Agronomy Research **20**(3), 603–616, 2022
https://doi.org/10.15159/AR.22.047

Wheat-Faba bean intercrops improve plant nutrition, yield, and availability of nitrogen (N) and phosphorus (P) in soil

G. Kaci[1,*], W. Ouaret[2] and B. Rahmoune[3]

[1]M'hamed Bougara University, Faculty of Sciences, Department of agronomy, DZ35000 Boumerdès, Algeria
[2]Miami University, Geospatioal Analysis Center, US-OH 45056 Ohio, USA
[3]High National School of Agronomy, Genetics Ressources and Biotechnology Laboratory, DZ16000 El Harrach, Algeria
[*]Correspondance: kaci.ghiles@gmail.com

Received: June 27th, 2022; Accepted: July 27th, 2022; Published: August 1st, 2022

Abstract. In order to promote agroecological practices, this study compares two cropping systems, i.e., intercropping versus sole cropping of a cereal - durum wheat (*Triticum durum Desf.*; and a nitrogen-fixing legume - faba bean (*Vicia faba L.*) on plant growth, Efficiency in the use of rhizobial symbiosis (EURS), grain yield and phosphorus (P) and nitrogen (N) accumulation in soil and plant. This study conducted during two cropping seasons in a field trial in the region of Tizi Ouzou, Algeria, shows that shoot dry weight (SDW), nitrogen nutrition index (NNI), phosphorus use efficiency (PUE), land use efficiency (LER), and grain yield were significantly higher for intercropped than for the sole cropped wheat. Furthermore, there was a considerable increase in soil P and N content across the two years of intercropping and sole cropping compared to the unseeded weeded fallow. Intercropping, it is claimed, improves wheat N nutrition by increasing the availability of soil-N for wheat. This increase might be due to reduced interspecific competition between legumes and wheat plants than intraspecific competition between wheat plants due to the legume's ability to compensate by atmospheric nitrogen fixation.

Key words: legume, cereal, eurs, yield, soil fertility.

INTRODUCTION

By 2050, the global human population will reach 9.8 billion people (Layek et al., 2018). As a result of this population expansion, new urban agglomerations and industrial infrastructures will develop, often encroaching on agricultural lands reducing the land available for cultivation and increasing greenhouse gas emissions that are harmful to the environment and human health. By consequence, food security has become a severe concern for most governments, particularly emerging countries.

Intensive agriculture can help achieve food security by increasing crop yields and meeting the requirements of the world's population. This agricultural intensification requires many chemical inputs, which causes environmental issues (Chen et al., 2019).

Wang et al. (2015) report that nitrogen fertilizers improve crop yields while the efficiency of rhizobial symbiosis (EURS) decreases, and the massive nitrogen remains in the soil profile. However, the N that remains in the soil can pollute groundwater through leaching and contaminate the air by promoting the volatilization of NO, N_2O, and NH_3 (Zhu & Chen, 2002).

Integrating legumes into cropping systems, either as intercrops or as relay crops, might be an alternative agronomic approach for better utilization of growth resources by utilizing their agroecological services (Scalise et al., 2015; Kaci et al., 2018; Chen et al., 2019).

Growing two or more crop species on the same farmland is known as intercropping (Willey, 1979). Intercropping systems, including legumes, can help the intercropped species by increasing the efficiency of soil resource utilization (particularly phosphate and nitrogen) and suppressing weeds, pests, and diseases (Peoples et al., 2018; Kherif et al., 2021).

Several authors have reported the benefits of cereal-vegetable intercropping on grain yield, nitrogen nutrition, Land Equivalent Ration (LER), and P uptake (Betencourt et al., 2012; Cong et al., 2015; Kaci et al., 2018; Tang et al., 2020; Kherif et al., 2021).

In a three-year experiment, Kaci et al. (2018) showed that intercropping wheat and faba bean boosts aboveground productivity, grain yield, and Nitrogen Nutrition Index (NNI) for intercropped wheat by improving the effectiveness of faba bean's rhizobial symbiosis (EURS). According to these authors, this rise might be attributable to reduced interspecific competition between legumes and wheat plants than intraspecific competition between wheat plants, thanks to the legume's adaptation by fixing atmospheric nitrogen.

Otherwise, phosphorus (P) is a nutrient that strongly limits plant growth in many soils (Raghothama, 1999; Hinsinger, 2001; Betencourt et al., 2012). For several decades, the extensive use of fertilizers has been the primary practice to overcome this limitation and maintain high-yielding agroecosystems. The mined phosphate rock used to produce P fertilizer remains a finite resource (Cordell et al., 2009; Dawson & Hilton, 2011; Betencourt et al., 2012). Therefore, increasing phosphate fertilizer use to improve agricultural production in increasing global food demand is no more a suitable alternative (Vance, 2001; Hinsinger et al., 2011; Betencourt et al., 2012). New techniques are needed to better exploit soil P resources through efficient cultivar selection or alternative agroecosystem management strategies to optimize P bioavailability (Vance, 2001; Lambers et al., 2006; Betencourt et al., 2012; Tang et al., 2020).

In this context, cereal/legume intercropping benefits on P acquisition have been reported (Betencourt et al., 2012; Tang et al., 2016; Tang et al., 2020). These benefits may be due to belowground complementarity or facilitation effects (Li et al., 2014). Complementarity is defined as less competition for soil nutrients between two different species grown in the same area compared to their respective monoculture. Regarding complementarity, the amount of P available to plants is primarily affected by the geometry and volume of the rhizosphere. Thus, increasing root surface area in intercropping systems induces better soil exploration (Hinsinger et al., 2011). Moreover, Cahill et al. (2010) report that environmental stimuli perceived by plants generate a modification in their root distribution according to nutrient availability and competition with root systems of other species.

Finally, the cereal/legume intercrop could improve its P uptake capacity by depleting specific inorganic pools. Without mentioning the transfer of nutrients or the improvement of P availability by the action of one species, white lupin intercropped with wheat preferentially use either citric acid-leachable P or a water-leachable soil P pool (Cu et al., 2005), supporting Turner (2008) hypothesis regarding resource sharing for soil phosphorus. However, similar to other cereal-legume intercropping models, these finds suggest that this strict complementarity is difficult to disentangle from other changes in the rhizosphere induced by intercropping, such as soil pH or changes in the enzymatic activity involved in solubilizing inorganic P (Li et al., 2003 and 2007; Alkama et al., 2009). However, even if the limits of complementarity are not clear, a general partitioning process likely shortens the period of competitive relationships between plants (Vance, 2001).

As intensive agriculture directly causes global environmental changes, agroecology has emerged as one of several options for reducing agriculture's environmental effect, particularly in smallholder farming systems. Investigating agroecological principles is necessary to comprehend the multiple practices for developing this cropping system, hence lowering agriculture's negative environmental impact and augmenting its resiliency. To this end, our study investigates the influence of the wheat/faba bean intercropping system on symbiotic root nodulation, critical for enhancing soil's nutrient bioavailability. Moreover, we examined how this system affects rhizobial symbiosis activity for plant nitrogen nutrition and P use efficiency compared to the mono-cropping system in a smallholder agriculture context under Mediterranean climatic conditions.

MATERIAL AND METHODS

Experimental site

The field experiments were conducted over two growing seasons: 2019 and 2020. They were located in a farmer's plot in the province of Tizi Ouzou, 100 km east of Algiers, Algeria. The main sites of the experiments were located at 36°41'51.4 "N 4°04'58.6"E.

The region has irregular rainfall, with an annual mean of 733 mm and 660 mm respectively in 2019 and 2020. The driest month was June (with rainfall of about 1 mm) in 2019 and July (with rainfall of about 0 mm) in 2020, while the highest rainfall was in November 2019 and December 2020 with 220 mm and 179 mm, respectively. The warmest month was July over the two growing seasons with a mean of 30 °C and 37 °C respectively in 2019 and 2020, while the coldest month was January (mean of 6 °C and 7 °C respectively in 2019 and 2020).

Within the study plots, there were mainly Calcisols (IUSS Working Group, 2015), which are typical soils of the Mediterranean part of the Magreb (e.g. Baraket et al., 2021). The average texture of investigated soils was clay loam with 47% of silt, 29% of clay and 24% of sand. Regarding soil chemical properties, the topsoil was alkaline (pH 8.7), with 17 g kg^{-1} $CaCO^3$ and relatively low organic matter content (2.4%). The agricultural conditions at this experimental soil correspond to an N deficiency (total N: 1.2 g kg^{-1} and inorganic N ($N\text{-}NH_4^+ + NO_3^-$): 9 mg N kg^{-1}) and P sufficiency (total P: 289 mg kg^{-1} and P Olsen: 23.5 mg P kg^{-1}).

Cropping systems and plant growth conditions

The field experiment was carried out with one durum wheat cultivar (*Triticum durum Desf.* cv. Vitron) and one faba bean cultivar (*Vicia faba L.* cv. Diva). The experimental design was a randomized complete block design with four blocks (four replicates); each block was divided into four sub-plots. Each subplot was composed of the following cropping systems: (1) durum wheat-faba bean intercropping system; (2) durum wheat sole cropping system; (3) faba bean sole cropping system; (4) unseeded weeded fallow surface. Over the two growing seasons, the experiments covered an area of 1,000 m^2, each sub-plot being 6 m × 10 m. According to the current farming practice, the seeding density was 350 plants per m^2 for durum wheat as a sole crop, 60 plants per m^2 for faba bean as a sole crop, 175 plants for durum wheat, and 30 per m^2 for faba bean as intercrops. Both species were sown in the same row for the intercropping system to maximize root proximity and rhizospheric interactions between durum wheat and faba bean. Before crop planting, the first 20 cm of soil were mechanically plowed using a rotary spading machine, then a passage with a rotary harrow was carried out to prepare the seedbed. Finally, the seeding was sown manually at 5 cm depth, followed by a smooth roller pass to promote the contact between soil and seeds. No chemical or fertilizer treatment was applied to the crops.

Plant and soil sampling and measurements

Throughout two growing seasons, soil and plants were sampled during the entire flowering stage of faba beans. With each cropping system, four sampling points were chosen for each subplot. A sample of 8–10 plants was taken with soil around the roots at each sampling point. To not destroy the roots, the soil surrounding the roots was carefully scraped to a depth of 30 cm, and soil samples were mixed into a single sample for each subplot. After that, this soil was sieved to less than 4 mm to remove the coarse fraction and then dried in ambient air for at least 48 h. Shoots were separated from the roots at the cotyledonary nodes for sampled plants. In addition, nodules were carefully separated from the roots of faba beans. Shoots, roots, and nodules were dried for 48 h at 65 °C and then weighted.

The total yield of both crops was determined following a manual harvest; for each cropping system and sub-plot, the crop was collected separately and weighed in the laboratory. In addition, after each harvest, the crop residues of each sub-plot were crushed mechanically using the stubble cutter and then incorporated into the soil. The N concentration in the soil was determined using the Kjeldahl method (Lynch et al. 1999), and the total P concentration in the plants (shoots, roots, and grains) and soil was determined using the malachite green method after digestion by nitric and perchloric acid (Petibon et al., 2000). The soil P availability was determined by extraction with NaHCO3 (Olsen method).

Efficiency in the use of rhizobial symbiosis (EURS)

Drevon et al. (2011) defined the relationship between changes in symbiotic nitrogen-fixing nodule biomass and plant biomass as an estimator of efficiency in using rhizobial symbiosis. This simple relationship can also be considered an indicator of symbiotic nodules' ability to fix atmospheric nitrogen. In addition, in practice, shoot biomass is often used instead of the total plant biomass to avoid the possible underestimation of root biomass during field sampling.

Nitrogen nutrition index (NNI)

NNI is defined as the ratio of actual crop N uptake (N_a) to the critical N uptake (N_c) (Eq. (1)), which is the minimum N uptake without deficiency to allow for the maximum growth rate at any time of plant growth (Eq. (2)) (Lemaire et al. 2008).

$$NNI = \%N_a \times \%N_c^{-1} \quad (1)$$

$\%N_c$ is determined with empirical dilution curve such as:

$$\%N_c = ac \times W^{-b} \quad (2)$$

where W – actual crop mass (t ha^{-1}); ac – critical plant N concentration for 1 t W ha^{-1}, and b – constant (Lemaire et al., 2008). For wheat, the values of ac and b are 5.3% and 0.44 (Lemaire et al., 2008).

P use efficiency (PUE)

PUE stands for plant P usage efficiency; numerous methods conceptualize and measure physiological and agronomic PUE. In our study, we used physiological PUE, which is defined as the ratio of whole plant dry weight (DWp) to plant phosphorus concentration (Pc) (Eq. (3)). (Vadez & Drevon, 2001; Benlahrech et al., 2018).

$$PUE = DW_p \times P_c^{-1} \quad (3)$$

Land Equivalent Ratio for Yield (LER_Y)

Willey & Osiru (1972) have defined the relative land area required when growing sole crops to produce yield obtained in an intercrop as the land equivalence ratio for yield (LER_Y). LER_Y indicates the yield advantage of the intercrop over the sole cropping system for a similar unit area between the two systems (Eq. (4)).

$$LER_Y = (Y_{W\text{-}IC} \times Y_{W\text{-}SC}^{-1}) + (Y_{F\text{-}IC} \times Y_{F\text{-}SC}^{-1}) \quad (4)$$

where $Y_{W\text{-}IC}$ and $Y_{F\text{-}IC}$ are the yields of wheat and faba bean intercropped. On the other hand, $Y_{W\text{-}Sc}$ and $Y_{F\text{-}SC}$ yield wheat and faba bean yield in the sole crop, respectively.

Statistical analysis and calculations

Before statistical analysis, the data were checked for homogeneity of variance. The R software was used to run one- and two-way analyses of variance (ANOVA) (R Core team 2016). Tukey's multiple comparison tests at $P = 0.05$ were used to select the means. A linear regression relationship between shoot (SDW) and nodule (NDW) dry weights were determined for the cropping systems with faba bean each year. In order to compare the biomass stocks per equivalent area units (g m^{-2}), SDW and, for faba bean, NDW per plant (g $plant^{-1}$) were converted into stocks as follows:

$$\text{SDW (or NDW) stocks} = \text{SDW (or NDW)} \times SD_{corr} \quad (5)$$

where SD_{corr} – sowing density (SD) of a given species corrected by the area actually occupied by this species. Thus, SD_{corr} = SD for sole crops, and SD_{corr} = SD / 0.5 = SD × 2 in intercropping since the area was halved in intercropping for each species.

RESULTS

Plant growth and nodulation

Wheat and faba bean shoot dry weight was significantly affected by cropping system as shown in Table 1; the table also shows that only wheat SDW was significantly affected by growing season. Fig. 1, A, shows that SDW per equivalent unit area of durum wheat (SDW g m^{-2}) was significantly higher in intercropping than in sole cropping (38% in 2019 and 47% in 2020). However, faba bean shoot dry weight decreased significantly under the intercropping system by 29% in 2019 and 24% in 2020 compared to sole cropping (Fig. 1, B). In the same way, the cropping system had a considerable impact on faba bean nodulation (Table 1).

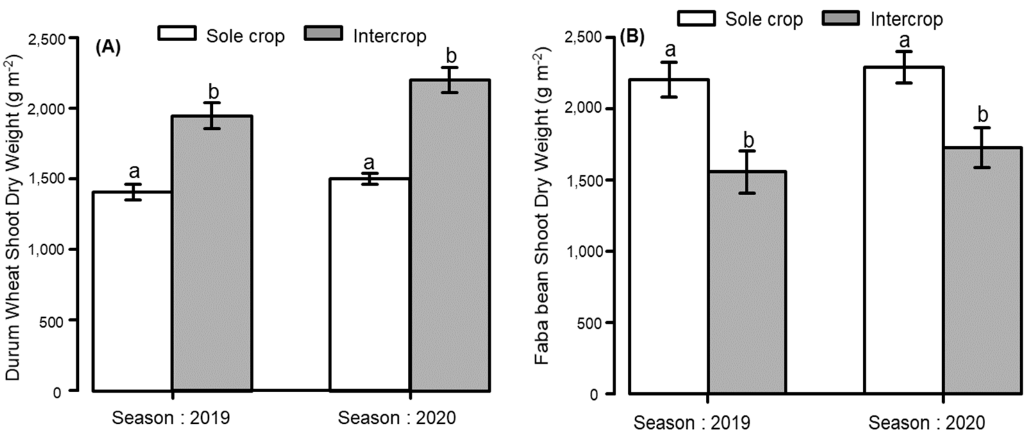

Figure 1. Durum wheat (A) and Faba bean (B) shoot dry weight for each year in sole cropping versus intercropping. Data are means and standard errors of 16 replicates harvested at 130 days after sowing. Within a given year, mean values labeled with different letters are significantly different at $P < 0.05$.

On another hand, when compared to sole cropping, intercropping significantly reduced nodule dry weight (NDW) and the number of nodules (NN) (Table 1). Regarding NDW, the loss was estimated to 28% in 2019 and 36% in 2020 (Fig. 2, A); for the number of nodules (NN), the diminution was estimated to 45% and 40% in 2019 and 2020, respectively (Fig. 2, B).

Table 1. *P*-values of two-way ANOVAs with factors growing season and cropping system on plants and soil variables

	Shoot dry weight (g m^{-2})		Nodule dry weight (g m^{-2})	Nodules number (Nod pl^{-1})	Soil N	Soil P
	Wheat	Faba bean	Faba bean		%	
Growing season	$1.73\times10^{-2*}$	0.32^{ns}	0.38^{ns}	0.33^{ns}	0.43^{ns}	0.39^{ns}
Cropping system	$9.33\times10^{-15***}$	$7.50\times10^{-6***}$	$2.94\times10^{-5***}$	$< 2\times10^{-16***}$	$1.55\times10^{-8***}$	$9.53\times10^{-11***}$
Growing season × Cropping system	0.26^{ns}	0.74^{ns}	0.42^{ns}	0.73^{ns}	0.98^{ns}	0.96^{ns}

$^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$; ^{ns} not significant ($P > 0.05$).

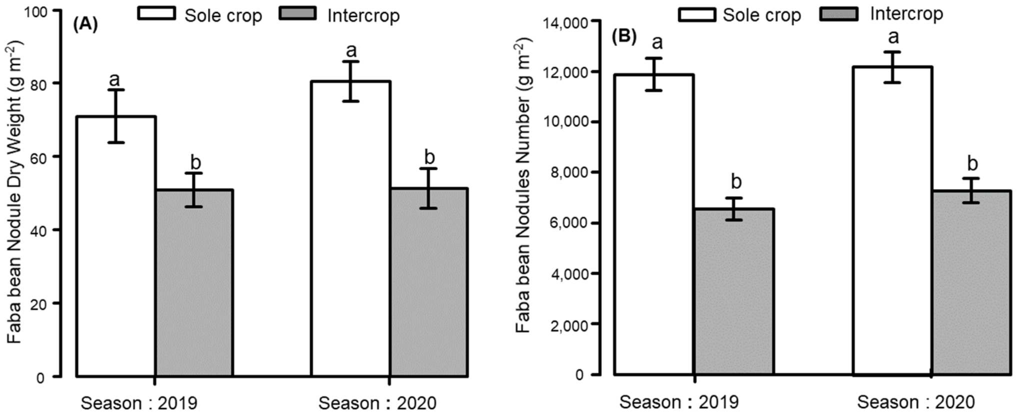

Figure 2. Faba bean nodule dry weight (A) and nodules number (B) for each year in sole cropping versus intercropping. Data are means and standard errors of 16 replicates harvested at 130 days after sowing. Within a given year, mean values labeled with different letters are significantly different at $P < 0.05$.

Efficiency in the use of rhizobial symbiosis (EURS)

EURS (calculated as the slope of the linear regression between plant and nodule biomass) were significantly different in Faba bean grown in intercrop and sole crop systems (Fig. 3). The shoot dry weight (SDW) of each faba bean plant was linked to the nodule dry weight (NDW). In both growing seasons, the EURS for intercropping was significantly higher than for sole cropping; in 2019, the EURS for intercropped faba bean (27.5 g SDW g^{-1} NDW) was 87% higher than sole cropped faba bean (14.7 g SDW g^{-1} NDW) (Fig. 3, A). In 2020, intercropped faba bean had a EURS of 26 g SDW g^{-1} NDW which was 47% higher than sole cropped faba bean (17.7 g SDW g^{-1} NDW) (Fig. 3, B).

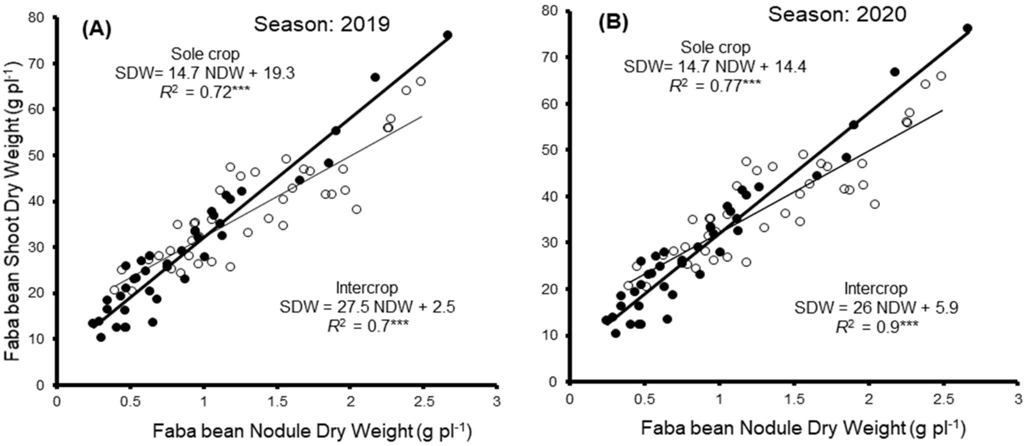

Figure 3. Efficiency in use of the rhizobial symbiosis for faba bean in sole cropping (white dots) versus intercrop ping (black dots) for (A) 2019; (B) 2020. The equations on the charts are the regressions for sole crops (light grey text) and intercrops (dark grey text). All regressions were established from sixteen replicates (sixteen plants). $*P < 0.05$; $**P < 0.01$; $***P < 0.001$.

Wheat Nitrogen Nutrition Index (NNI) and P Use Efficiency (PUE)

The two-way ANOVA in Table 2 shows that the growing season and cropping system significantly impact NNI and PUE. Fig. 4, A, indicates that the NNI for intercropping was higher than 1, but the NNI for sole cropping was less than 1. In 2019 and 2020, the NNI for intercropping was 64 and 91 percent higher than sole cropping, respectively. Furthermore, Fig. 4, B shows that PUE for intercropped wheat was much higher than sole cropped wheat by 97 percent and 124 percent, respectively, in 2019 and 2020.

Table 2. *P*-values of two-way ANOVAs with factors growing season and cropping system on grain yield, INN and PUE

	Grain yield (t ha^{-1})		Nitrogen nutrition index (NNI)	P use efficiency (PUE)
	Wheat	Faba bean	Wheat	Wheat
Growing season	0.62 ^{ns}	0.45 ns	$3.39\times10^{-5***}$	0.023^{*}
Cropping system	$1.95\times10^{-5***}$	0.30 ns	$< 2.2\times10^{-16***}$	$< 2\times10^{-16***}$
Growing season × Cropping system	0.75 ^{ns}	0.51 ns	0.088 ^{ns}	0.078 ^{ns}

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ^{ns} not significant ($P > 0.05$).

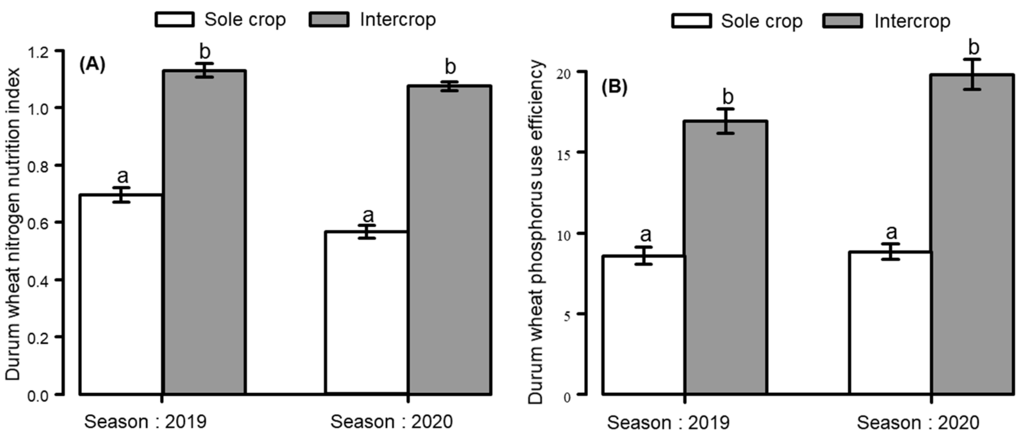

Figure 4. Durum wheat nitrogen nutrition index (A) and P use efficiency (B) for sole crops and intercrops. Means and standard error for sixteen replicates harvested at 130 days after sowing. For each year, mean values labeled with the same letters are not significantly different at $P < 0.05$.

Grain Yield and Land Equivalent Ratio for Yield (LER_Y)

Table 2 shows that cropping systems, not the growing season, had a significant effect on durum wheat grain yield; however, cropping systems and the growing season had no impact on faba bean grain yield. As shown in Fig. 5, A, wheat grain yield was 8 percent higher in intercropping than in sole cropping in 2019 and 7 percent higher in 2020.

Land Equivalent Ratio for yield was higher than 1 ($LER_Y > 1$) as reported in Table 2, indicating that the intercropping was more beneficial than the sole cropping for durum wheat grain yield.

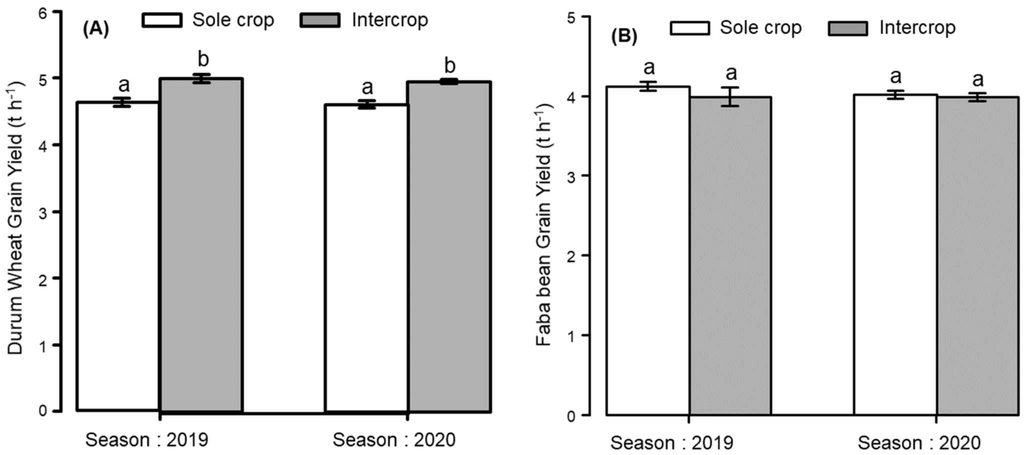

Figure 5. Durum wheat (A) and faba bean (B) grain yield for sole crops and intercrops. Means and standard error for sixteen replicates harvested at total maturity. For each year, mean values labelled with the same letters are not significantly different at $P < 0.05$.

Soil N and P Availability

Fig. 6 shows the average inorganic N (6A) and Olsen P (6B) concentrations in the rhizosphere for intercrops and sole crops, respectively. During both cropping seasons, the inorganic nitrogen concentration in the soil of the intercrops and sole crops was higher than that of the unseeded weeded fallow. The nitrogen concentration in the soil was significantly higher for intercrops than for unseeded weeded fallows by 68% and 72% in 2019 and 2020, respectively. In addition, soil N content was significantly higher under the intercropping system by 21% in 2019 and 2020 than sole cropped faba bean, 51% in 2019 and 46% in 2020 compared to sole cropped wheat (Fig. 6, A).

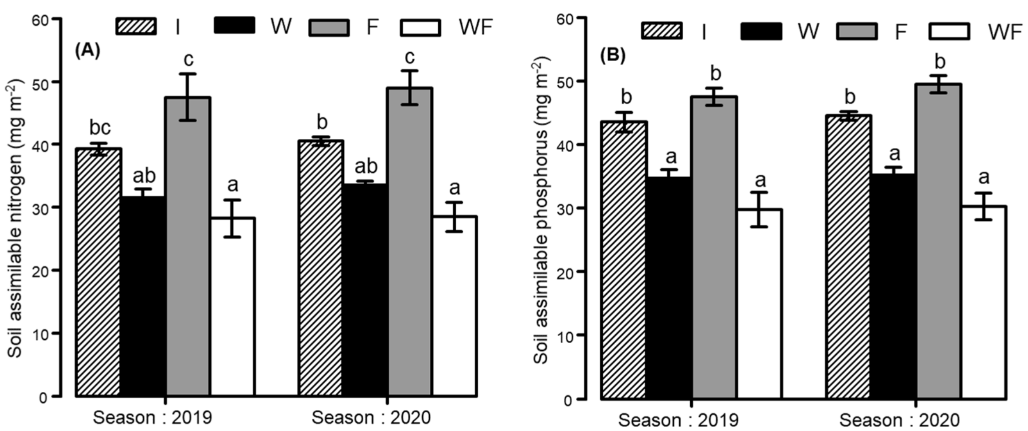

Figure 6. Soil nitrogen (A) and phosphorus (B) contents in sole cropping versus intercropping versus fallow for each year. Means and standard error of four replicates for intercropping and unseeded weeded control and eight replicates for rotation. For each cropping system, mean values labelled with the same letters are not significantly different at $P < 0.05$. Where I – intercrops; W – wheat sole crop; F – faba bean sole crop; WF – weeded fallow.

When faba bean was included in the cropping system, either intercropping or sole cropping, soil Olsen P concentrations were consistently higher compared to sole cropped wheat, and unseeded weeded fallow. Intercropping had the highest Olsen P levels, 37% higher in 2019 and 40% higher in 2020 than sole cropped wheat; it was also 60% higher than unseeded weeded fallow in 2019 and 2020, respectively.

DISCUSSION

To strengthen resilient and sustainable practices in agriculture, crop diversification in the same space (e.g., intercropping cereals-legumes) appears to be one of the agroecological practices that would enhance agroecosystem services (Daryanto et al., 2019; Kherif et al., 2021). Overall, our results indicate a significant increase in dry shoot weight for durum wheat intercropped with faba bean compared to sole cropped durum wheat for an N-deficient and alkaline soil. However, when faba bean was intercropped with durum wheat, the dry weight of shoots and nodules was significantly decreased, but the number of nodules was significantly increased. Previous field studies in the Mediterranean region have investigated the impact of intercropping in various legume-cereal systems on plant growth. It was found that the dry shoot weight of durum wheat was increased when intercropped with faba bean and cowpea (Betencourt et al., 2012; Kaci et al., 2018). Also, these authors confirm that shoot biomass and nodule biomass were significantly lower when cowpea and faba bean were intercropped with durum wheat. However, Maingi et al. (2011) and Banik et al. (2006) reported that nodular biomass of common bean and chickpea was significantly higher under intercropping, which may be due to the beneficial association between cereal and legume. As well, our study shows an increase in durum wheat yield under intercropping in both cropping seasons, confirmed by an LER_Y greater than 1, indicating a benefit to the associated grain. These results are in agreement with those of Kaci et al. (2018), who reported an increase in wheat yield when intercropped with faba bean during three cropping seasons, whereas other studies also report the benefits of cereal/legume association on grain yield (Darch et al., 2018; Mndzebele et al., 2020), such as Kherif et al. (2021) who reported an increase in the yield of wheat associated with chickpea compared to its Sole crop.

Furthermore, intercropping significantly affects the efficiency in the use of rhizobial symbiosis (EURS) in both growing seasons. The faba bean EURS was much higher for intercrops than for sole crops by 12.8 and 8.3 g SDW g^{-1} NDW respectively, in 2019 and 2020. This increase in EURS would result from the strong interspecific competition exerted by the roots of durum wheat on nutrients, especially under these conditions of N deficiency, which would stimulate biological N_2 fixation by legumes. This increase in EURS is also linked to a decrease in nodular biomass and in the number of nodules, which suggests a change in the population of efficient rhizobial strains inducing a high number of small nodules involved in efficient nodulation with intense nitrogenase activity (Alkama et al., 2012; Kaci et al., 2018; Chenene et al., 2021). Kaci et al. (2018) and Latati et al. (2019) also reported an increase in EURS of faba bean and chickpea when intercropped with durum wheat compared to their respective monoculture.

There was also a significant increase in NNI for durum wheat intercropped with faba bean in both growing seasons, with values greater than 1 indicating better nitrogen nutrition for the intercropped wheat compared to the sole cropped. According to

Callaway (1995), the ability of legumes to access the atmospheric N_2 pool via the symbiotic fixation mechanism appears to be an alternative to interspecific competition with cereals for the soil N pool, thus inducing a complementarity of N use between the two species. Furthermore, wheat PUE was significantly higher when intercropped with faba bean in both growing seasons. Our findings agree with those of Tang et al. (2020), who also report a 21% improvement in P use efficiency under the intercropping system. In this study, the increase in PUE is directly linked to the increase in soil Olsen P when legume is included in the cropping system. The increase in Olsen P availability under the association can be explained by several changes induced in the rhizosphere (proton release, organic acids exudation, acid phosphatases, etc.) by the high nitrogen-fixing activity of the legume (Tang et al., 2004; Alkama et al., 2009, 2012; Bargaz et al., 2012).

P availability (Olsen P) was not a limiting factor for crops; however, we found that P availability was higher in intercrops than monocrops and the unseeded weeded fallow. Several pieces of research have shown a significant effect of cereal-legume intercrops on P availability under P-deficiency conditions (Devau et al., 2011; Betencourt et al., 2012; Tang et al., 2020). As suggested by Wang et al. (2015) we presume that low N availability in the rhizosphere can promote P availability through root-induced processes in alkaline soil, such as rhizosphere acidification by legumes (exudation of phosphatases, carboxylates, and/or indirectly through microbial activities). Recent research has demonstrated the benefits of intercropping for cereals through the legume's facilitative mechanisms, which was responsible for increasing the availability of inorganic resources (e.g., inorganic P) through rhizosphere acidification during rhizosphere N_2 fixation, according to the stress gradient theory (Tang et al., 2020; Kherif et al., 2021). Where soil conditions are limited, as in P-deficient alkaline or calcareous soils, these positive interactions are precious (Drevon et al., 2011; Tang et al., 2020).

In this study's N-deficient soil, the availability of N in the rhizosphere of wheat-faba bean intercrops was significantly higher in both cropping seasons compared to sole crops; this increase was also accompanied by improved aboveground biomass and better symbiotic fixation of atmospheric N_2, implying the establishment of an interspecific complementarity that would facilitate nutrient acquisition while reducing competition. An increase in rhizosphere N content in cereal-legume intercrops compared to sole crops was previously reported by several authors like Kaci et al. (2018); Tang et al. (2020) and Rodriguez et al. (2020).

CONCLUSION

During this field trial conducted on a farming site over two cropping seasons, it became evident that wheat/faba bean intercropping is more advantageous than sole cropping. Indeed, we found that intercropped wheat had higher aboveground biomass, grain yield, nitrogen nutrition, and EUP than sole cropped wheat. These significant increases were accompanied by a physiological response of the related faba bean, which increased its capacity to fix atmospheric nitrogen to reduce interspecific competition for soil resources. Furthermore, we found that the availability of N and P in the rhizosphere of intercrops was higher than that of sole crops.

This finding demonstrated intercropping as one of the most effective agroecological systems and an alternative to intensive agriculture for ensuring ecosystem sustainability and reducing greenhouse gas emissions created by contemporary agriculture.

REFERENCES

Alkama, N., Bolou Bi Bolou, E., Vailhe, H., Roger, L., Ounane, S.M. & Drevon, J.J. 2009. Genotypic variability in P use efficiency for symbiotic nitrogen fixation is associated with variation of proton eux in cowpea rhizosphere. *Soil Biology and Biochemestry* **41**, 1814–1823.

Alkama, N., Ounane, G. & Drevon, J.J. 2012. Is genotypic variation of H^+ efflux under P deficiency linked with nodulated-root respiration of N_2-fixing common-bean (*Phaseolus vulgaris* L.)?. *Journal of Plant Physiology* **169**, 1084–1089.

Banik, P., Midya, A., Sarkar, B.K. & Ghose, S.S. 2006. Wheat and chickpea intercropping systems in an additive series experiment: Advantages and weed smothering. *European Journal of Agronomy* **24**, 325–332.

Baraket, F., González-Rosado, M., Brahim, N., Roca, N., Mbarek, H.B., Świtoniak, M., Chaker, R., Bellón, Á.S., Rigane, H., Gargouri, K. & Parras-Alcántara, L. 2021. Short and Long-Term Effect of Land Use and Management on Soil Organic Carbon Stock in Semi-Desert Areas of North Africa-Tunisia. *Agriculture* **11**, 12–67. https://doi.org/10.3390/agriculture11121267

Benlahrech, S., Kaci, G., Teffahi, M. & Ounane, S.M. 2018. Influence of inoculation and phosphorus regimes on symbiotic nitrogen fixation and phosphorus use efficiency of Algerian cowpea (*Vigna unguiculata* L. (Walp.)) landraces. *Agronomy Research* **16**, 337–348.

Betencourt, E., Duputel, M., Colomb, B., Desclaux, D. & Hinsinger, P. 2012. Intercropping promotes the ability of durum wheat and chickpea to increase rhizosphere phosphorus availability in a low P soil. *Soil Biology and Biochemistry* **46**, 181–190.

Cahill, J.F., McNickle, G.G., Haag, J.J., Lamb, E.G., Nyanumba, S.M. & St Clair, C.C. 2010. Plants integrate information about nutrients and neighbors. *Science* **328**, 16–57.

Callaway, R.M. 1995. Positive interactions among plants. *The Botanical Review* **61**, 306–349.

Chen, S., Waghmode, T.R., Sun, R., Kuramae, E., Hu, C. & Liu, B. 2019. Root-associated microbiomes of wheat under the combined effect of plant development and nitrogen fertilization. *Microbiome* **7**(1), 1–13.

Chenene, Y., Blavet, D., Belalmi, M., Kaci, G., Teffahi, M. & Ounane, S.M. 2021. Variation of chickpea nodulation in a Mediterranean agroecosystem: relationship with soil characteristics and thresholds for significant contribution to plant growth. *Agronomy Research* **19**, 42–56.

Cong, W.F., Hoffland, E., Li, L., Six, J., Sun, J.H., Bao, X.G., Zhang, F.S. & Van Der Werf, W. 2015. Intercropping enhances soil carbon and nitrogen. *Global Change Biology* **21**, 1715–1726.

Cordell, D., Drangert, J.O. & White, S. 2009. The story of phosphorus: global food security and food for thought. *Global Environmental Change* **19**, 292–305.

Cu, S.T.T., Hutson, J. & Schuller, K.A. 2005. Mixed culture of wheat (Triticum aestivum L.) with white lupin (Lupinus albus L.) improves the growth and phosphorus nutrition of the wheat. *Plant and Soil* **272**, 143–151.

Darch, T., Giles, C.D., Blackwell, M.S.A., Brown, G.L.K., Menezes-Blackburn, D., Shand, C.A., Stutter, M.I., Lumsdon, D.G., Mezeli, M.M., Wendler, R., Zhanf, H., Wearing, C., Cooper, P. & Haygarth, P.M. 2018. Inter- and intra-species intercropping of barley cultivars and legume species, as affected by soil phosphorus availability. *Plant and Soil* **427**, 125–138.

Daryanto, S., Jacinthe, P.A., Fuab, B., Zhao, W. & Wang, L. 2019. Valuing the ecosystem services of cover crops: Barriers and pathways forward. *Agriculture, Ecosystems & Environment* **270**, 76–78.

Dawson, C.J. & Hilton, J. 2011. Fertiliser availability in a resource-limited world: production and recycling of nitrogen and phosphorus. *Food Policy* **36**, 14–22.

Devau, N., Hinsinger, P., Le Cadre, E. & Gérard, F. 2011. Root-induced processes controlling phosphate availability in soils with contrasted P-fertilized treatments. *Plant and Soil* **348**, 203–218.

Drevon, J.J., Alkama, N., Araujo, A., Beebe, S., Blair, M.W., Hamza, H., Jaillard, B., Lopez, A., Martinez-Romero, E., Rodino, P., Tajini, F. & Zaman-Allah, M. 2011. Nodular diagnosis for ecological engineering of the symbiotic nitrogen fixation with legumes. *Procedia Environmental Sciences* **9**, 40–46.

Hinsinger, P. 2001. Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review. *Plant and Soil* **237**, 173–195.

Hinsinger, P., Betencourt, E., Bernard, L., Brauman, A., Plassard, C., Shen, J., Tang, X. & Zhang, F. 2011. P for two, sharing a scarce resource e soil phosphorus acquisition in the rhizosphere of intercropped species. *Plant Physiology* **156**, 1078–1086.

IUSS Working Group WRB. 2015. World Reference Base for Soil Resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. *World Soil Resources Report* 106, FAO, Rome, Italy, 203 pp.

Kaci, G., Blavet, D., Benlahrech, S., Kouakoua, E., Couderc, P., Deleporte, P., Desclaux, D., Latati, M., Pansu, M., Drevon, J.J. & Ounane, S.M. 2018. The effect of intercropping on the efficiency of faba bean – rhizobial symbiosis and durum wheat soil-nitrogen acquisition in a Mediterranean agroecosystem. *Plant, soil and environment* **64**, 138–146.

Kherif, O., Seghouani, M., Zemmouri, B., Bouhenache, A., Keskes, M.I., Rebouh, Y.N., Ouaret, O. & Latati, M. 2021. Understanding the Response of Wheat-Chickpea Intercropping to Nitrogen Fertilization Using Agro-Ecological Competitive Indices under Contrasting Pedoclimatic Conditions. *Agronomy* **11**, 12–25.

Lambers, H., Shane, M.W., Cramer, M.D., Pearse, S. & Veneklaas, E. 2006. Root structure and functioning for efficient acquisition of phosphorus: matching morphological and physiological traits. *Annals of Botany* **98**, 693–713.

Latati, M., Dokukin, P., Aouiche, A., Rebouh, N.Y., Takouachet, R., Hafnaoui, E., Hamdani, F.Z., Bacha, F. & Ounane, S.M. 2019. Species Interactions Improve Above-Ground Biomass and Land Use Efficiency in Intercropped Wheat and Chickpea under Low Soil Inputs. *Agronomy* **9**, 765–780.

Layek, J., Das, A., Mitran, T., Nath, C., Meena, R.S., Yadav, G.S., Shivakumar, G., Kumar, S. & Lal, R. 2018. Cereal+Legume Intercropping: An Option for Improving Productivity and Sustaining Soil Health. In: Meena, R., Das, A., Yadav, G. & Lal, R. (Eds). Legumes for Soil Health and Sustainable Management. *Springer International Publishing*, Singapore, 347–386.

Lemaire, G., Jeuffroy, M.H. & Gastal, F. 2008. Diagnosis tool for plant and crop N status in vegetative stage. Theory and practices for crop N management. *European Journal of Agronomy* **28**, 614–624.

Li, L., Zhang, F., Li, X., Christie, P., Sun, J., Yang, S. & Tang, C. 2003. Interspecific facilitation of nutrient uptake by intercropped maize and faba bean. *Nutrient Cycling in Agroecosystems* **65**, 61–71.

Li, L., Li, S.M., Sun, J.H., Zhou, L.L., Bao, X.G., Zhang, H.G. & Zhang, F.S. 2007. Diversity enhances agricultural productivity via rhizosphere phosphorus facilitation on phosphorus-deficient soils. The *Proceedings of the National Academy of Sciences* **104**, 11192–11196.

Li, L., Tilman, D., Lambers, H. & Zhang, F.S. 2014. Plant diversity and overyielding: insights from belowground facilitation of intercropping in agriculture. *New Phytologist* **203**, 63–69.

Lynch, J.M. & Barbano, D.M. 1999. Kjeldahl nitrogen analysis as a reference method for protein determination in dairy products. *Journal of AOAC International* **82**, 1389–1398.

Maingi, M.J., Shisanya, A.C., Gitonga, M.N. & Hornetz, B. 2011. Nitrogen fixation by common bean (*Phaseolus vulgaris* L.) in pure and mixed stands in semi-arid south east Kenya. *European Journal of Agronomy* **14**, 1–12.

Mndzebele, B., Ncube, B., Fessehazion, M., Mabhaudhi, T., Amoo, S., Venter, S. & Modi, A. 2020. Effects of Cowpea-Amaranth Intercropping and Fertiliser Application on Soil Phosphatase Activities, Available Soil Phosphorus, and Crop Growth Response. *Agronomy* **10**, 79–99.

Peoples, M.B., Hauggaard-Nielsen, H., Huguenin-Eli, O., Jensen, E.S., Justes, E. & Williams, M. 2018. The Contributions of Legumes to Reducing the Environmental Risk of Agricultural Production. In Lemaire, G., De Faccio Carvalho, P.C., Kronberg, S. & Recous, S (Eds). *Agroecosystem Diversity Reconciling Contemporary Agriculture and Environmental Quality* **1st edition**. Elsevier, Cambridge, 123–143.

Petibon, P., Roumet, C. & Jouany, C. 2000. Détermination de la teneur en phosphore par la méthode au vert de malachite : adaptation à de petits échantillons végétaux de faible teneur en phosphore. *Cahier Technique INRA* **43**, 3–8.

Raghothama, K.G. 1999. Phosphate acquisition. Annual Review of Plant Physiology and Plant. *Molecular Biology* **50**, 665–693.

Scalise, A., Tortorella, D., Pristeri, A., Petrovičová, B., Gelsomino, A., Lindström, K. & Monti, M. 2015. Legume-barley intercropping stimulates soil N supply and crop yield in the succeeding durum wheat in a rotation under rained conditions. *Soil Biology and Biochemistry* **89**, 150–161.

Tang, C., Drevon, J.J., Jaillard, B., Souche, G., Hinsinger, P. 2004. Proton release of two genotypes of bean (*Phaseolus vulgaris L.*) as affected by N nutrition and P deficiency. *Plant and Soil* **260**, 59–68.

Tang, X., Zhang, C., Yu, Y., Shen, J., Van der werf, W. & Zhang, F. 2020. Intercropping legumes and cereals increases phosphorus use efficiency; a meta-analysis. *Plant and Soil* **460**, 89–104.

Tang, X.Y., Placella, S.A., Daydé, F., Bernard, L., Robin, A., Journet, E.P., Justes, E. & Hinsinger, P. 2016. Phosphorus availability and microbial community in the rhizosphere of intercropped cereal and legume along a P-fertilizer gradient. *Plant and Soil* **407**, 119–134.

Turner, B.L. 2008. Resource partitioning for soil phosphorus: a hypothesis. *Journal of Ecology* **69**, 698–702.

Vadez, V. & Drevon, J.J. 2001. Genotypic variability in P use efficiency for symbiotic N_2 fixation in common bean (*Phaseolus vulgaris* L.). *Agronomie* **21**, 691–699.

Vance, C.P. 2001. Symbiotic nitrogen fixation and phosphorus acquisition. Plant nutrition in a world of declining renewable resources. *Plant Physiology* **127**, 390–397.

Wang, Z., Bao, X., Li, X., Jin, X., Zhao, J., Sun, J. & Christie, P. 2015. Intercropping maintains soil fertility in terms of chemical properties and enzyme activities on a timescale of one decade. *Plant Soil* **405**, 265–282.

Willey, R.W. 1979. Intercropping-Its mportance and research needs. Part I Competition and yield advantages. *Field Crop Abstract* **32**, 1–10.

Willey, R.W. & Osiru, D.S.O. 1972. Studies on mixtures of maize and beans (*Phaseolus vulgaris*) with special reference to plant population. The *Journal of Agricultural Science* **79**, 519–529.

Zhu, Z.L. & Chen, D.L. 2002. Nitrogen fertilizer use in China - Contributions to food production, impacts on the environment and best management strategies. *Nutrient Cycling in Agroecosystems* **63**, 117–127.