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Intercropping Promotes the Ability of Legume and Cereal to Facilitate Phosphorus and Nitrogen Acquisition through Root-Induced Processes

M. Latati , S. Benlahrech , M. Lazali , Tellah Sihem ,
G. Kaci , R. Takouachet , N. Alkama , F.Z. Hamdani ,
E.A. Hafnaoui , B. Belarbi , G. Ounane and
S.M. Ounane

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Abstract

Intercropping of cereal and legume can improve the use of resources for crop growth compared to cropping system. An increase in soil phosphorus (P) and nitrogen (N) acquisition by root-induced biochemical changes of intercropped species has been reported as key processes of facilitation and complementarily between both intercropping legumes and cereals. Indeed, the functional facilitation prevails over interspecific competition under nutrients limiting for crop growth. Results showed that P availability significantly increased in the rhizosphere of both species, especially in intercropping under the P-deficient soil conditions. This increase was associated with high efficiency in use of rhizobial, plant growth and resource use efficiency as indicated by higher land equivalent ratio (LER) and N nutrition index. In addition, the rhizosphere P availability and nodule biomass were positively correlated ($r^2 = 0.71^{**}$, and $r^2 = 0.62^{**}$) in the intercropped common bean grown at P-deficient soil. The increased P availability presumably improved biomass and yield in intercropping, although it mainly enhanced intercropped maize grain yield. Exploiting belowground parameters in a legume-cereal intercropping is likely necessary to maximize rhizosphere-interspecific interactions as a strategy to improve the symbiotic rhizobial efficiency and microbial activities, as a result of root-induced pH and N availability changes under low P soils.

Keywords: intercropping, symbiosis, legumes, cereals, phosphorus, Algeria

1. Introduction

Nitrogen (N) and phosphorus (P) are often considered to be the most important limiting factors, after water deficit and salinity, for plant growth and yield production in natural agroecosystems [1]. In cropping system and under stress conditions, the input of P and N via mineral fertilizers has been practiced to improve yielding agroecosystems [2–4]. However, the availability of P fertilizers is increasingly limited by the depletion of P mineral reserves with the growing food needs [5, 24]. Another approach is to increase the soil P availability that is often limited by adsorption on surfaces of mineral phases and fixation to cations such as Ca^{2+} , Al^{3+} or Fe^{2+} [6, 7].

Adopting sustainable technologies to better exploit soil nutrients resources, such as P and N, has been an interesting research challenge. Thus, the management of agricultural practices, including intercropped cultivation of cereals with legumes, is so far considered as one of the main agriculture sustainable components [2, 3, 6]. Recent studies reported that legumes-cereals in intercropping as compared to monocropping systems introduced greater environmental sources use efficiency for either plant growth or yields due to interspecific complementary, facilitation and competition between intercropped species [8–10, 17].

Increased acquisition of N has been mostly demonstrated in cereal-legume intercrops, compared to sole crops, only a few recent studies have reported the P or N-P interaction effect [6, 10, 11, 24]. Indeed, most of the former studies on cereal-legume intercropping implicitly assume that the legume enhances P and N acquisition by the cereal because of legumes' ability to increase large amounts of P-mobilizing compounds that ultimately increase P availability [6, 7, 12].

Root-induced some biological and chemical changes that can help to alter the rhizosphere processes of both intercropped legumes and cereals through (i) proton release by roots of N_2 -fixing legumes [13, 14]; (ii) alkalization can also increase rhizosphere P availability in noncalcareous soils [7, 15]; and (iii) CO_2 emissions from the soil surface, which are the result of the overall activity of soil microorganisms and root-nodule symbionts, may be involved in the control of P availability in an alkaline soil [4].

In this context, fallow-cereal-rotation is the common cropping system for cereals production in Algeria. Actually, replacing fallow by legume crops in such farming systems of Algeria has become a strategic necessity for food security in a context of rising prices of food products [2, 13]. However, northern Algeria soils are among the most alkaline and calcareous soil in the Mediterranean conditions with high pH (7.5–8.5) and are considered Mediterranean zones [10, 16]. The following revision of the literature focuses on advantage of intercropping legumes-cereals under Algerian agroecosystems conditions.

2. Plant growth and nodulation under legumes-cereals intercropping

Although consistent progress has been made in exploring the intercropping cereal-legume advantages for better growth and productivity, this cropping system needs to be more deeply

investigated in order to point out abiotic stress tolerance traits such as those associated with the low nutrients availability in the soil [10]. The increase in cereals biomass and grain yield in association with a legume has been demonstrated for maize when it was grown intercropped with cowpea [7, 14] and also durum wheat in intercropping with faba bean. Legumes-cereals dual intercropping, provide the P and increase its availability for cereals [6, 10]. Recent studies show that total shoot dry weight of mixed cereals and legumes (above-ground biomass) was significantly higher in intercropping than in sole crop (**Figure 1**) [10]. Recent studies reported a significant increase in above-ground biomass of intercropped faba bean during continuous maize-faba bean intercropping for 9–10 years [12]. Legumes, with their adaptability to different cropping patterns and their ability to fix N_2 , may offer opportunities to sustain increased plant biomass for intercropped species [2, 6, 7]. Several studies have addressed the effect of intercropping in increasing nodule growth [2, 18].

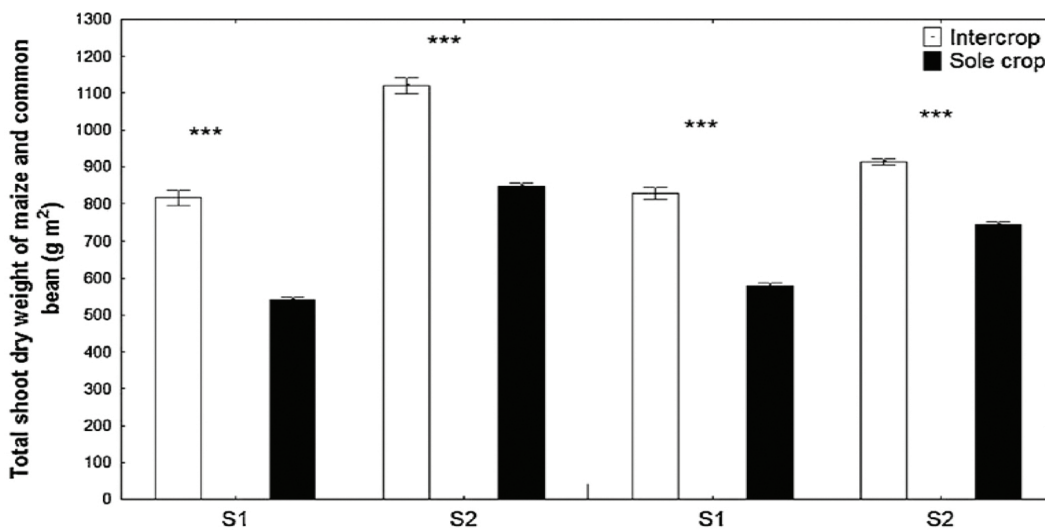


Figure 1. Total shoot dry weight (maize and common as intercrops or monocrops) per land area.

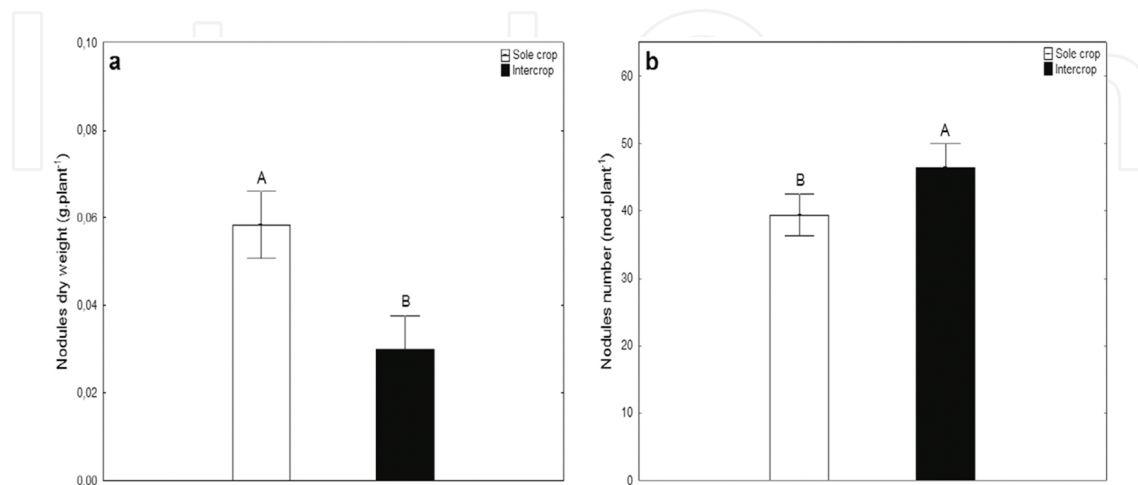


Figure 2. Dry weight of nodules (a) and number of nodules (b) for cowpea in sole cropping and intercropping.

However, nodule biomass for intercropped legumes were significantly decreased compared to monocropped legumes. A limited number of recent studies have addressed the same effect of intercropping on nodule growth for chickpea and common bean [2, 6]. In low P alkaline soil, it was reported a greater cowpea nodule number weight under intercropping with maize due to complementarily effect [7].

The decrease in nodule biomass was partly compensated by an increase in nodule number (**Figure 2a** and **b**) [7], which could be due to a change in the population of efficient rhizobial strains involved in root infection and efficient nodulation with higher nitrogenase activity [7, 19].

3. Increased efficiency in use of the rhizobial symbiosis (EURS)

The increase in the EURS of intercropped legumes in intercropping can be explained by interspecific competition for nitrogen use by the dual intercropping. Field research studies show a significant increase in N_2 fixation by common bean, as a result of competition with either durum wheat or with maize [2, 8].

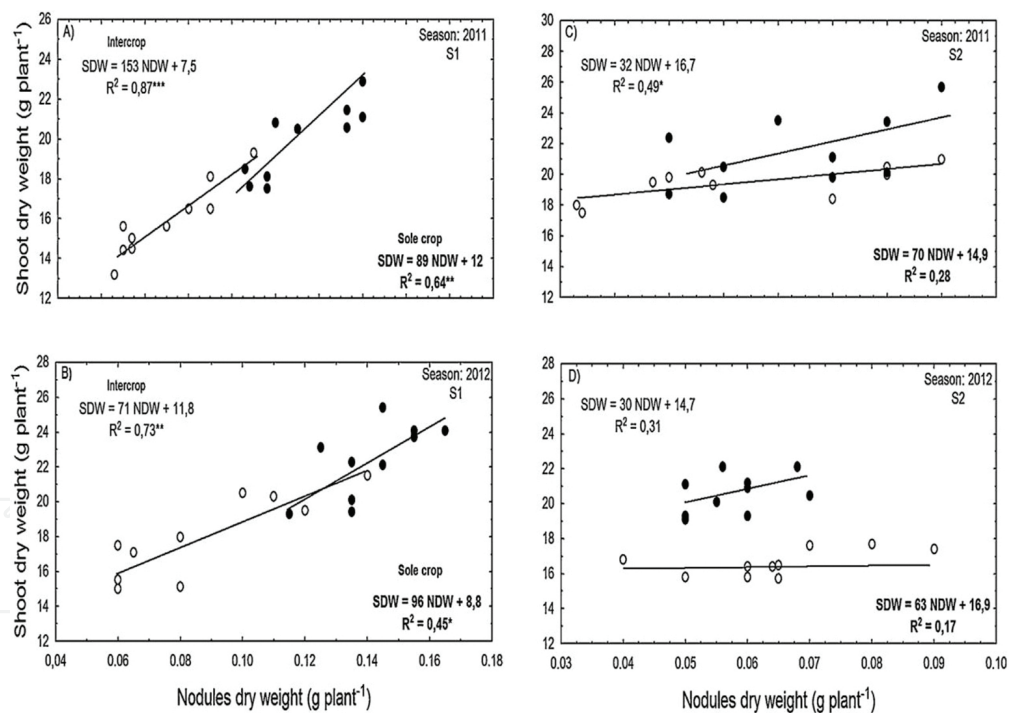


Figure 3. Efficiency in use of the rhizobial symbiosis in common bean as sole crops (filled circle) or intercrops (opened circle) under S1 (P deficient) and S2 (P sufficient) conditions.

An increase in EURS (mostly during low P availability: **Figure 3**) [10] indicating a tight relationship between legume N_2 fixation, growth and total grain yield. However, detecting differences in EURS between legumes grown in both sole and intercrops may offer an important clue in investigating key processes that influence P availability under P deficiency, where

legume's reliance to N_2 fixation presumably increased in parallel to a number of rhizosphere-induced changes (proton release, organic acids exudation, acid phosphatases, etc.) that contributed to increase P availability (**Figure 4**) [10] and growth [20].

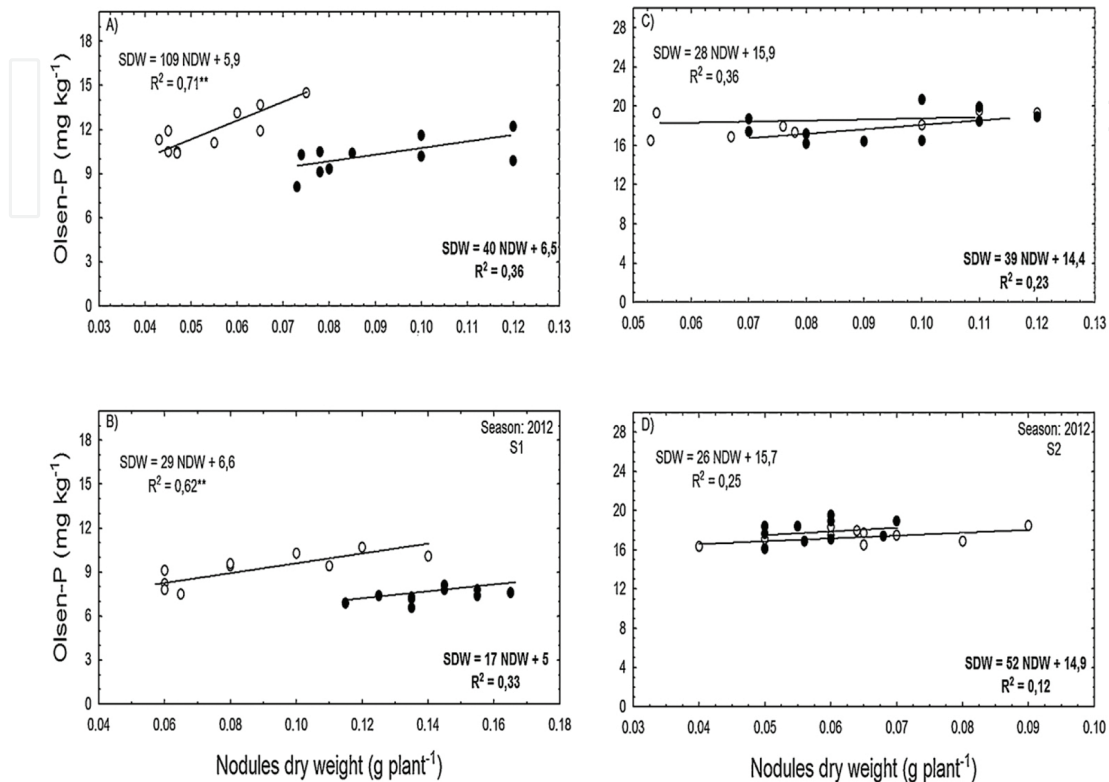


Figure 4. Correlation between rhizosphere soil Olsen P and nodule dry weight of common bean grown as sole crop (filled circle) or intercrop (opened circle) under S1 (P deficient) and S2 (P sufficient) conditions.

Recent studies were reported a high EURS of cowpea and common bean among intercrops treatment compared to corresponding EURS as sole crop, the increase in EURS by intercropping was significantly observed under low P conditions in either alkaline or calcareous soil [7, 10].

4. Phosphorus availability and root-induced changes

Several studies have reported the decline in the availability of P in the rhizosphere via root uptake during the crop cycle [11, 22]. Nevertheless, recent studies show an increase in P availability in the rhizosphere of intercropped legumes and cereals [22]. Recent researches reported an increase in inorganic P availability (Olsen-P) in the rhizosphere of both intercropped legumes and cereals [7, 10, 21]. These authors suggested that P deficiency can promote P availability through the root-induced processes (**Figure 5**) [7] in an alkaline soil, for example, rhizosphere acidification by legumes, nodules root respiration, exudation of phosphatases, carboxylates and/or indirectly through microbial activities [7, 14, 22].

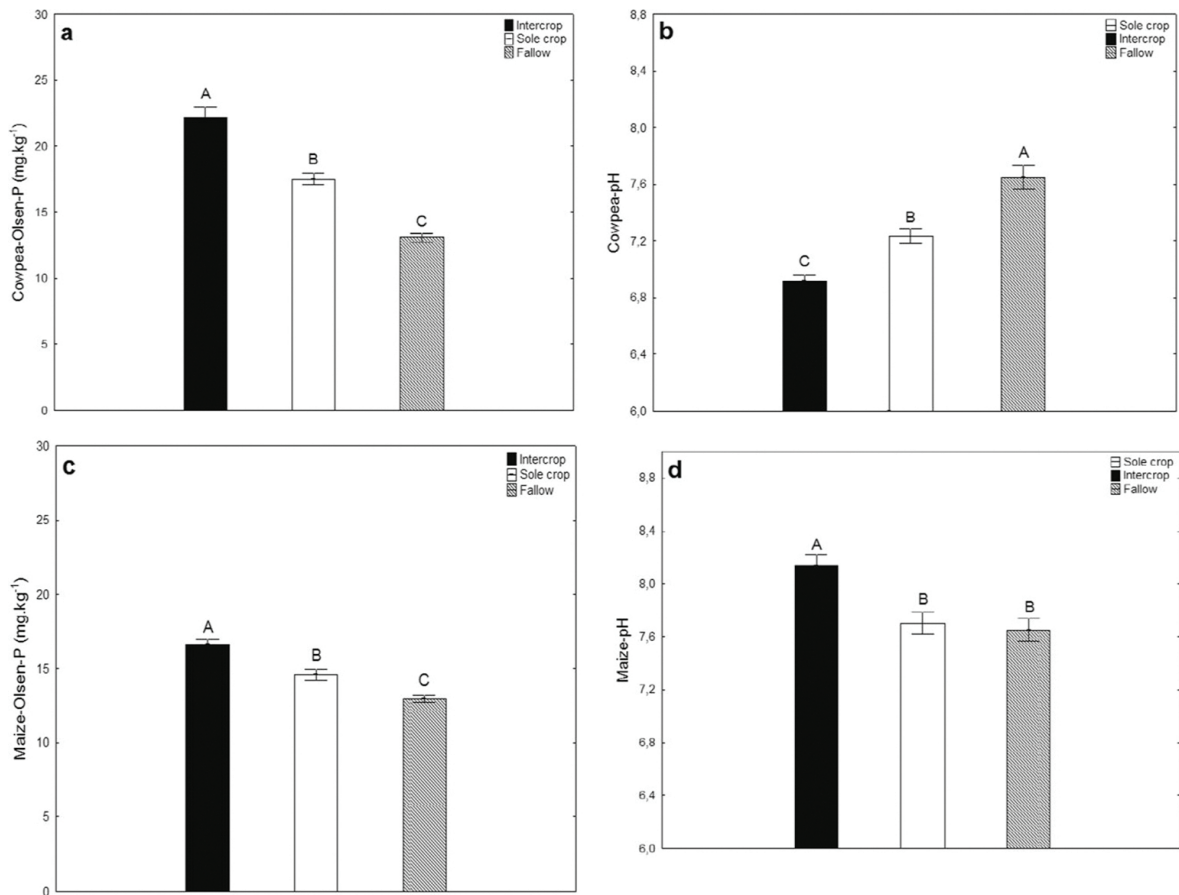


Figure 5. Olsen phosphorus (a, c) and pH (b, d) in the rhizosphere of cowpea and maize as sole crop and intercrop and in the fallow.

Indeed, nutrient limitation is the norm in native soils, especially in alkaline or calcareous soils, including many aridisols and some entisols, which are characterized by poor availability of P and N are less favorable than in most managed systems [2, 3].

Recent studies observed, under field experiments, a significant increase in P availability in the rhizosphere of both common bean and cowpea intercropped with maize [7, 10]. An increase in P availability was reported to (i) an acidification in the rhizosphere of cowpea and common bean in intercropping, (ii) alkalization in the rhizosphere of maize, it was significant only for the maize in intercropping and (iii) an increase of nodules-root respiration in intercropping compared to the monocropping system. Few research studies suggest that the availability of P in the rhizosphere is affected not only by changes in pH, but also by interacting with other root-induced changes such as an increase in EURL and C-CO₂ flux from microbial and root activity (**Figure 6**) [7].

However, species interactions resulted in an increase in growth only for maize in the alkaline and calcareous low P soil. In the other hand, these authors were reported a significant correlation between nodule biomass and Olsen-P in the rhizosphere of intercropped common bean in low P conditions indicates a positive effect of nodule growth in altering rhizosphere P availability.

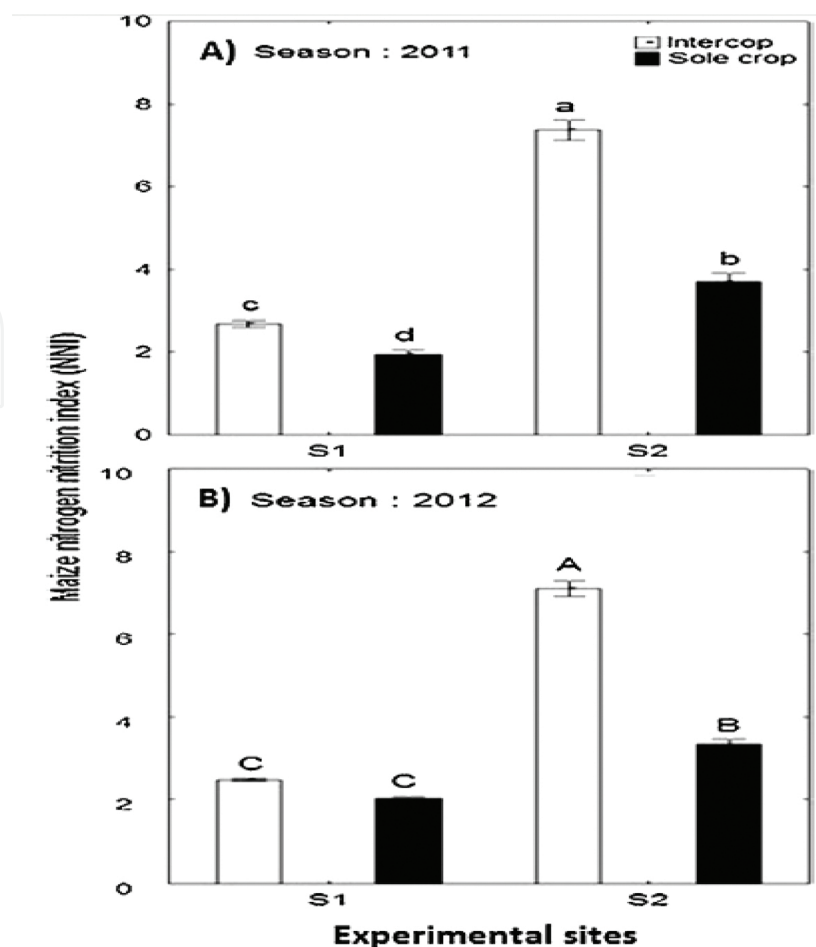


Figure 6. A, B: Nitrogen nutrition index (NNI) of maize as sole crop or intercrop under S1 (P-deficient) and S2 (P-sufficient) conditions.

5. Phosphorus and nitrogen nutrition under legumes-cereals intercropping

For intercropped cereals, an increase in P and N concentration and plant biomass, associated with an increase in grain yield, is assumed to result from the positive effect of legumes on P availability [2, 7]. Li et al. [23] and Latati et al. [10] reported an improvement in the growth of intercropped maize by improved P nutrition. For intercropped legumes, no facilitation was observed; these authors suggest that phosphatase activity produced by either chickpea or common bean increased the mineralization of organic P and its absorption by the associated maize.

In one of last research study, results showed that the EURS was significantly increased in both common bean and cowpea intercropped with maize. Such an increase is associated with high N and P availability in the rhizosphere of common bean and cowpea in intercropping, as a result, increase in N (Table 1) [2] and P uptake in shoot and seed of intercropped maize, especially for under low P and N conditions [7, 10].

Sites	Crop	Common bean			Maize		
		Shoot N concentration (mg g ⁻¹)	Root N concentration (mg g ⁻¹)	Seed N concentration (mg g ⁻¹)	Shoot N concentration (mg g ⁻¹)	Root N concentration (mg g ⁻¹)	Seed N concentration (mg g ⁻¹)
S1	Intercrop	45.3 ± 0.1 b	14.2 ± 0.3 c	54.7 ± 0.4 d	29.6 ± 0.2 a	4.1 ± 0.04 c	23.7 ± 0.2 b
S1	Sole crop	58.2 ± 0.08 a	17.5 ± 0.2 b	59.5 ± 1.1 b	25.8 ± 0.3 b	3.8 ± 0.1 c	18.4 ± 0.6 d
S2	Intercrop	38.4 ± 0.4 d	15.4 ± 0.1 c	71.3 ± 0.2 a	30 ± 0.2 a	5.7 ± 0.06 b	19.3 ± 0.08 d
S2	Sole crop	36.2 ± 0.3 e	11.3 ± 0.6 d	57.2 ± 0.08 c	25.3 ± 0.2 b	7.5 ± 0.08 a	20.8 ± 0.1 c
S3	Intercrop	40.7 ± 0.06 c	17.1 ± 0.1 b	58.9 ± 0.2 bc	23.8 ± 0.4 c	3.6 ± 0.1 cd	27.5 ± 0.08 a
S3	Sole crop	37.6 ± 0.1 d	21.4 ± 0.2 a	58.4 ± 0.2 bc	19.7 ± 0.3 d	3.2 ± 0.2 d	20.6 ± 0.1 c
		Shoot N concentration	Root N concentration	Seed N concentration	Shoot N concentration	Root N concentration	Seed N concentration
		<i>p</i> Values	<i>p</i> Values	<i>p</i> Values	<i>p</i> Values	<i>p</i> Values	<i>p</i> Values
Sites		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Crop		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Sites × crop		<0.001	<0.001	<0.001	0.34	<0.001	<0.001

Table 1. Nitrogen concentration in shoots, roots and seed for maize and common bean in sole crop and intercropping.

Indeed, legume had a positive effect on interspecific competition through nitrogen partitioning with the intercropped cereal via increased of N₂ fixation under intercropping system. Analyzing the nitrogen nutrition index (NNI) in maize also added value in explaining the intercropping grain yield advantage and resource use improvement. This is clearly seen under P-deficient soil where intercropped maize (compared to sole-cropped maize) increased maize NNI nutrition (**Figure 6**) [10]. Enhancing the maize NNI appears to be in agreement with the increased total N uptake under P-deficient soil, but to a more extent in P-sufficient soil where higher maize root biomass would have greatly competed for soil N uptake [15].

6. Advantage of intercropping on grain yield and nutrients uptake

In terms of grain yield, intercropping had a positive and significant effect on the total grain yield as attested by the higher LER (yield advantage) over that found in sole cropping. This observation under field experiments indicates an increased crop performance and resource use efficiency of limiting resources (**Table 2**) [10], but to a larger extent in the P-deficient soil where LER of grain yield and total P and N were significantly higher compared to P-sufficient soil [10, 14].

Season	Exper. sites	LER (yield)	LER (TDW)	LER (N)	LER (P)
2011	S1	2.45 ± 0.2 ^a	2.02 ± 0.09 ^{ab}	2.06 ± 0.1 ^b	2.1 ± 0.1 ^a
	S2	1.67 ± 0.1 ^b	1.91 ± 0.1 ^{ab}	2.67 ± 0.07 ^a	1.76 ± 0.009 ^{ab}
2012	S1	2.71 ± 0.1 ^a	2.3 ± 0.1 ^a	2.02 ± 0.04 ^b	1.93 ± 0.2 ^{ab}
	S2	1.85 ± 0.2 ^b	1.67 ± 0.03 ^b	2.79 ± 0.09 ^a	1.55 ± 0.05 ^b
<i>p</i> Values					
Exper. site		<0.001	0.002	<0.001	0.005
Season		0.13	0.82	0.6	0.09
Site × season		0.37	0.018	0.4	0.9

Table 2. Land equivalent ratio (LER) for grain yield, total biomass (TDW), nitrogen (N) and phosphorus (P) uptake under S1 (P deficient) and S2 (P sufficient) conditions.

The complementarity of N and P use between cereals and N₂-fixing legumes, where the two species compete for the same soil's pool of N and P, the legume, through symbiotic N₂ fixation, can essentially access to the additional pool of atmospheric N₂ [10].

Facilitation occurs some species increases either growth or N-P nutrition of another species [25]. Recently, some research studies reported that advantage of both intercropping maize-common bean and maize-cowpea was confirmed for N and P acquisition by either chickpea or durum wheat [10].

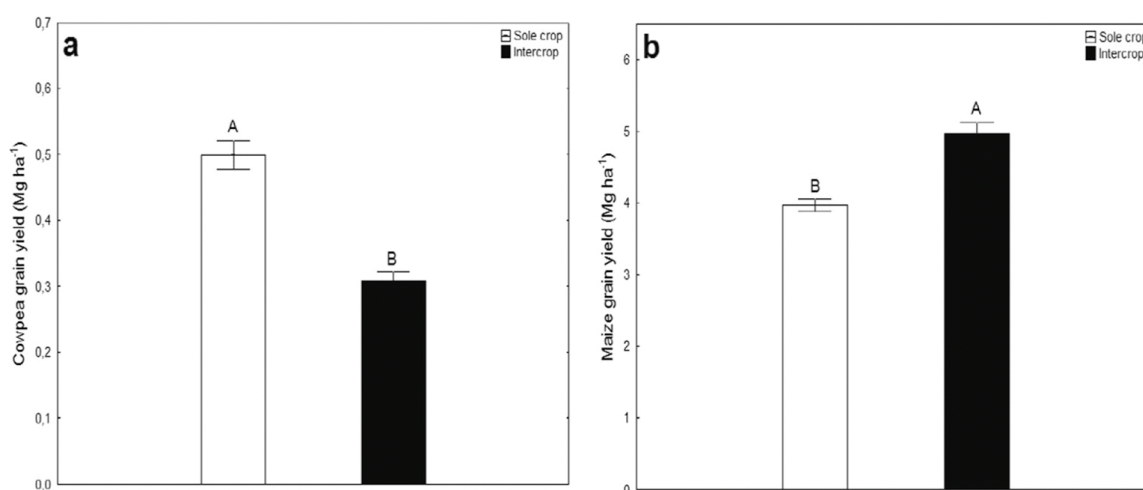


Figure 7. Grain yields (Mg ha⁻¹) of cowpea (a) and maize (b) in different cropping systems.

This intercropping advantage recorded more than 24% N uptake compared to sole crop. Similarly, under Mediterranean conditions with P-deficient soils, it was confirmed that maize grain yield in a maize-cowpea (Figure 7) [7] and common bean-cowpea intercropping under

P-low soil substantially increased (25%) compared to sole-cropped maize [7, 10]. Likewise, grain yield of either maize [26] or durum wheat [14] was increased when intercropped with cowpea and faba bean; respectively. In another study, above- and belowground interactions in a wheat-soybean intercropping differentially contributed (30% and 23%, respectively) in yield increase [27].

7. Conclusion

The main aim of this revision of the literature was to explain the effect of intercropping chickpea and durum wheat on N and P acquisition, especially under Mediterranean conditions.

Intercropping of cereal and legume can improve P and N use efficiency for crop growth and grain yield compared to sole crops. Enhanced soil P and N acquisition by root activity of either intercropped legume or cereal has been proposed as a mechanism of facilitation. It has also been reported that facilitation was more pronounced by interspecific competition when P and N are more limiting for crop growth. Biomass, grain yield and consequently the taken up amount of N and P of intercropped cereals were significantly increased compared to those observed as sole crop. Presumably, pH change, increase in EURLS and root respiration in legumes rhizosphere were the root-induced processes implied in the enhanced N and P availability for intercropped cereals. Indeed, in low P calcareous soils, the increased P availability can significantly improved aboveground of biomass in intercropping, though it mainly enhanced grain yield for intercropped cereals.

As conclusion, research findings reported in this present revision suggest that intercrops promote an advantage in grain yield and N-P nutrition for both cereal and legume. This legumes facilitation would have been related to root-induced changes modifying N and P bioavailability in the rhizosphere, as a result of enhancing in EURLS in low P soils conditions.

Author details

M. Latati^{1*}, S. Benlahrech¹, M. Lazali², Tellah Sihem¹, G. Kaci¹, R. Takouachet¹, N. Alkama³, F.Z. Hamdani¹, E.A. Hafnaoui¹, B. Belarbi¹, G. Ounane¹ and S.M. Ounane¹

*Address all correspondence to: m.latati@yahoo.com

1 National High School of Agronomy (ENSA), Department of Plant Production, Laboratory of Integrative Improving of Plan Production, Avenue Hassane Badi, El Harrach, Algiers, Algeria

2 University of Djilali Bounaama Khemis Miliana, Route Theniet El Had, Soufay, Ain Defla, Algeria

3 University of Mouloud Mammeri, Agronomy Department, Tizi Ouzou, Algeria

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