on N_2 fixation were studied using the ^{15}N isotope dilution principle (Chalk, 1998). One of the ^{32}P-labelled subplots received $K^{15}NO_3$ (10 atom% ^{15}N excess). The remaining five subplots received equivalent amounts of unlabelled KNO_3. Fertilizer was applied 10 days after emergence, and the crops did not receive other fertilizer applications.

Management practise

The site was managed with no use of herbicides and with mechanical weeding two times during emergence and two times during early tillering. Scarecrows and fencing were used to avoid birds and hares.

^{32}P technique

The 14.3 day half-life of ^{32}P and its specific fixation to soil particles permits temporal and spatial estimations of root activity over several months.

In the laboratory, gelatine capsules (volume: 0.5 mL) were placed over dry ice. Into each capsule, 0.45 mL of carrier-free $H^{32}PO_4^-$ solution (8 MBq mL^{-1} day 0) was dispensed. The filled capsules were quickly closed, frozen over dry ice and kept frozen until used in the field.

The ^{32}P was deposited at four distinct soil depths of 12.5, 37.5, 62.5 and 87.5 cm using PVC-tubes (1.2 cm in outer diameter) (Figure 2a). The PVC-tubes were pushed down in pre-drilled holes (1 cm auger bit) using a steel push rod. For each depth 4 × 4 PVC-tubes were installed in four rows in a 60 × 60 cm square grid established in the subplot centre. After installation, each tube was closed with a lid.

The day after installation of PVC-tubes, the frozen capsules were transported to the experimental plot in

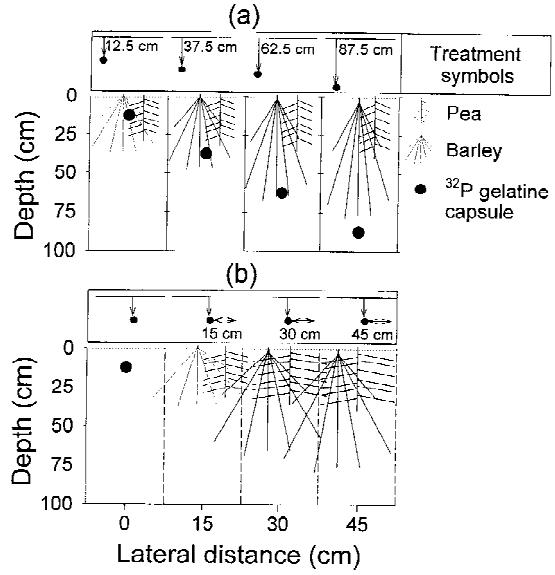

Figure 2. Schematic illustrations of the ^{32}P placements in the field when estimating root depth in 12.5, 37.5, 62.5 and 87.5 cm soil layer (a) and lateral root growth (b). The lateral root growth illustration is exemplified using the 12.5 cm soil depth. Lateral root growth in the other three layers was estimated identically.

trays with dry ice. The capsules were handled with tweezers and carefully dropped to the bottom of the tubes. After deposition of the capsules 10 mL of water was added to each tube to secure a fast capsule disintegration and finally the tubes were filled with washed sand. A GM-detector was used to check for radioactive contamination of the aboveground tube and soil surfaces. No contamination was detected.

Sampling and analytical methods

The last but one matured leaf was collected for radioassay analyses from 25 individual plants at each sampling. The sampling of pea and barley leaves within (Figure 2a) and in the rows alongside the ^{32}P microplot (Figure 2b) represented depth and lateral root development, respectively. Samples from plants adjacent to the unlabelled subplot were collected in an identical manner and used for background correction. Leaf sampling was finalised 81 days after emergence assuming that the grain filling growth period was dominated by retranslocation of already assimilated resources rather than new root growth.

After the final leaf sampling, all ^{32}P microplots (0.36 m^2) were harvested on the same day by cutting the plants at the soil surface to get a measure of total ^{32}P activity in aboveground biomass.

Each biomass sample was dried at 70 °C for about 24 h to constant weight. The samples were ground and 500 mg sub samples were digested in conc. HNO_3 and 70% $HClO_4$ 4:1 solution for 2–3 h. The digests were radioassayed for ^{32}P (cpm mg^{-1} dried leaf plant biomass) using a scintillation counter in Cerenkov mode (Packard TR 1900). The count rates were corrected for background and decay.

The ^{32}P activity in the sampled plant material was used as a qualitative measure of root distribution. A maximum threshold of 50 cpm mg^{-1} dry matter was assumed to indicate full root exploitation at a specific depth.

Three harvests were carried out during the experimental period by cutting the plants above the soil surface. The first harvest was taken at the tillering growth 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)) 35 days after emergence (Figure 1). The second harvest (63 days after emergence) was taken at the end of the elongation growth stage in barley (stage 53–59) corresponding to post flowering in pea (stage 205–206). The third harvest was taken at maturity 105 days after emergence. At each harvest, two rows of 1 m (0.45 m^2) were harvested in the plots without ^{15}N applied and one row of 60 cm in the plots with ^{15}N applied. The harvested plant biomass was separated in pea, barley and weed fractions, the latter including non-recognizable dead tissue. At the final harvest, grain dry matter yield was determined separately for both pea and barley after treshing. The samples were dried at 70 °C to constant weight and total dry matter production determined. Total N and ^{15}N contents were determined on 5–10 mg subsamples of finely ground material using an elemental analyser (CE Instruments EA 1110) coupled in continuous flow mode to an isotope ratio mass spectrometer (Finnigan MAT DeltaPlus).

The day after harvest, soil samples were collected to 100 cm depth below the harvested area. Samples were collected using a 2.5 cm diam. soil corer at 0–25, 25–50, 50–75 and 75–100 cm. In each plot, cores were taken at two points in and two points between rows. Samples from similar layers were bulked and mixed thoroughly and kept at < 5 °C before extractions, which took place the following day. Soil inorganic N was extracted in 2 *M* KCl (1:10 soil: extractant). The KCl extracts were frozen prior to analyses of NO_3^-/NO_2^- and NH_4^+ with standard colorimetric methods using a segmented flow injection autoana-

lyser (Technicon Autoanalyzer II). The NH_4^+ content was always less than 5% of the total soil inorganic N and consequently the sum of NH_4^+ and NO_3^- is given as inorganic N.

Soil water content

Soil water content was measured using time domain reflectometry (TDR) at 25, 50 and 75 cm soil depths. The measurement system for the TDR used are based upon a cable tester (Tektronix 1502C) coupled to a handheld computer (Husky FS/2) (Thomsen, 1994; Thomsen and Thomsen, 1994). The apparent soil dielectric constant was measured by TDR using waveguides of two parallel 0.65 cm steel rods placed 5.1 cm apart (Thomsen and Thomsen, 1994). 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.

Calculations and statistics

The degree of variability in the root distribution using the qualitative ^{32}P estimates caused an average coefficient of variation (CV) from 25 to 65%. There was no consistency in comparing CV's from either crop species, cropping strategy, root depth or lateral root growth. Due to the different means in the ^{32}P activity, CV was used instead of standard error or deviation. For that reason, no statistical analyses were performed for the measured ^{32}P variables. All other measured variables were assumed to be normally distributed and statistical ANOVA analyses were performed using SAS software (SAS, 1990). The significance of difference between treatments was estimated using the Tukeys Studentized Range Test with $\alpha = 0.05$ if a main effect or interaction was significant.

Nitrogen in crops derived from ^{15}N labelled fertilizer N, soil N and N_2 fixation in pea was calculated using conventional ^{15}N isotope dilution equations (Chalk, 1998). Sole cropped barley was used as the reference crop for calculating N_2 fixation in sole cropped and intercropped pea.

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):

$$L_B = Y_{barley,ic} / Y_{barley,sc} \quad (1)$$

$$L_P = Y_{pea,ic} / Y_{pea,sc} \quad (2)$$

$$LER = L_B + L_P \quad (3)$$

LER values > 1 indicates an advantage from intercropping in terms of the use of environmental resources for plant growth.

Results

Climatic conditions and soil water content

Rainfall during the experimental period in spring 1999 was in total 18% greater than the 25 year average (Figure 1). There was no significant difference in soil water content between treatments in either the 0–25, 25–50 or 50–75 cm soil layer, although pea SC plots tended to have the lowest soil water content in the 0–25 cm soil layer later in the growing season (50–81 days after emergence) (Figure 3). However, comparing pea SC, barley SC and pea-barley IC, the patterns of soil water distribution in the soil profiles differed supporting the null hypothesis. Distribution of root systems among species and cropping system influenced the water content down the soil profile. Comparing the soil water content of the three soil layers the pea-barley IC tended to display the lowest differences followed by barley SC and pea SC, showing intermediate and greater differences. In the pea SC plots, there was a significant difference between the three soil layers at day 12 and 28 after emergence and with a consistent difference during the flowering growth stage from day 54 and onwards. In the barley SC plots, there was a consistent significant difference between the three soil layers during the tillering growth stage from day 12 to 29 after emergence and on the final ^{32}P sampling at day 81. In the pea-barley IC plots, there was no significant difference between the three soil layers until the final measurement.

Dry matter production and nitrogen accumulation

At 35 days after emergence, barley SC had the greatest aboveground dry matter (DM) yield. At day 63 and 105 barley SC and barley IC yields were equivalent and significantly greater ($p<0.001$) than pea SC and pea IC yields (Figure 4a).

The accumulation of N in barley and pea increased steadily throughout the growth season (Figure 4b). Barley accumulated similar amounts of N when grown as a sole crop (68 kg N ha^{-1}) and intercrop (83 kg

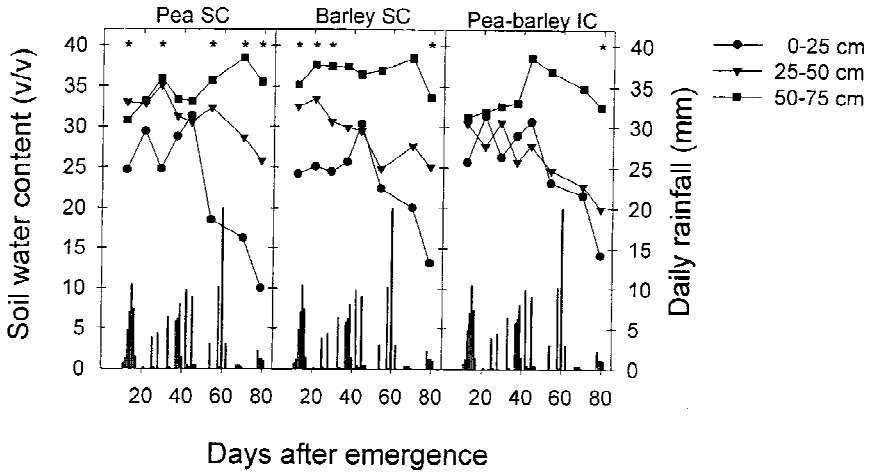

Figure 3. Volumetric water content in sole crops (SC) and intercrops (IC) of pea and barley in the 0–25, 25–50 and 50–75 cm soil layers determined by time domain reflectometry during the experimental period. Values are the mean (n = 3). The symbol (*) indicates significant differences ($p<0.05$) between soil layers on each sampling day. Columns show the daily rainfall.

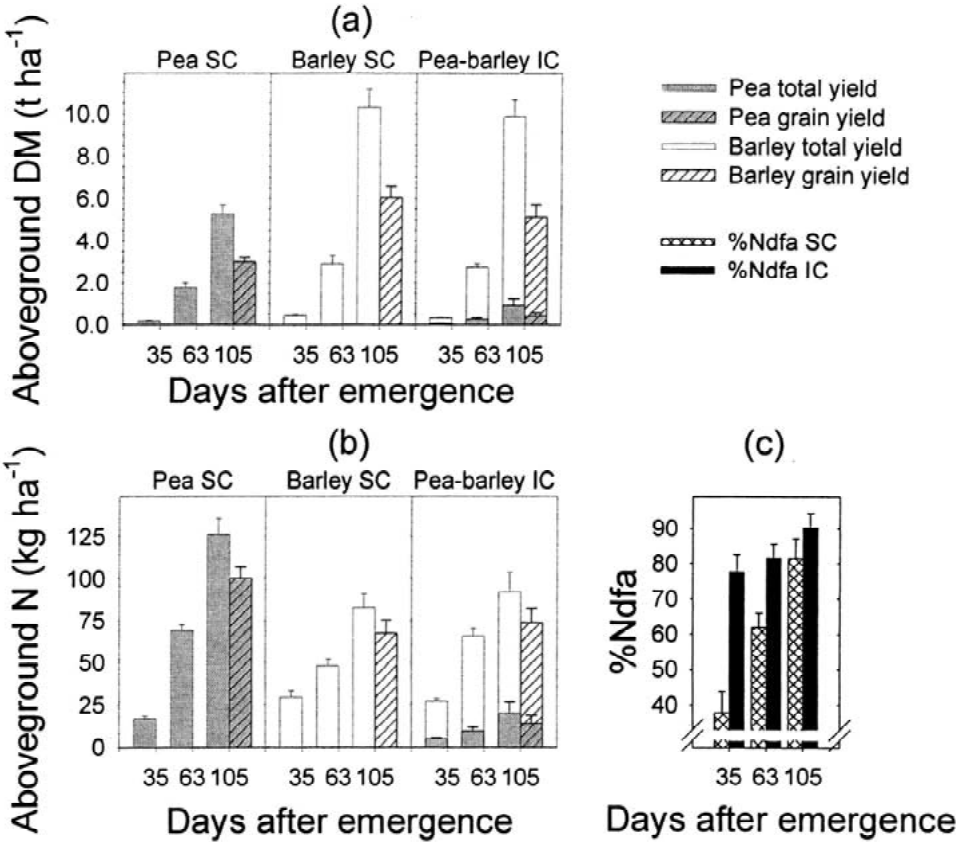

Figure 4. Total aboveground dry matter (DM) production (a), nitrogen (N) accumulation (b) and percentage N derived from fixation (%Ndfa) (c) in sole crops (SC) and intercrops (IC) of pea and barley. Values are the mean ($n = 3$) ± SE.

N ha^{-1}), whereas the total N acquired by pea in the intercrop was 85% lower than in the sole crop (Figure 4b).

The percentage of total aboveground N accumulation derived from N_2fixation (%Ndfa) in pea SC increased from 40% to 80% during growth, whereas pea IC had an almost constant %Ndfa of 85% (Figure 4c). There was no significant difference in %Ndfa between pea SC and pea IC at the final harvest and thus the total amount of N fixed was proportional to biomass yields. The total amount of N_2 fixed was 95 and 15 kg N ha^{-1} in pea SC and pea IC, respectively, corresponding to 80% and 90% of the total N accumulated aboveground in pea.

Utilization of plant growth factors

The pea partial land equivalent ratio (L_P) declined after the pre-flowering stage (day 35) whereas barley partial land equivalent ratio (L_B) showed an increase until the end of the elongation stage (day 63) (Figure 5). Early interspecific competition was indicated by L_P and L_B 35 days after emergence with values lower and greater, respectively, than the 0.5 anticipated from sowing density. In all three harvests, the L_B values were greater than 0.5, while the L_P values varied between 0.14 and 0.35 showing that barley was the dominant component in the intercrop.

The Land Equivalent Ratio (LER = L_P+L_B) based on aboveground DM accumulation varied between 1.03 and 1.10 comparing the three harvests. The LER values based on total N accumulation indicated that N was used 10 – 30% more efficiently in intercrops than sole crops (Figure 5).

Temporal and spatial root development

The barley root system was fully established 25 days after germination in the 12.5 cm soil layer indicated by the criteria of tentative counts above 50 cpm mg^{-1} whereas the same was observed 10 days later for pea (Figure 6a). In the early growth phases, there was a tendency towards faster root depth growth rate in pea IC roots compared to pea SC roots (Figure 6a). Pea roots did not become active in the soil layers from 37.5 to 87.5 cm until 81 days after emergence (Figures 6b–d).

In contrast, it was possible to track the barley root system activity to 62.5 and 87.5 cm 63–76 days after emergence. Except at 12.5 cm depth, barley IC seemed to have a root system that grow faster and deeper than barley SC throughout the experimental period.

Independent of cropping system the 15 cm lateral distribution of barley roots at 12.5 cm soil depth was well-established 35 days after germination (Figure 7a). The lateral development of pea roots was slightly faster for pea SC than for pea IC with roots in the 12.5 cm soil depth within 50 and 60 days after emergence (Figure 7a). In contrast to lateral root development at 15 cm, both pea SC and pea IC seemed to have a more active lateral root system at 30 cm at 12.5 cm soil depth compared to both barley treatments (Figure 7b). It was not possible to detect any lateral root system development at 45 cm at any depth.

For both barley treatments, lateral root development at 15 cm was observed to 62.5 cm soil depth (Figures 7c–d). As with the estimates of root depth (Figure 6) barley IC seemed to have faster lateral root development at 15 cm than barley SC from 37.5 cm depth downwards throughout the experimental period (Figure 7).

The study showed that about 95% of the pea root system developed in the upper 12.5 cm of soil, whereas 9–14% of the barley root system was distributed from 62.5 to 87.5 cm (Figure 8). Barley IC had twice the proportion of its root system at 62.5 cm compared with barley SC.

Soil inorganic N

At sowing, the soil contained 20, 10 and 1 kg extractable inorganic N ha^{-1} in the 0–25, 25–50 and 50–100 cm soil layers. A similar vertical distribution of inorganic N was observed during the experimental period (Figure 9).

At 36 days after emergence, there was a significantly greater inorganic N content (10–15 kg N ha^{-1}) in the 0–50 cm soil layer below pea SC compared to 5 and 1 kg inorganic N ha^{-1} below pea-barley IC and barley SC, respectively. There was a significantly greater inorganic N content (12 kg ha^{-1}) in the 0–25 cm soil layer below pea SC 106 days after emergence compared to the other treatments holding about 5 kg inorganic N $layer^{-1}$ ha^{-1} independent of soil depth, crop species and cropping strategy.

Discussion

Use of plant growth resources

Barley displayed a greater competitive ability to take up soil inorganic N than pea, thereby forcing pea to rely on N_2fixation, as found by Jensen (1996)

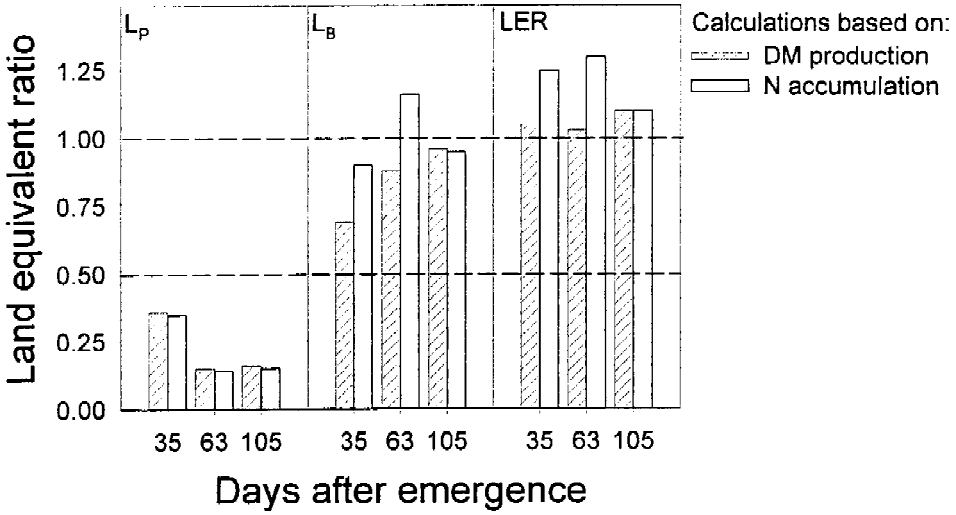

Figure 5. Pea and barley partial land equivalent ratio (L_P and L_B, respectively) and land equivalent ratio (LER). The calculations were based on total harvested aboveground dry matter (DM) production and nitrogen (N) accumulation. Values are the mean (n = 3).

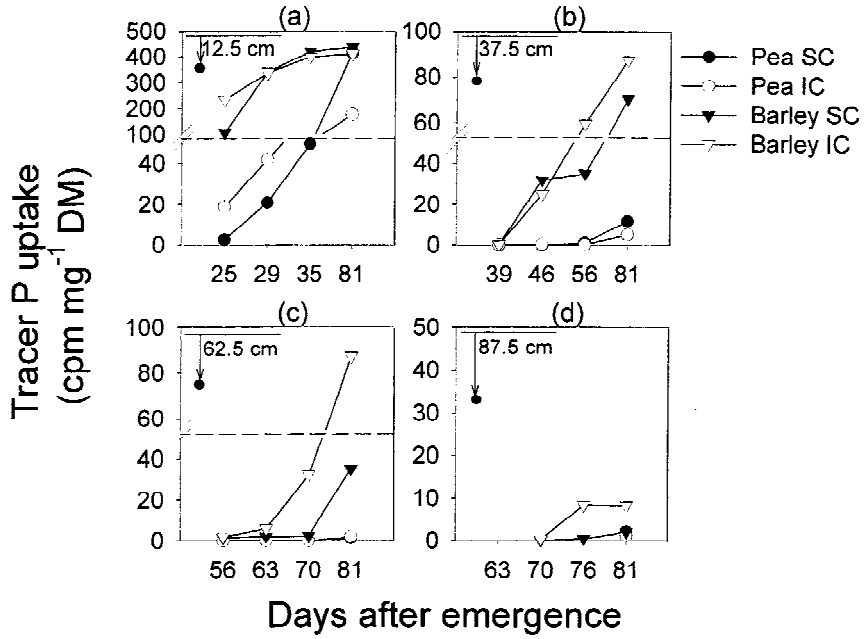

Figure 6. Temporal root depth development in sole crops (SC) and intercrops (IC) of pea and barley measured by countinuous leaf sampling in microplots with ^{32}P depositions in the 12.5 (a), 37.5 (b), 62.5 (c) and 87.5 cm soil layer (d). For further explanations, see Figure 1a. The y-axis breaks and the horizontal dotted line indicate the criteria of tentative counts above 50 counts per minute (cpm) mg^{-1} dry matter (DM) level indicating a fully developed root system in the specific depth. SC = sole cropping and IC = intercropping. Values are the mean (n = 3). Further explanations see Figure 2a.

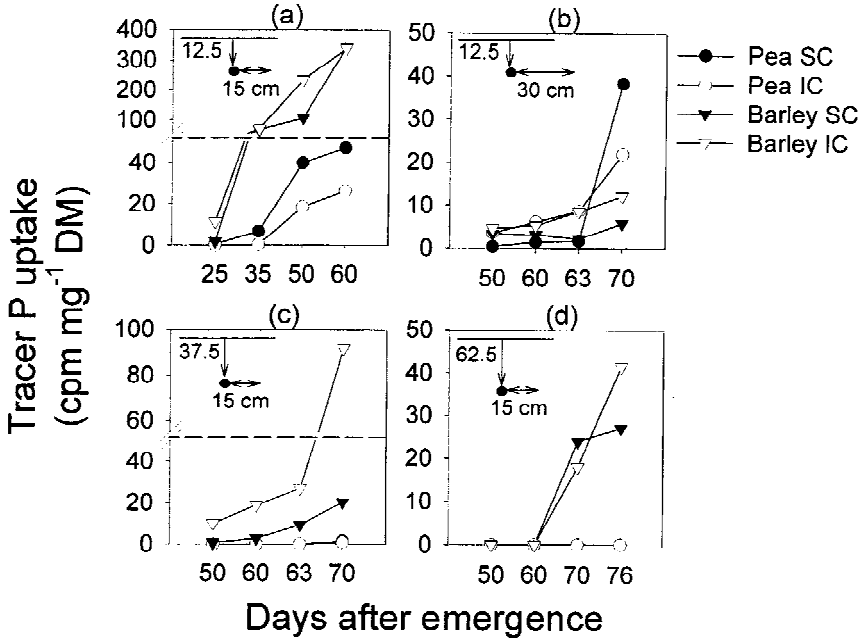

Figure 7. Temporal lateral root development in sole crops (SC) and intercrops (IC) of pea and barley measured by continuous leaf sampling beside microplots with ^{32}P depositions: 12.5 cm depth and 15 cm lateral distance (a), 12.5 cm depth and 30 cm lateral distance (b), 37.5 cm depth and 15 cm lateral distance (c) and 62.5 cm depth and 15 cm lateral distance (b). SC = sole cropping and IC = intercropping. For further explanations, see Figures 2b and 6.

and Hauggaard-Nielsen et al. (2001). Nitrogen fixed in the early growth stages was imported into the intercrop system without significantly reducing the amount of harvested barley grain relative to the sole crop yields. However, the present study supports the general picture that yields of legume components in cereal-legume intercrops is significantly depressed by the cereal components (Ofori and Stern, 1987). A dwarf determinate pea cultivar, like cv. *Focus* used in the present study, may not be able to grow to the top of the intercrop canopy, causing strong effects of shading from barley. In agreement with a study by Tofinga et al. (1993), we found that competition from barley had little effect on the %N in pea grains, but significantly reduced the pea total N accumulation and increased the proportion of N derived from fixation. Hence, a farmer can produce the same cereal yield in a pea-barley IC, with similar crop proportions as in the present study, as in barley sole cropping, but in addition the farmer gains N from pea N_2 fixation. When the target for the intercrop is to improve utilisation of N sources in agroecosystems limited in plant available N, the present study illustrates how to implement N complementarity to the cropping fields. However, if the target is to produce silage with a high proportion of pea and thereby protein the present pea-barley intercrop should be changed improving pea yields. The LER values were greater than one at all three harvests, indicating a more efficient utilization of plant growth factors by intercrops compared to sole crops (Willey, 1979). Comparing partial LER values, barley was clearly the dominant component of the intercrop, displaying a considerably greater competitive ability to acquire growth limiting factors than pea. Already, 35 days after emergence, the pea partial LER was 0.35 indicating that competition for growth factors was strong during the early growth stages. Jensen (1996) showed that LER values did not correlate well with initial concentration of soil inorganic N, indicating that other factors, such as canopy structure and rooting pattern, may also influence intercropping performances.

Root system interaction and competition

The degree of root interactions in an intercrop may vary, depending on the degree of similarity in growth and development of component crops (Ofori and Stern, 1987). Significantly greater soil mineral N content in the 0–50 cm soil profile below sole cropped pea, compared to both sole cropped barley and intercropped pea-barley, indicated that barley had a

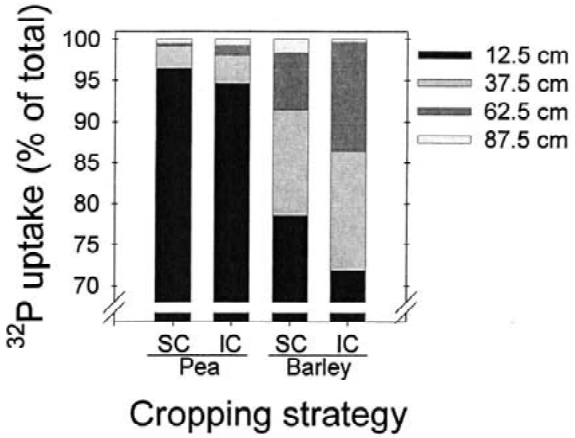

Figure 8. ^{32}P uptake from four soil depths: 12.5, 37.5, 62.5 and 87.5 cm as percentage of total ^{32}P activity in harvested biomass 81 days after emergence. SC = sole cropping and IC = intercropping.

stronger competitive ability for moisture and nutrients in the early establishment growth stage compared to pea (Cooper and Ferguson, 1963).

The onset of soil N uptake sets in earlier in barley than pea (Jensen, 1996), and a 10 days head start for barley compared to pea in the 12.5 cm soil layer was observed in the present study. The rapid root penetration of barley down the soil profile (Figure 6) may minimise drought limited nutrient constraints that could potentially be brought about by the interspecific competition in an intercrop.

It was not possible to verify the above statement for soil water content measured with TDR equipment. However, comparing water contents of the three soil layers 0–25, 25–50 and 50–75 cm under all cropping strategies, differences between soil layers were lower under the pea-barley IC than under both pea and barley SC. Thus, in the pea-barley intercrop, there might be a more fully exploitation of the soil profile. The shallow pea root system (Figure 8) resulted in less utilisation of deeper soil water resources. Similar findings were shown by Izaurralde et al. (1994), including greater water use efficiency in a pea-barley intercrop than in either of the sole crops.

Cropping strategy and root growth pattern

The growth dynamics of intercropped compared to sole cropped barley gave rise to a faster and deeper root distribution (Figures 6 and 7). Furthermore, intercropped barley showed a faster lateral root growth than sole cropped barley from the 37.5 cm soil depth and down the profile. Thus, barley intercropped with pea induced a more complete exploitation of the soil profile compared to sole cropped barley indicating a potential improvement in the search of natural nutrient sources.

The pea root system distribution in the upper soil layers appeared more rapid for sole cropped than intercropped pea (Figures 6 and 7). It may indicate a reduced availability of plant growth resources in the intercropped compared to the sole cropped pea (Ofori and Stern, 1987). In order to improve the intercropped pea yield, and thereby increase the import of fixed N to the system, it is essential to increase the pea N_2 sink strength (Van Kessel and Hartley, 2000). Root growth pattern may be changed by management parameters employed and improved growth of intercropped pea may be the result of changes in interspecific competition. One way of changing current management practise could be choice of appropriate intercrop cultivars (Davis and Woolley, 1993; Nelson and Robichaux, 1997), another relay intercropping (Midmore, 1993) and a third more uniform spatial distribution of the individual intercrop plants over the field area while sowing (Hühn, 2000).

^{32}P methodology evaluation

The method should be characterised as a technique providing qualitative information on whether living plant roots are present at a particular location in the soil. Deciding to use this methodology, we assumed that both pea and barley were able to exploit soil volumes containing ^{32}P. However, differences in the root surface area of pea and barley (Jacobsen and Nielsen, 1993; Jensen, 1985) may lead to corresponding differences in their absorption capacity which may be of importance when studying the absorption of an immobile nutrient such as P (Marschner, 1986). Uptake of deposited ^{32}P and hence leaf ^{32}P activity may thus be influenced not only by root location in the soil profile, but also by root morphology.

Abbott and Fraley (1991) emphasised that researchers should be aware of the sometimes considerably variable ^{32}P uptake, as observed in the present study. Reasons for this variability are different levels of dilution with exchangeable soil phosphorous and inhomogeneous root development due to heterogeneity of soil physical parameters, water content and soil density. However, the method showed some obvious advantages being superior to conventional excavation and soil coring techniques typically applied in root dynamic studies. The ^{32}P method is (a) faster, (b) more

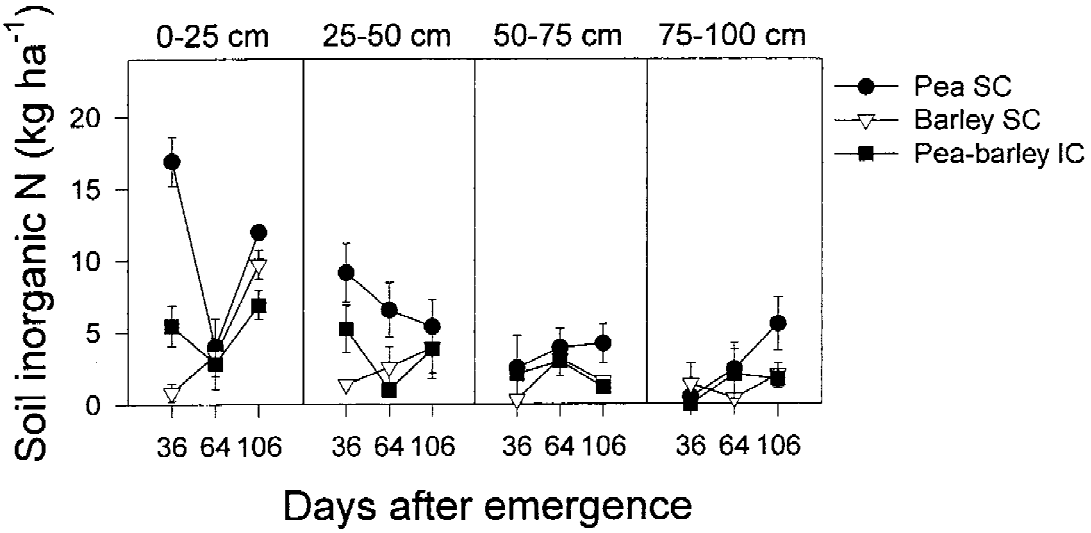

Figure 9. Soil inorganic N in 0–25, 25–50, 50–75 and 75–100 cm soil depth below sole crops (SC) and intercrop (IC) of pea and barley. Values are the mean ($n = 3$) ± SE.

sensitive to finer root members, (c) non-destructive to plants, (d) able to differentiate between active and inactive roots and (e) able to differentiate roots of individual plants in competitive field situations.

From a practical point of view, the methodology was successful and convenient. Firstly, the preparation of the radioactive ^{32}P solution/capsules is done in the laboratory where all appropriate precautions for contamination can be taken. Secondly, accurate amounts of radioactive tracers are precisely placed at specific soil depths and due to encapsulation any contamination hazards of the soil layers around the deposition is avoided. Thirdly, the tube installation procedure used minimises changes of soil structure and compression of soil material caused by preparing an access hole for the capsules. In addition, the 2 mm diameter difference between auger and PVC-tubes avoid air gaps along the soil-tube interface.

Conclusion

By using the *in situ* ^{32}P labelling method, it was found that barley had a faster distribution of its root system compared to pea, which supported our first hypothesis and the finding that barley is the stronger competitor in a pea-barley intercrop. Another important finding was that intercropping compared to sole cropping induces a deeper growing barley root system, as stated in our second hypothesis. The faster lateral root development by both species supports that finding indicating a potential improvement in the search of nutrient sources, as stated in our third hypothesis. The ^{32}P methodology was found to be a valuable tool for studying *in situ* root dynamics and this facilitating the search for improvements in the management of intercropping systems.

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