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Complementary resource use in intercropped faba bean and cabbage by increased root growth and nitrogen use in organic production

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Abstract

Intercropping can improve yield and nitrogen use efficiency in organic vegetable production by pairing crops with complementary resource use. An intercrop field experiment was conducted to determine yield, root growth and nitrogen (N) dynamics using faba bean (*Vicia faba* L.) grown as a vegetable and pointed cabbage (*Brassica oleracea* var. *capitata* cv. conica). Both crops were grown in monocropping (MC) and intercropping systems (IC). Minirhizotrons were used to measure root growth. Yield of pointed cabbage per metre row was 28% higher under the IC system than under MC, whereas faba bean yield as fresh seeds did not differ. The land equivalent ratio was 1.06, showing that improved yield under IC resulted from efficient land resource use. Even though MC cabbage had the highest aboveground biomass, total N accumulation was higher under IC and MC faba bean systems. Both root frequency and intensity were greater under IC faba bean rows compared with MC faba bean because of the presence of cabbage roots in faba bean rows. Monocropped cabbage had the highest root intensity and the lowest amount of soil mineral N in the 0–1.5 m depth after harvest. Monocropped cabbage was efficient in assimilating N, whereas MC faba bean was efficient in exporting N as harvestable yield. The nitrogen use efficiency using the IC system (75%) was higher than growing faba bean (44%) and cabbage (65%) alone. Thus, faba bean as an intercrop in organic cabbage production systems improves land and N use efficiency by complementary root growth.

KEYWORDS

land equivalent ratio, nitrogen use efficiency, pointed cabbage, root growth, soil mineral nitrogen

1 | INTRODUCTION

Vegetable production systems require high amounts of nitrogen (N). Excess fertilizer application and poor timing of mineral N availability relative to crop N demand may result in leaching of nitrate and reduction in N use efficiency (NUE). Leached N is lost to the environment after leaving the rooting zone, posing serious threats to groundwater quality (Tei et al., 2020). Intercropping, that is, cultivating two crop species simultaneously, has the potential to reduce nitrate leaching and increase NUE by improving N utilization and increasing root exploitation of N (Xie & Kristensen, 2017; Zhang et al., 2016). However, to avoid yield reductions because of interspecific competition for N, crops chosen for intercropping should be species that are unlikely to compete with one another for N, that is, use resources in complementary ways. Legumes such as faba bean (*Vicia faba* L.) are effective in intercropping systems because they are less competitive for soil mineral N because of their ability to fix atmospheric N. The ability to fix N results in higher yields and improved NUEs (Bedoussac et al., 2015). Tang et al. (2018) observed more efficient N utilization and lower N loss using garlic (*Allium sativum* L.) and faba bean grown for grain yield in intercropping systems than when either species was cultivated alone. Furthermore, when faba bean was intercropped with wheat (*Triticum aestivum* L.), growth and grain yield of wheat increased 19%–28% and 20%–28%, respectively, relative to wheat monocrop (Xiao et al., 2018).

The use of faba bean as a protein source for humans has gained interest worldwide, especially in temperate regions and in a variety of products (Köpke & Nemecek, 2010), which is a further incentive for growing faba bean as an intercrop harvested for fresh pods in organic production. Fresh faba bean pods are a new vegetable crop in the Nordic region, and knowledge is limited of its horticultural potential (Lepse et al., 2017).

Only a few studies have provided data from intercropping vegetable crops. For example, Santos et al. (2002) found that broccoli (*Brassica oleracea* L. var. *italica*) intercropped with beans (*Phaseolus vulgaris* L.) or potato (*Solanum tuberosum* L.) in additive designs provided a higher yield than any of those crops grown alone, with a land equivalent ratio (LER) of 1.34 and 1.27, respectively. The LER is the relative area of land required by solely grown crops (monocrops) to produce the same yield as a given intercrop combination. Thus, LER is used to compare the productivity and feasibility of an intercropping system over a monocropping system. Similarly, intercropping cabbage (*Brassica oleracea* L. var. *capitata*) with romaine or cos lettuce (*Lactuca sativa* L. var. *longifoila*), leaf lettuce (*L. sativa* L. var. *crispa*), onion (*Allium cepa* L.) and snap bean (*Phaseolus vulgarism* L. var. *nanus*) improves yield and profitability (Guvenc & Yildirim, 2006). Most studies of vegetable intercropping systems have focused on yield and profitability, not on N dynamics or root growth.

Roots play an important role in determining the NUE of cultivated crops, with differences among crop species in rooting patterns and relative capacities to deplete soil mineral N (Kristensen & Thorup-Kristensen, 2007). For example, intercropping shallow-rooted leek (*Allium porrum* L.) with deep-rooted dyer's woad (*Isatis tinctoria* L.) results in better root exploitation and reduced nitrate leaching in deep soil layers compared to monocropped leek without affecting the marketable yield of leeks (Xie et al., 2017). Similarly, when cauliflower (*Brassica oleracea* L. var. *botrytis*) was intercropped with an overwintering grass-clover, nitrate leaching was lower than when cauliflower was grown alone and required fertilizer use was 50 kg N ha^{-1} less (Xie & Kristensen, 2016). However, the above-mentioned studies focussed on intercropping vegetable species with a catch crop, grown with the sole purpose of increasing the NUE of the production system, not on intercropping two vegetables. Therefore, the main objective of this study was to evaluate intercropping as a strategy for improving NUE in an organic production system of two vegetables by understanding the role of rooting patterns, competition for resources and uptake of soil mineral N in driving productivity and NUE. In our experiment, we intercropped faba bean grown as a vegetable crop and pointed cabbage to quantify root growth, plant and soil mineral N concentrations, and yield parameters relative to their respective monocrop (MC) and intercrop (IC) systems.

We hypothesized that intercropping faba bean with pointed cabbage will result in more efficient use of N in both species than would occur in the respective monocrop systems because: (1) intercropping improves the LER of the IC system (LER > 1) as faba bean is less competitive than cabbage for mineral N, (2) intercropping increases NUE because of complementary N use, and (3) intercropping increases root intensity and root depth compared with monocropped faba bean.

2 | MATERIALS AND METHODS

2.1 | Field site and experimental design

A field experiment was conducted at Aarhus University, Årslev Research Centre, Denmark (10°27’E, 55°18’N) from April to August 2018. The average temperature was 15.8°C, and cumulative precipitation was 207 mm during the experimental period. Cumulative rainfall from May to July 2018 was lower than the prior four-year average

(Figure 1). Soil type was a sandy loam (Typic Agrudalf) with a pH of 6.8. The extractable nutrients in the top soil layer (0–0.25 m) were 30 mg P_2O_5 (P extracted with 0.5 M $NaHCO_3$, Olsen P method), 155 mg K_2O (K extracted with 0.5 M CH_3COONH_4 and 3 mM LiCl, flame photometry [768 nm]) and 52 mg Mg (Mg extracted with 0.5 M CH_3COONH_4 and 3 mM LiCl, atomic absorption spectroscopy [285 nm]) per kilogram dry soil. The soil texture was 12.8% clay, 15.3% silt, 70% sand and 1.9% organic matter in the 0–0.25 m soil layer, 14.9% clay, 14.8% silt, 69.3% sand and 1% organic matter in the 0.25–0.5 m soil layer, 18.5% clay, 13.2% silt, 67.9% sand and 0.4% organic matter in the 0.5–1.0 m soil layer and 18.1% clay, 14.6% silt, 67.1% sand and 0.2% organic matter in the 1.0–2.5 m soil layer. The experimental field had been farmed organically since 2013, following Danish regulations without any chemical pesticides or inorganic fertilizers.

Faba bean (cultivar Hangdown grunkernig) and pointed cabbage (cultivar Caraflex) were both grown as individual monocrops (MC) and together as intercrops (IC). In the IC system, both crops were sown/planted in alternating rows following a replacement design, such that plant population density for each species in the IC crop was half of that of the population density in its MC counterpart (Schröder & Köpke, 2012). Our experimental layout was a complete randomized block design with four replicates. The size of each experimental plot was 4.8 × 10 m, comprising nine crop rows with 0.5 m spacing between rows. The seedbed was prepared with a cultivator and bed former, working the soil to 0.2 m depth.

Spring barley (*Hordeum vulgare* L.), with an undersown grass-clover mixture, had been previously grown in the field and was incorporated into the soil at the end of November 2017. Faba bean was sown in the field on 17 May 2018 with a 0.1-m interplant distance. Pointed cabbage was transplanted into the field on 29 May, with an interplant distance of 0.35 m. Fertilizer N was aimed to be applied to the field at the national recommended quantity for each species and crop system (MC cabbage: 180 kg N ha^{-1}, MC faba bean: 50 kg N ha^{-1}, IC: 115 kg N ha^{-1}) using fast releasing fertilizers, comprised of red clover silage from on-farm production and commercially available crushed lupine seeds, and a slow releasing compost made from waste from gardens and parks. The potential N mineralization from soil during crop growth was estimated to be 88 kg N ha^{-1} (Hart et al.,1994), and fertilizer application was corrected for this amount as N input. For MC cabbage plots, fertilizer was provided via silage at a rate of 60.5 kg N ha^{-1}. For IC plots, silage was applied at a rate of 6 kg N ha^{-1}. Compost was applied at a rate of 12 kg N ha^{-1} in all plots and was the only fertilizer for MC faba bean plots. A second dose of fertilizer using crushed lupine seeds was applied for MC cabbage (11 kg N ha^{-1}) and IC cabbage (1 kg N ha^{-1}). Silage and compost were applied on 9 May and lupine seeds on 14 June. Potential N mineralization (88 kg N ha^{-1}) combined with the compost application (12 kg N ha^{-1}) exceeded our fertilizer target (50 kg N ha^{-1}) in the faba bean MC, resulting in a total amount of plant available N of 100 kg N ha^{-1} for the growing period. All plots were weeded on 14 and 27 June. Pointed cabbage was hand harvested on 26 July, and faba bean pods were hand harvested six times during the period 31 July–16 August.

2.2 | Soil and plant sampling

Soil samples were taken from each plot after harvest (27–29 August) using a machine-driven soil piston auger with a 14-mm inner diameter. Twelve soil samples were obtained from five depth intervals from each plot (at 0–0.25, 0.25–0.5, 0.5–1, 1–1.5 and 1.5–2.5 m), which were then combined into one composite soil sample per depth interval per plot. All soil samples were frozen at −18°C until later laboratory analyses. Before each analysis, the soil samples were thawed and 100 g of soil (fresh weight) was extracted with 1 M KCl for one hour (one part soil: two parts solution). The extractant was centrifuged, and the supernatant solution was then analysed for NH_4^+-N and NO_3^--N content with standard colorimetric methods

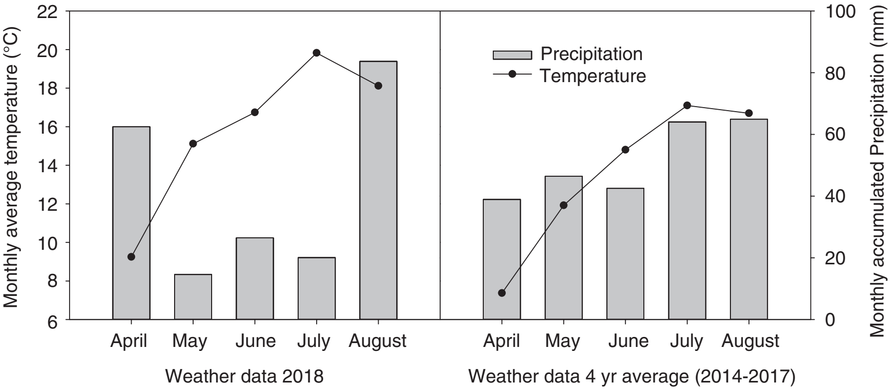


FIGURE 1 Monthly average temperature and cumulative precipitation for 2018 and a four-year average (2014–2017)

using an AutoAnalyzer 3 (Bran +Luebbe). Aboveground plant parts were hand harvested from two 6-m-long rows from each plot avoiding border rows, and the yields (fresh weight) and total aboveground biomass (dry weight) were calculated. Marketable yield was assessed based on market standards, such as product size and incidence of pest and disease damage (e.g., pointed cabbage heads >350 g head^{-1}). Faba bean yield was reported as the fresh weight of seeds after removal from pods if not specified and as fresh weight of pods, specified as such. For the dry matter determination of cabbage heads, faba bean pods, seeds and residues, plant parts were chopped, mixed, weighed and oven-dried at 80°C for 20 h and weighed again. The dried plant materials were then combusted at 900°C, and N content was determined based on molecular N by TruSpec CN analysis (LECO) using the VDLUFA method (VDLUFA, 1991).

2.3 | Root measurements

Root growth was measured with minirhizotrons, which are 3-m-long transparent plastic tubes. These tubes were inserted into the soil at an angle of 30° to a depth of 2.4 m shortly after sowing/transplanting. Two plastic tubes per plot were inserted in the rows of three replicate plots. In the IC plots, one tube was installed in the pointed cabbage row and another in the adjacent faba bean row. Following Kristensen and Thorup-Kristensen (2004), the roots were filmed inside out from the tube three times (29 June, 23 July and 21 August) at the tube's upper surface with a mini video camera set at a resolution of 800 × 600 pixels. Prior to insertion of the tubes into the soil, two counting grids were inscribed (40 × 40 mm in size) on the upper sides of the tubes. Observations from these grids were used to record the root frequency (presence or absence of roots in the observation grid), modified root intensity (root intensity$_{\text{mod}}$: number of roots crossing each counting grid) and root depth (deepest root observed in the observation grids) according to Hefner et al. (2019). In the tubes of intercropping plots, roots were distinguished between faba bean and cabbage in order to study the effects of intercropping on root growth. Roots of faba bean and cabbage are to some degree visually distinguishable in intercropped rows based on differences in root morphological characters (i.e., faba bean roots are thicker, lighter in colour and have less dense lateral roots than cabbage roots).

2.4 | Calculations and statistical analyses

Land equivalent ratio was calculated following Mead and Willey (1980), wherein:

$$\text{LER} = \frac{\text{cabbage yield (IC)}}{\text{cabbage yield(MC)}} + \frac{\text{faba bean yield (IC)}}{\text{faba bean yield (MC)}}. \quad (1)$$

The total yield (fresh weight) was used for the calculation. A LER > 1 indicates that the IC system is more productive than MC for the same unit of land, whereas LER < 1 indicates a non-profitable intercropping system supporting a high level of interspecific competition. A LER for aboveground N accumulation (LER-N) was also calculated, following Willey (1979), wherein yield was replaced with plant N accumulation in the above formula.

Nitrogen accumulation in the whole plant at time of harvest was calculated from the N content in plant parts, their dry matter content and their aboveground plant biomass. Nitrogen balance was calculated as N input (fertilizer N + N fixation) – N output (harvestable product). Potential soil N mineralization was not included as N input. Biological N fixation was estimated according to the methods of Anglade et al. (2015), based on a linear relationship between N yield and biological N fixation as follows:

$$\left[\alpha_{\text{cult}} \times (\text{Y}/\text{NHI}) + \beta_{\text{cult}}\right] \times \text{BGN}.$$

The α_{cult} and β_{cult} are the slope and intercept coefficients determined by regression analysis, Y is the N in harvested yield (kg N ha^{-1} year^{-1}), NHI is the N harvest index, and BGN is a multiplicative factor (1.3) to take into account the belowground contributions. Nitrogen output was the amount of N accumulated in the harvestable portion of the crops, such as cabbage heads and faba bean pods with the unharvested portions left in the field after harvest. The NUE was calculated as the percentage of N output per N input (OECD, 2001, 2008).

The N uptake efficiency (NUpE) was calculated as the ratio between accumulated N in plants and total available N (soil mineral N at harvest +N accumulated in plants). The N utilization efficiency (NUtE) was calculated as the total amount of N in the harvested crop relative to the total amount of N accumulated by the plants (harvestable products + residues) (Xu et al., 2012). To compare the yield between MC and IC systems, crop yield per metre of cultivated row was calculated. Root depth penetration rate (mm day^{-1} °C^{-1}) was assessed as the slope of a simple linear regression model of average root depth against cumulative daily temperature from the time of sowing/planting to time of harvest (Barraclough & Leigh, 1984).

The yield, marketable yield, total aboveground biomass, soil mineral N, plant N accumulation, LER, NUE, NUpE, NUtE and N balance were modelled using generalized linear mixed models (GLMM) (Jørgensen & Labouriau, 2012) defined with the Gamma distribution and a Gaussian random component representing the blocks. The models for total aboveground biomass, N accumulation, soil mineral N and N balance used an identity link function, while the models for the other quantities used a logarithmic link function, allowing to infer ratios by defining suitable contrasts. The comparisons between faba bean fresh pods under different cropping systems and the N dynamics were made using Kruskal–Wallis tests.

The characterization of the rooting system made with the minirhizotrons followed the methodology described in Hefner et al. (2019) and Pelck and Labouriau (2020), according to which two characteristics were modelled: the root frequency, measuring the scatter of the rooting system and the root intensity$_{\mathrm{mod}}$, characterizing the local intensity of the root colonization in the field. We used a GLMM defined with the binomial distribution and the logistic link function for modelling the rooting frequency. In the case that root frequency values reached 100%, a comparison to other treatments was not possible, which was the case for MC cabbage in 0.25–1 m depth in August. The root intensity$_{\mathrm{mod}}$ was inferred using a GLMM defined with the Poisson distribution, the logarithmic link function and an offset with the logarithm of the number of observed windows. Both models contained a Gaussian random component representing the combination of the minirhizotron tubes and the soil depth zones and a fixed effect representing the combination of soil depth, observation time and crop system. The root intensity$_{\mathrm{mod}}$, calculated in this way, expresses the mean number of roots crossing reference lines per observational windows in the minirhizotron tubes, which is a quantity that is proportional to the mean length of the roots visible in the observational windows (Pelck & Labouriau, 2020).

All statistical analyses were performed using the software R version 3.6.3 (R Core Team, 2020); post hoc analyses and contrast-related calculations were done using the R package post hoc (Labouriau, 2020). All the models were validated by residual analyses and tests of goodness of fit. Different lowercase letters in figures and tables indicate significant differences between treatments ($p < .05$).

3 | RESULTS

3.1 | Crop yield and N accumulation

Total and marketable yields (Mg ha^{-1}) of pointed cabbage and faba bean were significantly higher under MC systems than the IC system, which possessed only 50% of the plant population density for each species of the MC systems (Table 1). Calculating yield per metre row, total cabbage yield and marketable yield were 28% and 26% higher in the IC system than in the MC system. In contrast, faba bean total and marketable seed yield per metre row did not differ significantly between the IC and MC systems even though there was an indication of reduced yield

TABLE 1 Total and marketable yield (fresh weight) of cabbage and faba bean in mono (MC) and intercropping (IC) systems

	Total yield		**Marketable yield**	
Cropping system	**Mg ha^{-1}**	**Kg m^{-1} row**	**Mg ha^{-1}**	**Kg m^{-1} row**
Cabbage heads				
Cabbage MC	30.9 (26.1–36.5)^{b}	1.62 (1.37–1.92)^{a}	18.9 (16.0–22.4)^{b}	0.99 (0.84–1.17)^{a}
Cabbage IC	18.9 (15.9–22.3)^{a}	2.07 (1.75–2.45)^{b}	12.1 (10.2–14.3)^{a}	1.33 (1.13–1.58)^{b}
P-value	<.001	.005	<.001	<.001
Faba bean (fresh seeds)				
Faba bean MC	5.37 (4.54–6.36) ^{b}	0.28 (0.24–0.33)^{a}	5.06 (4.27–5.98)^{b}	0.27 (0.22–0.31)^{a}
Faba bean IC	2.40 (2.03–2.84) ^{a}	0.24 (0.20–0.28)^{a}	2.25 (1.90–2.66)^{a}	0.23 (0.19–0.27)^{a}
P-value	<.001	.066	<.001	.063
Faba bean (pods)				
Faba bean MC	18.6 (16.6–18.7) ^{b}	0.97 (0.87–1.00)^{b}	18.3 (16.4–18.7)^{b}	0.96 (0.86–0.98)^{b}
Faba bean IC	8.26 (7.46–8.54) ^{a}	0.83 (0.75–0.85)^{a}	8.11 (7.32–8.40)^{a}	0.76 (0.72–0.83)^{a}
P-value	.021	.021	.021	.021

Note: Estimates are given with 95% confidence intervals in parenthesis ($n = 4$). Lowercase letters indicate significant differences among cropping systems.

under IC ($p < .07$). However, fresh faba bean pod yield per metre row was 20% lower under IC than MC (Table 1). The ratio between marketable and total yield did not differ (results not shown). The LER for IC was 1.06 based on partial LERs of 0.61 and 0.45 for cabbage and faba bean, respectively (results not shown). This indicated that intercropping enhanced the productivity of the system.

Total aboveground biomass in the IC system was higher than in the MC faba bean system but was lower than in the MC cabbage system (Figure 2a). We found that N accumulation in aboveground biomass was higher in IC than in MC cabbage, but N accumulation of MC faba bean did not differ from IC and MC cabbage (Figure 2b). The proportion of N accumulated in the harvested yield was higher in MC faba bean (47%) than in IC (39%) and MC cabbage (32%). The LER-N was 1.11.

3.2 | Root growth

The roots of cabbage grew significantly deeper in June (0.6 m) and August (1.5 m) than did faba bean roots (0.2 and 0.6 m, respectively) (results not shown). By August, IC had grown deeper roots (1.3 m average root depth of IC-grown cabbage and faba bean) than the MC faba bean, but root depth did not differ significantly between cropping systems during early growth stages. Mean root depth penetration rates were 0.31 (95% confidence interval 0.09–0.71) mm day^{-1} °C^{-1} for MC faba bean ($R^2 = .23$) and 0.89 (95% confidence interval 0.48–1.30) mm day^{-1} °C^{-1} for MC cabbage ($R^2 = .76$) from sowing/planting to harvest (no base temperature). For MC faba bean, the penetration rate estimated for each of the periods June, July and August was 0.03 (95% confidence interval 0.00–0.06) mm day^{-1} °C^{-1}, 0.33 (95% confidence interval 0.04–0.63) mm day^{-1} °C^{-1} and 0.01 (95% confidence interval 0.30–0.32) mm day^{-1} °C^{-1}, respectively. The observed absence of growth of the roots in August explains the lack of fit of the linear regression used for determining the penetration rates of MC faba bean.

In general, faba bean had a lower root intensity$_{\text{mod}}$ and shallower root growth, reaching less than 1 m deep at harvest, than cabbage, which had a dense root system with roots growing to 1.75 m depth (Figure 3). Root frequency and intensity$_{\text{mod}}$ of MC faba bean were lower than MC cabbage in all soil layers, except in the top 0.25 m soil layer in June, July and August. However, when faba bean was grown in the IC system, the root frequency was increased compared with MC faba bean in the 0.25–0.5 m soil layer in June and July and in the 0.75–1 m soil layer in August. Similarly, the root intensity$_{\text{mod}}$ of MC cabbage was higher than of MC faba bean in all soil layers, except the 0–0.25 m soil layer, at all three sampling times and the 0.5–0.75 m soil layer in June (Figure 3). The roots of MC faba bean were only found in the 0–1 m soil layer, whereas roots were found in 1.75 m depth under IC-grown faba bean rows. The root frequency of intercropped cabbage was lower than MC cabbage in the 1–1.5 m soil layer in August. Similarly, the root intensity$_{\text{mod}}$ of IC-grown cabbage was lower than of MC cabbage in the 0.5–0.75 m soil layer in June and in the 1.25–1.5 m soil layer in August (Figure 3).

3.3 | Soil Mineral N

At harvest, MC faba bean had retained more mineral N in the soil at 0.25–1.5 m depth than MC cabbage and IC. Similarly, soil mineral N content was higher in the 0–0.25 m soil layer in MC faba bean than in MC cabbage (Figure 4). At the 1–1.5 m soil layer, mineral N content differed significantly among all three cropping systems, with highest N values in soils of MC faba bean, followed by N in soils of IC and MC cabbage. Soil mineral N content did not differ among cropping systems in the deepest soil layer (1.5–2.5 m depth) (Figure 4).

3.4 | Nitrogen dynamics

The N balance (input minus output) was positive for all three cropping systems, meaning that N was either retained in or lost from the production systems. The highest N retention was found in MC faba bean and the lowest in IC (Table 2). The NUE was highest in the IC system, followed by the MC cabbage system and then by the MC faba bean system. The NUpE was higher in IC and MC cabbage systems than in the MC faba bean system, and NUtE was highest in the MC faba bean system, followed sequentially by the IC and MC cabbage systems (Table 2).

4 | DISCUSSION

4.1 | Productivity and competition

Harvesting immature faba beans for fresh consumption is new in Denmark. Faba bean pod yield of 18.6 Mg ha^{-1} (Table 1) is higher than yields measured in other locations, for example Italy and Central Chile, which ranged from 7.6 to 17.9 Mg ha^{-1} depending on the genotypes and growing environment such as temperature and radiation (Baginsky et al., 2013; De Cillis et al., 2019). The higher productivity of faba beans in our trial could be related to the warm summer in Denmark in 2018 (Figure 1). Even though faba bean pod yield was lower in the IC system, the fact that the LER

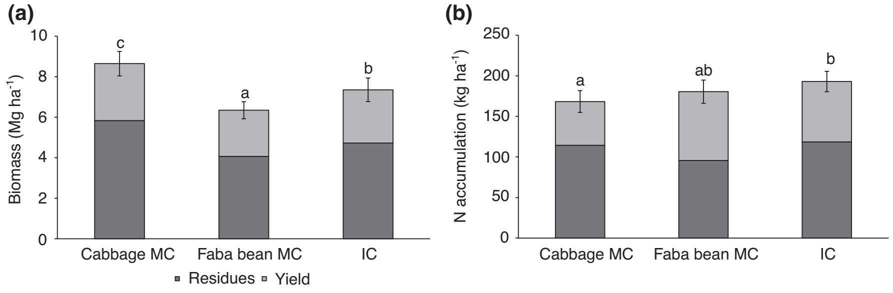
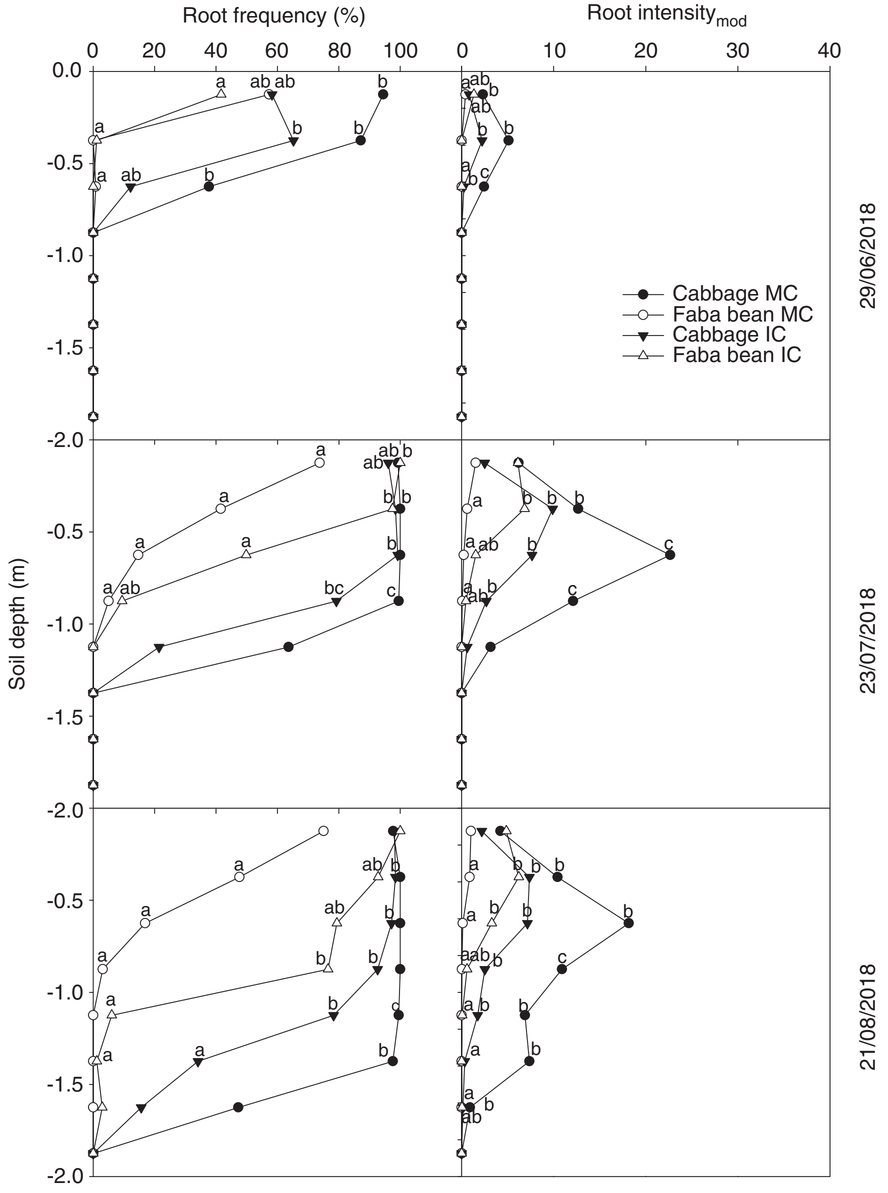


FIGURE 2 (a) Biomass (dry weight) and (b) nitrogen accumulation in the total aboveground biomass (harvestable products and residues) at harvest for cabbage and faba bean in mono (MC) and intercropping (IC) systems. Lowercase letters indicate significant differences at 5% level of significance among treatments. Bars show 95% confidence intervals ($n = 4$)

FIGURE 3 Root frequency and intensity$_{\mathrm{mod}}$ in minirhizotrons placed in rows of cabbage and faba bean in mono (MC) and intercropping (IC) systems at 0.25 m soil layers in 0–2 m depth. The lowercase letters indicate significant differences among cropping systems at a 5% level of significance ($n = 3$). Estimates and confidence intervals are provided in supporting information (Table S1)



was 1.06 confirmed our first hypothesis that the LER would be improved when intercropping pointed cabbage and faba bean. When Jeromela et al. (2017) studied brassica-legume intercropping systems, they found LER values ranging from 1.02 to 1.25 when sown in the spring, depending on the species employed. Altogether, IC studies provide a compelling reason to explore brassica-legume IC combinations because such systems have the potential to use less land area to

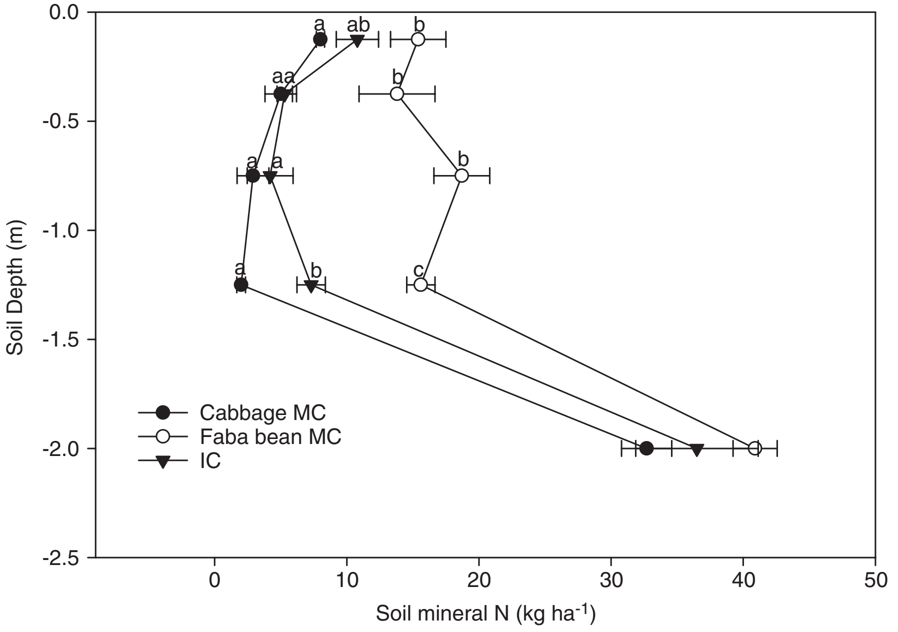


FIGURE 4 Soil mineral nitrogen in layers in the 0–2.5 m soil depth for cabbage and faba bean in mono (MC) and intercropping (IC) systems at time of harvest. The letters indicate significant differences among cropping systems at a 5% level of significance (n = 4). Estimates and confidence intervals are provided in supporting information (Table S2)

TABLE 2 Estimated nitrogen (N) fixation, N balance, N use efficiency (NUE), N uptake efficiency (NUpE) and N utilization efficiency (NUtE) of cabbage and faba bean in mono (MC) and intercropping (IC) systems

Cropping system	Estimated N fixation (kg N ha^{-1})[†]	N balance (kg N ha^{-1})[‡]	NUE (%)[‡]	NUpE (%)[‡]	NUtE (%)[‡]
Cabbage MC	–	29 (27–32)^{a}	65 (62–68)^{b}	78 (76–86)^{b}	32 (31–34)^{a}
Faba bean MC	177	105 (96–109)^{b}	44 (42–49)^{a}	63 (58–69)^{a}	48 (42–50)^{c}
IC	82	25 (23–31)^{a}	75 (69–77)^{c}	76 (70–80)^{b}	38 (37–42)^{b}
P-value		.015	.007	.0210	.007

Nitrogen balance was calculated as N input (fertilizer N + N fixation) – N output (harvestable product) and NUE was calculated as N output/N input. N uptake efficiency (NUpE) was calculated as accumulated N in plants/total available N (soil mineral N at harvest +N accumulated in plants). N utilization efficiency (NUtE) was calculated as N in the harvested crop/accumulated N in plants. Details are given in the Materials and Methods section.

†Estimated N fixation is calculated based on Anglade et al. (2015).

‡Estimates (n = 4) are given with 95% confidence intervals in parenthesis. The lowercase letters indicate significant differences among cropping systems at 5% significance level.

produce the same yield provided by MC systems. An additional benefit of using an IC system for faba bean is that the seeds are protein-rich and represent a low-cost protein source of plant origin, a source gaining increasing interest for sustainable food production (Köpke & Nemecek, 2010; Lybæk & Hauggaard-Nielsen, 2019).

Increased cabbage productivity under the IC system in our study shows the competing ability of cabbage compared with faba bean. When intercropping two species, the dominant species can increase its yield and nutrient uptake (Zhang & Li, 2003), whereas the other crop's yield is reduced because of interspecific competition for nutrients. Other studies have shown that faba bean is less competitive when intercropped with brassica species, such as mustard (Schröder & Köpke, 2012) and cabbage (Lepse et al., 2017), which also results in increased yields of its companion crops.

Brassica species have a high N requirement, and therefore, N uptake in brassicas is considerable. Nitrogen accumulation of pointed cabbage was 168 kg ha^{-1} in our study, but white cabbage can assimilate about 400 kg ha^{-1} during a growing season (Everaarts & Booi, 2000). Pairing legumes with a non-legume increases the IC system's N availability because of the legume's ability to fix atmospheric N, which is then transferred to the companion (non-legume) crop. The companion crop takes up N contained in legume root exudates or N released through decomposition of nodules and small roots (Tang et al., 2018). This N transfer occurs when growing cereals and grain legumes together, as well when growing garlic with faba bean (Tang et al., 2018; Thilakarathna et al., 2016) or growing brassica with a legume under greenhouse conditions (Cortés-Mora et al., 2010). Our results confirm that higher N availability contributed to a higher competitiveness and productivity for cabbage.

4.2 | Root growth and soil N dynamics

Monocropped faba bean had shallow roots, whereas root depth exploration increased under intercropped faba bean rows because of the presence of cabbage roots from the neighbouring rows. In general, faba bean grown as a grain crop has a rooting depth ranging from 0.9 to 1 m (Ehlers et al., 1991; Li et al., 2006). However, in our study, faba bean exhibited a shallower rooting depth (0.6 m), possibly, because when grown as a vegetable crop, faba bean has a shorter growing season than when grown to maturity for seed yield. We reported for the first time (to our knowledge) a root depth penetration rate for faba bean. This was 0.31 mm $\text{day}^{-1}\ {}^{\circ}\text{C}^{-1}$, which was in the range of rates reported for other legumes. Root systems tend to be shallower under drought conditions, in order to best utilize nutrients and soil moisture, and roots may only grow deeper when water is available in deeper soil layers (Manschadi et al., 1998). The low rainfall in May (which required us to irrigate the field) may have limited deeper root growth of faba bean. Even though other studies have found that faba bean roots continue to grow until the pod filling stage (Brown et al., 1989; Manschadi et al., 1998), we found that faba bean roots did not grow much after July. The low determination coefficient of 0.23 for the root depth penetration rate confirms that depth penetration levelled off in July (results not shown). Faba bean root $\text{intensity}_{\text{mod}}$ and frequency were highest in the top soil layer, confirming Manschadi et al. (1998) who found that 60% of the faba bean roots were confined to the top 0.15 m soil layer even at the pod filling stage.

Both root frequency and the root $\text{intensity}_{\text{mod}}$ were 5–28 times higher in soils of faba bean when grown under the IC system than MC faba bean, which was due to the occurrence of cabbage roots extending into the intercropped faba bean row. Based on the visually distinguishable characters in root morphology, we found that cabbage roots started to show up at a depth of 0.15 m and were present to the bottom of the rooted zone in faba bean rows (results not shown). Similar observations have been made with roots of neighbouring crops when faba bean is intercropped under field conditions with safflower (*Carthamus tinctorius* L.), white mustard (*Sinapis alba* L.) (Schröder & Köpke, 2012) and maize (Li et al., 2006). Thus, our findings confirm our third hypothesis that root intensity was higher under IC compared with MC faba bean.

Root $\text{intensity}_{\text{mod}}$ was higher in MC cabbage than in MC faba bean from the early growth stages. However, cabbage root $\text{intensity}_{\text{mod}}$ was lower in the IC system than in the MC cabbage system, possibly as a result of higher N availability under IC because of less N uptake by faba bean or because of N transfer from faba bean to cabbage. Furthermore, the increase in cabbage yield we found in the IC system could be due to a greater soil volume exploited by cabbage roots in response to low interspecific competition by faba bean. That is, less interspecific competition could have resulted in a shallower and a less ramified root system under IC cultivation than under MC cultivation. Similarly, Cortés-Mora et al. (2010) found that root ramification of rapeseed is reduced in all soil layers when grown with faba bean under greenhouse conditions, because of the additional N source that is available for rapeseed grown adjacent to legumes. In conclusion, reduced root intensity and increased yield of cabbage under IC conditions indicate complementary resource utilization in the IC system.

Our study confirmed that faba bean, having a shallow root system, was inefficient in assimilating deep soil mineral N, posing a higher risk for nitrate leaching after harvest. The high soil mineral N under IC in 1.0–1.5 m depth compared with MC cabbage could be due to the additional soil mineral N available for cabbage under faba bean rows. The lower N competition under IC can be explained by a complementary niche separation on resource utilization among the intercrops with root traits playing a major role. Roots did not grow deeper than 1.5 m in any of our cropping systems, possibly explaining the high soil mineral N content in the deepest soil layers we measured (1.5–2.5 m). Crops with deep roots and a capacity for root proliferation from an early growth stage (e.g., cabbage) tend to be effective in reducing the risk of nitrate leaching (Dunbabin et al., 2003). In our study, the low mineral N content left by MC cabbage was notable considering the higher N fertilizer application of this system.

4.3 | Complementary resource use and N use efficiency

Intercropping improved NUE relative to the MC systems and N balance compared with MC faba bean because the cabbage-faba bean combination improved N uptake and utilization efficiencies. The improved NUE of the IC system was due to the combined effects of leaving less residual soil N than MC faba bean and a more efficient accumulation of N in the aboveground biomass than in MC cabbage. Improved N uptake and accumulation capacity under IC was further supported by the positive LER-N value. This result corresponds with Schröder and Köpke (2012), who found that LER-N was positive when faba bean was intercropped with oil crops (e.g., safflower and mustard), irrespective of soil type. As discussed earlier, complementary resource use and root interactions could have improved the N availability and uptake we found in the IC system, despite that the estimated N fixation by the faba bean was less in this system. However, the lower soil mineral N content and the intercropping (Nyfeler et al., 2011) may have stimulated N fixation by the faba bean in the IC system above the level reported in the estimated N fixation. Root interactions can play an important role in facilitation or competition of the intercrop for nutrients (Zhang et al., 2016; Zhang & Li, 2003). Thus, complementary resource utilization under IC resulted in improved N accumulation, confirming our second hypothesis.

Although N accumulation and NUpE are important for determining NUE in cultivated fields, the proportion of N stored in harvestable products (NUtE) also plays a major role in determining the overall NUE of a system (Xu et al., 2012). The NUtE indicates how much N is exported out of the field as harvest products. We attribute the highest NUtE values for MC faba bean in our study to the high N concentration in faba bean seeds (4.8%) compared with the low N concentration in cabbage heads (1.9%) (results not shown). Despite faba bean capacity to store high N concentrations in its seeds, we found that the lowest NUpE resulted in the lowest NUE and the highest amount of excess N in the MC faba beans, which increased the risk of N leaching as discussed earlier.

Unlike MC faba bean, we found that MC cabbage had an efficient N depleting capacity. However, the N stored in cabbage heads was less than in faba bean seeds, resulting in a significant proportion of accumulated N in crop residues left in the field after harvest. About 63% of this residual N will likely be mineralized over winter and potentially lost via leaching to groundwater (Katroschan et al., 2014). However, N released from crop residues can be utilized by growing winter cover crops, which could reduce N leaching (Tei et al., 2020). Although we found that while the N balance of MC cabbage was similar to the N balance of the IC system, NUE was lower in the MC cabbage than in the IC system. An explanation could be the lower proportion of N stored in the harvestable product of MC cabbage than in the IC system. In our study, IC improved NUE relative to the MC systems because the cabbage–faba bean combination improved N assimilation and utilization efficiencies.

5 | CONCLUSION

The LER of 1.06 shows a good application potential of intercropping faba bean as a vegetable with cabbage, as it indicates a modest yield advantage compared with the respective MC systems. Monocropped faba bean had higher risk for nitrate leaching because of its shallow root growth and reduced N uptake in the deep soil layers. Intercropping increased root intensity in the faba bean rows and decreased it in the cabbage rows owing to the cabbage roots exploring the soil under faba bean rows. Although MC cabbage was more efficient in assimilating N, MC faba bean was better at storing N in the harvestable products. Intercropping cabbage and faba bean were N efficient because of the complementary resource use and added benefits of improved N utilization and N uptake, making this a promising production system. Still, these findings need to be validated under different climatic and agronomic conditions.

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DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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