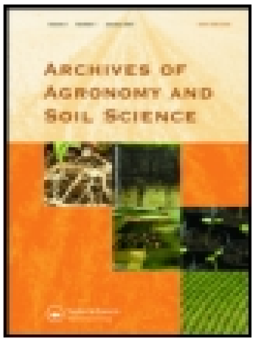

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On farm analysis of the effect of the preceding crop on N uptake and grain yield of durum wheat (*Triticum durum* Desf.) in Mediterranean conditions.

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Abstract

One of the challenges of eco-efficient agriculture is the development of operational farming practices to increase the level of agricultural production, maximize the efficiency of resource use and reduce environmental impacts. Based on the efficiency frontier concept and the decomposition of resource use efficiency, we used a three-quadrant framework allowing to carry a functional analysis of the cropping system. Using a data envelope approach, we established boundary curves which represent the maximum achievable performances (yield, N uptake) when N is the only limiting factor. This framework has been first implemented and tested using published data from 112 agronomic situations of rainfed durum wheat in experimental fields in northern Syria and then further applied on a data set of 245 agronomic situations of durum wheat in farmers' fields in two grain-producing regions of Tunisia. The results demonstrated the impact of preceding crops: durum wheat following legumes or vegetable showed a higher potential for N uptake but with only a minor effect on its conversion into grains. This positive effect of diversified rotation on potential N uptake by durum wheat is partly of-set by increased N uptake gaps in farmer's fields indicating a higher effect of other limiting factors.

Keywords: eco-efficiency, resource efficiency, crop successions, N uptake gap

Introduction

South Mediterranean countries have to meet the challenge of increasing food production, especially through yield increase of strategic crops such as cereals, and simultaneously cope with unfavorable crop growth conditions due to water scarcity and uneven access to fertilizer (Pala et al. 2007). Although water availability is considered as the main limiting factor of cereal grain production in the South Mediterranean (Garabet et al. 1998), nitrogen (N) availability is also a key factor (Boussen et al. 2005). Cereals need large amounts of N to produce both straw, frequently used for animal feeding, and grain yield with high levels of proteins especially for durum wheat (Latiri et al. 1998). Therefore, most farmers use significant amount of N fertilizers on cereals in the region. However, N losses through volatilization and leaching are frequent in the region, especially during rainy years, impacting both soil N availability for crops and surface and ground water quality (Karrou et al. 2001). Therefore, reducing the amounts of N fertilizer used in cereal-based cropping systems can be considered as a major driver of sustainability.

Reducing N input, while increasing cereal grain yields, requires a significant increase in N-use efficiency (Porter et al. 2013), which is commonly considered to be antagonist with productivity (Oweis and Hachum 2009). However, different farming practices have been reported to simultaneously increase crop productivity and maximize N-use efficiency. According to Rahman et al. (2014), the use of alternative sources of N such as biological fixation by legumes and/or residual soil N pools as well as improved fertilization practices are relevant strategies to improve both the autonomy of farming systems regarding N fertilizers and the N-use efficiency. Crop rotations have been increasingly recognized to benefit to growth and yield of subsequent cereals, even in water-limited environments as they improve soil moisture as well as soil N availability through legume N-fixing processes (Ryan et al. 2008b), and therefore enhance N capture and conversion (De Wit 1992). They would also break diseases and weeds cycles (Ryan et al. 2008b).

The simultaneous increase in both yield and N-use efficiency is at the core of the "eco-efficient" agriculture which targets efficient and sustainable use of resources in agricultural production and land management (Keating et al. 2010). In his pioneering work on resource use efficiency in crops, De Wit (1992) proposed to decompose the resource use efficiency into processes underlying resource capture and conversion. To do so, the amount of N uptake was considered as intermediate variable between N input and crop yield in order to analyze the functional determinants of biomass production. More recently, the eco-efficiency concept has been introduced by Keating et al. (2010). It relies on the hypothesis that the maximum resource efficiency of each cropping system, i.e. the potential amount of any agricultural output (e.g. crop yield) achieved at a given level of resource input (e.g. amount of N fertilizer), can be characterized by a non-linear function of resource input called eco-efficiency frontier. The eco-efficiency frontier cannot be transgressed without significant changes in the cropping system, such as changing crop genotype (Keating et al. 2010) or by enhancing crop diversity with associations or rotations (Gaba et al. 2015). Eco-efficiency frontiers were further used to compare resource efficiency across farmers' fields (Carberry et al. 2013) and were shown relevant to analyze regional yield gaps (van Ittersum et al. 2013). Yield gaps represent differences between actual farmers' yields and the maximum yield that can be attained if no resource is limiting or if only one resource is limiting (e.g. N-limited potential yield) (Keating et al. 2010; van Ittersum and Rabbinge 1997). Combining the eco-efficiency approach with the De Wit (1992) decomposition framework can provide an operational tool to make use of experimental and farmers' field measurements into a more comprehensive diagnosis and to identify which mechanisms need to be amplified to improve the productivity and efficiency of cropping systems. This approach has been first tested with an extensive set of experimental data in Syria and further applied in a large network of farmer's fields in Tunisia with less variables measured, in order to analyze the extend of the effect of the preceding crop on N uptake and grain yield of durum wheat.

Material and Methods

The three quadrants diagram

The three-quadrant framework of De Wit (1992) is a simple way (Figure 1d) to integrate three key concepts in agronomy: (i) the limiting factor (von Liebig, 1855; Figure 1a), (ii) the yield gap (van Ittersum and Rabbinge 1997; Figure 1b) and (iii) the eco-efficiency frontier (Keating et al. 2010; Figure 1c). Such a synthetic framework, which can be implemented with simple field measurements or farmer surveys, allows analyzing the effect of crop management and crop rotation on the efficiency of the crop for the capture and conversion of a resource (here N).

The amount of N uptake is introduced as an intermediate variable to decompose the overall N-use efficiency (ratio between yield and N-input), into N capture efficiency (quadrant I) and N conversion efficiency (quadrant II). N capture efficiency is given by the ratio between the amount of N uptake and the total amount of N-input, while N conversion efficiency is given by the ratio between grain yield (or total biomass or grain protein yield depending on the question to be addressed) and the amount of N uptake. In each quadrant, a curve delimitating the upper limit of all observed situations for each preceding crop of durum wheat can be fitted. In theory the resulting curves (I, II and III, Figure 1d) represent a boundary which defines the maximum achievable performance (N uptake, yield) for a given level of resource (N-input, N uptake) when this resource (here N) is the only limiting factor. In practice, in the rainfed Mediterranean systems were our data have been collected, it is likely that water availability may also influence the parameters of this curve.

The shape of these output-input response boundary curves can be intuitively designed as concave downward, indicating that for each additional increment of input, the marginal increase in performance is smaller than from the previous input increment (von Liebig 1855; Mitscherlich 1909; Singleton et al. 1992). For example, the boundary curve of N capture could be modeled as follows (Fermont et al. 2009) (Equation 1):

$$Nup = \frac{\mathrm{Nmax}}{1 + (\mathrm{k}\exp^{-\mathrm{r}x})} \qquad (1)$$

Where Nup is the N uptake by the crop for a given level of N input (x) when there is no limiting resources or factors others than N, in rainfed systems as stated above, Nmax is the curve asymptote which reflects the maximum N uptake, and k and r are constants that influence the intercept and slope, respectively. These parameters can be related to biophysical processes: k is influenced by the amount of N supplied by other sources of N than fertilizers such as mineralization of soil organic matter during the crop cycle, while r stands for the ability of the plant to capture soil mineral N (Delogu et al. 1998). Indeed, N uptake by crops could start before fertilization, reflecting the use of soil N made available by mineralization of soil organic matter, by residual N pools of the preceding crop (Fustec et al. 2010) or by atmospheric deposition (Ladha et al. 2016). Therefore, the fitted curve has a positive intercept. In addition, we assume that small amounts of nitrogen supplied in excess have no negative effect on N uptake (Cox and Reisenauer 1973; Wang et al. 2011), explaining why this curve does not decrease with high amounts of nitrogen fertilizer.

Similarly, for quadrant III, the boundary curve of durum wheat response to N-input could be modeled as (Equation 2):

$$Ya = \frac{\mathrm{Ymax}}{1 + (\mathrm{k}\ \mathrm{exp}^{-\mathrm{r}x})} \qquad (2)$$

Where Ya is the N-limited grain yield for a given level of N-input (x) and Ymax is the curve asymptote which reflects the maximum level observed in the target variable (durum yield).

Once N has been captured by crops (quadrant I), N conversion (quadrant II) is no longer dependent on soil fertility factors but depends mainly on plant factors (e.g. plant genetics, functional traits, phenology) and other external factors such as weather conditions (e.g. water scarcity, extreme heat) or pests and diseases. According to Spiertz and De Vos (1983), the relationship between N uptake and yield (quadrant II) may be approximately linear at low values of N uptake, but above a certain level the curve should deviate downwards, reflecting an increase in tissue N content. A second-order polynomial model equation is expected to fit well such curve shape (Equation 3), where Ya is the yield for a given level of N uptake (x) when there is no limiting resources or factors others than N (and water in our rainfed conditions):

$$Ya = ax^2 + bx \qquad (3)$$

The curve has the origin as intercept since crop growth is not possible with zero N uptake (De Wit 1992).

Data sets to implement the three-quadrant framework

In a first step, the three-quadrant framework was implemented with all the measured variables needed, in order to test the above described *a priori* shapes of boundary curves for each preceding crop of durum wheat. As some of these variables are hardly available in farmers field surveys (see below in Tunisia), we used an extensive dataset obtained by ICARDA in a similar rainfed Mediterranean conditions. The experiments were conducted in the Tel-Hadya experimental station, in northern Syria between 1985 and 1989 (Harris 1990; Ryan et al.

2008a). In this region, annual rainfall varies from 200 to 600 mm, with high inter-annual and within-season variability (Cooper et al. 1987). The soil has a clay texture with organic matter content varying from 0.8 to 1%. Data on grain yields and total dry matter of durum wheat, were collected from wheat plots grown with four N fertilization rates (0, 30, 60 and 90 kg N ha^{-1}), in seven two-year rotations from 1985/1986 to 1988/1989. The various preceding crops of wheat were: fallow, watermelon, wheat, chickpea and other legumes (lentil, vetch and medic). N concentration in grain and straw, as influenced by N-rate and crop rotations were measured between 1989–1990 and 1997–1998 (Ryan et al. 2008a).

After checking the framework consistency regarding boundary curve shape (see equations 1 to 3) with these experimental data were all variables have been measured, we used it to analyze a database obtained with a survey of farmers' fields in Tunisia for which only some of the variables can be easily collected (amount of N applied, grain and straw yield). The purpose of the study was to assess, at low cost and for a large network of farmers' fields, whether higher eco-efficiency frontiers, allowing to increase both yields and N-use efficiency (quadrant III) of durum wheat, may be achieved with non-cereal preceding crop. Data on rainfed durum wheat were collected in two Tunisian regions: Fernena, and Lebna catchment. Fernena belongs to the governorate of Jendouba which is located in the North-West of Tunisia, in a sub humid bioclimatic area characterized by a mean annual rainfall of 650 mm (Rezgui et al. 2005). The Lebna catchment is situated in the Cap Bon peninsula in the North-East of Tunisia. The climate varies from sub-humid in the extreme upstream of the basin to semi-arid regime over the eastern part with an average annual rainfall ranging from 400 to 800 mm (Mekki et al. 2018). The annual average Penman-Monteith reference crop evapotranspiration over the 2004–2014 period is 1366 mm (Zitouna-Chebbi et al. 2018). The data set collected was based on farmers surveys conducted on a sample of 245 agronomic situations (i.e. the combination of a field, a year and a preceding crop) of rainfed durum wheat which are representative of the diversity of farmers' practices, in the study area. A first survey was conducted in 2011/2012 on 115 agronomic situations in Fernena and the second was carried out on 130 agronomic situations in the Lebna catchment, for 2012/2013 and 2013/2014 cropping seasons. The various preceding crops were: cereals (wheat, barley, and oats), vegetables (potato, onion and watermelon) and legumes (chickpea, vetch, medic and faba bean). The number of fields per preceding crop is 83, 41, 32 and 89 for cereals, vegetables, chickpea and other legumes respectively. The most prevalent soil at Fernena was a silty clay loam with an average organic matter content of 2 % (Table 1). In the Lebna catchment, soil textures were very variable ranging from clay to sandy loam with organic matter content varying from 0.5 % to 2.2 % (IAO 2002). Organic matter content is on average similar for the various preceding crops, but it shows a high variation in each class of preceding crop with reported coefficients of variation higher than 45 %, which might be due to intra-regional variability of soils or between regions (Table 2). The resulting database contains information on wheat yields (grain and straw), nitrogen fertilization (N applied, number and date of N-application), preceding crop and other information about the crop management system (sowing dates, soil tillage, pesticide use).

Estimation of N uptake in farmer's fields

For the Tunisian database, due to a lack of grain and straw N concentration measurements, which were not possible in such large farmers' fields survey, we established a simple model (Equation 4) to estimate N uptake for each field, assuming that N uptake by durum wheat is the sum of N in grain and straw (Ayadi et al. 2014):

$$N\ uptake\ =\ (DM\ grain \times \%\mathrm{N\ grain}) +\ (DM\ straw \times \%\mathrm{N\ straw}) \qquad (4)$$

To parameterize this model, we collected published data on N concentration (grain and straw), dry matter (grain and straw), harvest index (HI) and nitrogen harvest index (NHI) from experimental results on durum wheat in different regions and with a wide range of climate, soils, varieties and management type (Table 3).

In addition to this literature survey (Table 4), we implemented an experimental trial with four randomized blocks at the INRA experimental station in Montpellier, for the four durum wheat varieties used by farmers in Tunisia (Karim, Nasr, Maali and Razek). We measured N concentration, dry matter and harvest index for these four varieties (Table 4). Results suggest that there was no significant difference of N concentration in grain and straw between varieties (Table 4) which were all also very close of the average value of the durum wheat varieties reported in previous studies.

Since N concentration in straw was highly variable across the data set of Table 4 (CV of 37.9% for straw compared to 13.2% for grain) it was not possible to estimate N uptake using N content in grain and straw as parameters (Equation 4). On the contrary, nitrogen harvest index showed a low variability across the whole data set of Table 4 (e.g. CV of 11.1 % across 66 agronomic situations in a wide range of soil, climate, varieties and crop management). Thus, we considered that the best model to estimate the amount of N uptake by durum wheat in each Tunisian farmer's field would be given by the equation (5) with one variable (DM grain) depending on the agronomic situation and two parameters (%N grain and NHI) kept constant across all situations (Equation 5):

$$N\ uptake\ = \frac{DM\ grain \times \%\text{Ngrain}}{\text{NHI}} \qquad (5)$$

This model of N uptake was evaluated (Figure 2) on the experimental data set from ICARDA's research station at Tel-Hadya where the four components of the equation (4) have been measured. A common measure of model quality is the relative root mean square error (RRMSE), which corresponds to the square root of the average errors between simulated data and measured data, divided by the average of the measured data (Wallach et al. 2014). The model was found to simulate reasonably well N uptake with a RRMSE less than 20% (Figure

2). The error was very low below N uptake of 40 Kg N/ha, then increased without between 40 and 120 kg N ha^{-1}, to show a systematic underestimation above 120 kg N ha^{-1}. Since the model was based on grain biomass, this underestimation could be due to the negative correlation between the nitrogen concentration in grain (%N grain) and grain biomass at high yield levels as shown by Bogard et al. (2010) on wheat.

Determination of boundary curve parameters for wheat depending on the preceding crop

Using data collected from wheat plots at Tel Hadya station between 1985/1986 and 1988/1989, and then Tunisian data from farmers surveys conducted in 2011/2012, 2012/2013 and 2013/2014, distinct boundary curves for N capture (Equation 1) were fitted according to rotation type. Forage legumes (medic and vetch) and lentil were grouped together into a single category named "other legumes", both for the Tel Hadya data set and for the Tunisian data set (for vetch, medic and faba bean). Indeed, according to Ryan et al. (2008a), these preceeding crop contributed to a quite similar amount of N to the following durum wheat and higher than the effect of chickpea. Similarly, experiments from Beck et al. (1991) in the same experimental station during the same period showed that the apparent N budget of chickpea is negative while it is positive for lentil.

To estimate the parameters of the boundary curves for each preceding crop, we first selected a series of points across the whole range of N-input for which N uptake (or grain yield) was maximum using the procedure described by Shatar and Mc Bratney (2004). We then fitted a non-linear model (Equation 1 or 3) on this subset of point, and Nmax (or Ymax), k and r were estimated by the generalized least square method using R programming environment. In order to test whether the boundary curve of durum wheat was influenced by the preceding crop, we performed model comparisons on parameters Nmax, k, and r between these non-linear regression models with or without rotation as a fixed effect. We compared each time the boundary curve of each rotation to the highest boundary curve. To do so, we compared two nonlinear models for each rotation. The first model was fitted (with the nls procedure in R) through the boundary points selected on the whole cloud of data point. The second model was fitted through the boundary points selected over the cloud of data points corresponding to this rotation only. For both models, boundary points were selected according to Shatar and Mc Bratney (2004) method, with a window width equal to 10% of the difference between min and max of observations. We used the Akaike criterion (AIC) to decide on the best model: a global model, and a specific model (a rotation effect was introduced on every parameter of the boundary curve). This adjustment was performed using *nls* and *gnls* functions from *nlme* package in R (Pinheiro and Douglas 2000).

Parameters of the boundary curve for N conversion (quadrant II) were also determined by fitting a non-linear regression model (Equation 3) on boundary points selected with the same procedure as above-mentioned. This was possible only for the experimental data in Syria where the N uptake was measured and not in the Tunisian farmer's fields (in absence of measurement of grain and straw N concentrations), where it was estimated by the model described in 2.3 which led to force the boundary curves of quadrant II to a linear shape. The nonlinear model (Equation 3) was compared to the linear model in the experimental situation, by using the Akaike criterion (AIC), in order to analyze the error induced in quadrant II by the method used to estimate N uptake in farmers' fields.

N uptake gap

For each preceding crop, the boundary curve of N uptake was further used to analyze, for each farmer field (represented by a point below the boundary curve), the relative N uptake gap calculated as follow (Equation 6):

$$Relative\ N\ uptake\ gap = \frac{(Attainable\ N\ uptake - Actual\ N\ uptake) \times 100}{Attainable\ N\ uptake} \qquad (6)$$

Where the attainable N uptake is the amount of N uptake given by the boundary curve for each level of N input, i.e. when there is no limiting factors or resources other than N (in rainfed conditions).

The value of the N uptake gap is therefore a measure of the influence of other resources and factors than N on the ability of the durum wheat crop to capture N from the soil.

Results

Test of boundary curves shape on experimental fields in Syria

Although it was adjusted to the same equation (1), the relationship between N applied and N uptake, that represents N capture (Figure 3a), was significantly influenced by the preceding crop, as shown by the lower value of the Akaike's Information Criterion (AIC) for the crop specific model (gnls) compared to the global model (nls) (Table 5). The highest value for the maximum N uptake (Nmax parameter) was found for wheat grown after legumes (excluding chickpea), followed by fallow, then watermelon, and chickpea (Table 5). As expected from the literature, the lowest value for the maximum N uptake was found for wheat mono-cropping.

Boundary curves (Equation 3) representing N conversion into durum wheat grain (Figure 3b) were also significantly different according to the preceding crop. Maximum yield was significantly higher for wheat grown after fallow and watermelon than after legumes and cereal crops. However, this difference was smaller than the difference between boundary curves of N capture (Figure 3a). This data set also allows to test the use of the linear model, imposed by the data set in the Tunisian farmer's fields, instead of the expected polynomial curve to describe the N conversion boundary curve. The comparison of the model, used to establish boundary curves to a linear model shows that polynomial model allows to adjust data better than the linear model, as shown, mostly, by the lower value of the Akaike's Information Criterion (AIC). However, the difference between both models was not significant for all the preceding crops, as shown by the case of wheat following watermelon and chickpea (Table 6). This indicates that the simplification of the relationships in quadrant b of Figure 4, due to lack of data on N concentration of grain and straw N uptake (Equation 5), which imposed a linear function instead of the polynomial function (Equation 3), should not impact the overall comparison between preceding crops for their effect on durum wheat, most of this effect being explained by the ability of the crop to capture N rather than its ability to convert it into grain (Figure 3).

Boundary curves (Equation 2) of wheat response to nitrogen applied (Figure 3c) were also found significantly different with the preceding crop. The highest maximum yield (Ymax parameter) was found for wheat grown after watermelon (6.3 t ha^{-1}) followed by fallow (Ymax= 5.1 t ha^{-1}) and legumes (5 t ha^{-1}). By contrast, the lowest Ymax (1.6 t ha^{-1}) was found for wheat in monoculture.

Application of the framework in farmer's fields in Tunisia

Boundary curves between N uptake and N-input were again found significantly different between the preceding crops (Figure 4a, Table 8), despite the variability of soils, years and crop management represented in the database of 243 agronomic situations. Despite the large variability of N uptake for a given level of N-input in this dataset, a large difference was found in maximum N uptake (Nmax given by the asymptote of the boundary curve in Figure 4a) between wheat following cereal and the other crops. The highest value for Nmax was obtained for a wheat following a legume (165 kg ha^{-1}), followed by vegetables, and chickpea. By contrast, the lowest value for Nmax was found for wheat in cereal-wheat rotation (98 kg ha^{-1}). The highest potential N capture efficiencies derived from this Nmax were found for wheat following legumes (2.14 and 1.33 kg N uptake/kg N applied, for 60 kg applied N ha^{-1} and 120 kg N ha^{-1} respectively) while the lowest N capture efficiency was found for wheat monocropping (1.3 and 0.78 kg kg^{-1} respectively). Vegetables and chickpea led to intermediate values of N capture efficiency of durum wheat (Figure 4a, Table 8). Due to the structure of error on N uptake prediction in these field conditions (see part: *Estimation of N uptake in farmer's fields*), estimated values of N uptake were not judged reliable enough to analyze the effect of rotation on N conversion in farmers' fields in quadrant b (Figure 4b), which was therefore represented by a single linear relationship. As a consequence, boundary curves of wheat response to nitrogen, characterizing the eco-efficiency frontier for each preceding crop (Figure 4c), showed the same trend as for N capture. The highest Ymax (5.8 t ha^{-1}) was obtained for wheat following legumes (excluding chickpea), followed by vegetables and chickpea. By contrast the lowest Ymax (3.5 t ha^{-1}) was found for wheat in cereal-wheat rotation.

When considering all the fields surveyed, a large variability (from 0 to 81%) was observed in N uptake gap (i.e. the relative distance to the boundary curve in quadrant a in Figure 4) of durum wheat compared to the boundary curve of the corresponding preceding crop (Figure 5). The average relative N uptake gap across the whole data set was 30%. When durum wheat was grown after chickpea or cereal, more than 60% of farmers' fields had relative gaps lower than this 30% average gap. By contrast, only 30% of farmers' fields grown after a legume had relative gaps lower than average. Vegetables preceding crops have an intermediate position, with 50% of farmer's fields below the average gap. There was no significant relationship between N uptake gap and the level of N applied, since any level of N input could result equally in any type of gap (Figure 6).

Discussion

A data-parsimonious functional analysis of preceding crop effect on N use efficiency across farmers' fields

Our case study in Tunisia, show that the three quadrant framework can be used with farmers data (e.g. amount of N applied, grain and straw yields, and if possible grain and straw N content) for a functional analysis of the effects of crop rotation (e.g. type of preceding crop) and management (e.g. N fertilization) on resource use efficiency in durum wheat-based systems in rainfed conditions. The relevance and robustness of the framework, which was previously tested with the Syrian dataset, lies in its ability to disentangle the effects of physiological processes (uptake vs conversion). It makes use of classical experiments and field surveys data bases in which grain and straw N content are frequently lacking, to define functional hypothesis (e.g. based on soil-plant biophysical processes) for further research and extension activities on how to improve simultaneously yield and N use efficiency.

Our results confirm that cereal monocultures have poor grain yield response to N in comparison with more diversified rotations, most of this effect being due to N capture rather than N conversion. While these results are common in experimental conditions (e.g. Figure 3) we demonstrate here, with data easily available by farmers interviews, that they also apply in these conditions with even a larger effect of rotation on N capture by durum wheat (Figure 4a) than in experimental conditions. This implies that, in farmer's field conditions, a non cereal legume crop is able to create a strong lift in the eco-efficiency frontier (Figure 4c) which is high enough to compensate for the reduction of wheat frequency imposed by the rotation with other crops. As suggested by López-Bellido and López-Bellido (2001), there is therefore an opportunity to significantly improve N capture efficiency of durum wheat cultivation by diversifying crop rotations. The highest boundary curve of N capture was found for wheat grown after legumes (vetch, medic and faba bean). Legumes had probably higher fertilizing effects than other preceding crops, because of soil N enrichment through symbiotic N-fixing processes (Burns and Hardy 1975). But they could also have improved soil structure, by increasing soil aggregates stability and soil porosity (Masri and Ryan 2006), therefore promoting soil N mineralization and plant absorption. They may also have limited weeds, pests and diseases specific to wheat. Chickpea, which is also a legume crop, had a lower effect than other legumes probably because of its lower N fixation efficiency, leading to less input from the atmosphere, and because of its higher NHI, leading to a lower return to soil through crop residues (Beck et al. 1991). From the equation of the boundary curve in Figure 3a, we hypothesize that processes acting on soil N availabity would explain the increase along the x-intercept (influenced by parameter k in Equation 1) while processes acting on other limiting factors would explain the increase in the asymptote (parameter Nmax in Equation 1). The third parameter (r in Equation 1) could reflect the method of N application and especially the timing with regards to plant stages and the form of mineral fertilizers that could influence the efficiency of nitrogen capture (López-Bellido et al. 2005). Our dataset does not allow a deeper analysis of biophysical processes and how they were related to farming practices and to the preceding crop. As shown by Porter et al. (2013), the analysis of N capture efficiency would require adding other intermediate variables (e.g. soil N availability), splitting quadrant a in two by adding a soil N availability axis, and allowing further analysis of limiting factors in farmers' fields. For example, the beneficial effect of vegetables in the rotation, especially on k parameter, could be the result of N rich residues left to the soil or to an overfertilisation during the vegetable crop cycle which is quite common for such type of crops, leaving N surplus for early stages of durum wheat.

Variability of nitrogen uptake gap in durum wheat in Tunisia

Once the boundary curves describing the situation when N is major limiting factor, under rainfed conditions, have been established it remains to be analyzed if, in farmer's field conditions, the higher potential N uptake created by rotation is realized or not. This analysis of N capture efficiency by durum wheat can be performed for each rotation system using the relative gap between actual N uptake levels in each field and the potential values when water and N are the only limiting factors, given by the corresponding boundary curves at the same amount of N applied (N uptake gap). Our results obtained in Tunisia show a high variability in N input and N uptake levels across farmers' fields, resulting in a wide range of N capture gaps (Figure 5). A part of this gap may depend on N management and application, e.g. N was applied not at the right plant stage or was followed by a dry event resulting in immobilization in soils or a wet event resulting in N leaching. In Tunisia, N fertilizers are generally applied at late stages, e.g. after apical differentiation, and only if the beginning of the growing season had enough rainfall (Latiri et al. 1998). This can alter final protein composition and N accumulation in the spike (Ayadi et al. 2014). Since our farmer field network was based on rainfed durum wheat only, it is likely that soil water deficit could explain a large part of N uptake gaps, especially by lowering N absorption rates by wheat plants. In the South Mediterranean, it was largely proved that water deficits affect many plant processes involved in biomass production and N uptake (Latiri et al. 1998; Albrizio et al. 2010; Quemada et al. 2016). Finally, biotic factors such as weeds, pests and diseases could also impact N capture gaps. Our data did not allow further analysis of these processes as this would require an extension of the framework to other state variables of the agrosystem such as P uptake or weed biomass at harvest as shown for example by Delmotte et al. (2011) on rice.

Overall the crop preceding durum wheat had both an influence on potential N uptake (Figure 4a) and on the distribution of N uptake gaps (Figure 5). For instance, diversifying rotations with legumes shifted the boundary curve towards higher N uptake levels and increased at the same time the frequency of high relative absorption gaps in comparison with cereal-wheat or chickpea-wheat rotations, even though they were cultivated on the same types of soils. Under field conditions, the combination of these two effects (higher potential and higher gap) could therefore result in a much lower positive net effect on N absorption and yields of durum wheat than suggested by the shift of the boundary curves. It is likely that diversifying rotations are key to create high potentials of N absorption by durum wheat through their positive effects against weeds, pests and disease (Nmax in Figure 4a). However, the risk of N deficit if the N-effect of the preceding crop is not sufficient and/or the risk of shifting the hierarchy of limiting factors towards another factor than N such as soil water deficit (Hochman et al. 2014) clearly remains.

Conclusion

The three-quadrant framework allowed disentangling plant processes underlying N capture and conversion into grain, making use of easy to access data in farmers' fields. Using data collected in long-term experiments in Syria and from farmers' fields in two Tunisian regions, we showed that new efficiency frontiers can be achieved by diversifying crop rotation in cereal-based systems, resulting in higher yields and N-use efficiency potentials. In particular, crop rotation with legumes and vegetables improved N capture capacity of the system, highlighting tracks for designing eco-efficient cereal-based systems in the Mediterranean region. Nevertheless, the level and frequency of N uptake gaps showed that diversified crop rotations, especially legumes-wheat rotation created a higher potential by moving the efficiency frontier upwards but didn't ensure the realization of this N uptake potential in most of the farmer's fields. There are therefore other crop management factors to be taken into account in farmers' fields (irrigation, weed and pest control…) that could also improve nitrogen capture in combination with diversified rotations.

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References

Albrizio R, Todorovic M, Matic T, Stellacci A.M. 2010. Comparing the interactive effects of water and nitrogen on durum wheat and barley grown in a Mediterranean environment. Field Crop Res.115 (2):179–190.

Ayadi S, Karmous C, Hammami Z, Trifa Y, Rezgui S. 2014. Variation of durum wheat yield and nitrogen use efficiency under Mediterranean rainfed environment. IJACS J. 7 (10):693–699.

Beck DP, Wery J, Saxena MC, Ayadi A. 1991. Dinitrogen fixation and nitrogen balance in cool-season food legumes. Agron J. 83 (2):334–341.

Bogard M, Allard V, Brancourt-Hulmel M, Heumez E, Machet J. 2010. Deviation from the grain protein concentration – grain yield negative relationship is highly correlated to post-anthesis N uptake in winter wheat. J Exp Bot. 61(15):4303–4312.

Boussen H, Mellek-Maalej E, Asr N.Z, Ben Mechlia N. 2005. Efficience d'utilisation de l'eau et de l'azote chez le blé dur : Etude comparative de deux variétés à haut potentiel de production [Water and nitrogen use efficiency in durum wheat : Comparative study of two varieties with high production potential]. Proceedings of the International conference on: water, land and food security in arid and semi-arid regions. Sep 6-11; Bari: 1–11.

Burns RC, Hardy RWF.1975. Nitrogen Fixation in Bacteria and Higher Plants. Berlin, Heidelberg, New York: Springer Verlag. (Molecular Biology, Biochemistry and Biophysics; vol. 21).

Carberry P.S, Liang W, Twomlow S, Holzworth D.P, Dimes J.P, Mc Clelland T, HuthN.I, Chen F, Hochman Z, Keating B. a. 2013. Scope for improved eco-efficiency varies among diverse cropping systems. Proc Natl Acad Sci. 110 (21):8381–8386.

Cooper P.J.M, Gregory P.J, Tully D, Harris, H.C. 1987. Improving water-use efficiency of annual crops in the rainfed farming systems of West Asia and North Africa. Exp Agric. 23 (2):113–158.

Cox M, Reisenauer W. 1973. Growth and ion uptake by wheat supplied nitrogen as nitrate , or ammonium, or both. Plant Soil 38 (2):363–380.

De Giorgio D, Montemurro F. 2006. Nutritional status and nitrogen utilization efficiency of durum wheat in a semiarid Mediterranean environment. Agr Med. 160:91-101.

Delmotte S, Tittonell P, Mouret J.C, Hammond R, Lopez-Ridaura S. 2011. On farm assessment of rice yield variability and productivity gaps between organic and conventional cropping systems under Mediterranean climate. Eur J Agr. 35 (4):223-236.

Delogu G, Cattivelli L, Pecchioni N, Falcis D.D, Maggiore T, De Falcis D, Stanca A. 1998. Uptake and agronomic efficiency of nitrogen in winter barley and winter wheat. Eur J Agr. 9 (1):11–20.

Desai R.M, Bhatia C.R. 1978. Nitrogen uptake and nitrogen harvest index in durum wheat cultivars varying in their grain protein concentration. Euphytica. 27 (2):561–566.

De Wit C.T. 1992. Resource use efficiency in agriculture. AGR SYST. 40:125–151.

Ehdaie B, Waines J.G. 2001. Sowing date and nitrogen rate effects on dry matter and nitrogen partitioning in bread and durum wheat. Field Crop Res. 73 (1):47–61.

Fermont A.M, Van Astena P.J.A, Tittonell P, Van Wijk K.E. 2009. Closing the cassava yield gap: An analysis from smallholder farms in East Africa. Field Crop Res. 112:24–36.

Fustec J, Lesuffleur F, Mahieu S, Cliquet J.B. 2010. Nitrogen rhizodeposition of legumes–A review. Agron Sustain Dev. 30 (1):57–66.

Gaba S, Lescourret F, Boudsocq S, Enjalbert J, Hinsinger P, Journet E.P, Navas M.L, Wery J, Louarn G, Malézieux E, Pelze E, Prudent M, Ozier-Lafontaine H. 2015. Multiple cropping systems as drivers for providing multiple ecosystem services: from concepts to design. Agron Sustain Dev. 35 (2):607-623.

Garabet S, Ryan J, Wood M. 1998. Nitrogen and water effects on wheat yield in a Mediterranean-type climate . II . Fertilizer-use efficiency with labelled nitrogen. Field Crop Res. 58 (3):213–221

Harris H.C, 1990. Productivity of crop rotations. Farm Resource Management Program. Aleppo, Syria: ICARDA. Annual Report for 1989:137–157.

Hochman Z, Prestwidge D, Carberry P.S. 2014. Crop sequences in Australia's northern grain zone are less agronomically efficient than implied by the sum of their parts. Agr Syst. 129:124–132.

IAO. 2002. Land resources of the Oued Lebna catchment (Tunisia). Florence, Italy: Istituto Agronomico per l'Oltremare. 20th course: Professional master on remote sensing and natural resources evaluation: 133 p.

Karrou M. 2001. Stratégie d'amélioration de l'efficience de l'utilisation d'azote. [Strategy to improve nitrogen use efficiency]. H.T.E.N. 118:93–96.

Keating B. A, Carberry P.S, Bindraban P.S, Asseng S, Meinke H, Dixon J. 2010. Eco-efficient Agriculture: Concepts, Challenges, and Opportunities. Crop Sci. 50:109–119.

Ladha J. K, Tirol-Padre A, Reddy C. K, Cassman K, Verma S, Powlson D. S, van Kessel C, Richter D.B, Chakraborty D, Pathak H. 2016. Sientific Reports. 6 (19355):1–9.

Latiri-Souki K, Nortcliff S, Lawlor D.W. 1998. Nitrogen fertilizer can increase dry matter, grain production and radiation and water use efficiencies for durum wheat under semi-arid conditions. Eur J Agron. 9:21–34.

López-Bellido R.J, López-Bellido L. 2001. Efficiency of nitrogen in wheat under Mediterranean conditions: Effect of tillage, crop rotation and N fertilization. Field Crop Res. 71 (1):31–46.

López-Bellido L, López-Bellido R.J, Redondo R. 2005. Nitrogen efficiency in wheat under rainfed Mediterranean conditions as affected by split nitrogen application. Field Crop Res. 94:86–97.

Masri Z, Ryan J. 2006. Soil organic matter and related physical properties in a Mediterranean wheat-based rotation trial. Soil Tillage Res. 87 (2): 146–154.

Mekki I, Bailly J.S, Jacob F, Chebbi H, Ajmi T, Blanca Y, Zairi A, Biarnès A. 2018. Impact of farmland fragmentation on rainfed crop allocation in Mediterranean landscapes: A case study of the Lebna watershed in Cap Bon, Tunisia. Land Use Policy. 75: 772–783.

Melki M, Samaali S, Mechri M, Saidi W. 2015. Étude qualitative et quantitative de la production du blé dur (*Triticum durum* Desf .) conduit sous différentes modalités de fractionnement de nitrate d'ammonium. [Qualitative and quantitative study of durum wheat (*Triticum durum* Desf.) production, conducted under different forms of ammonium nitrate splitting]. J N Sci. 20 (6):810–817.

Mitscherlich E. A. 1909. Das Gesetz des Minimums und das Gesetz des abnehmenden Bodenertrages. [The Law of the Minimum and the Law of Decreasing Land Revenue]. Landwirtschaftliches Jahrbuch der Schweiz. 38:537–552.

Ottman MJ, Doerge T.A, Martin E.C. 2000. Durum grain quality as affected by nitrogen fertilization near anthesis and irrigation during grain fill. Agron J. 92 (5):1035–1041.

Oweis T, Hachum A. 2009. Optimizing supplemental irrigation: Tradeoffs between profitability and sustainability. Agric Water Manag. 96:511-516.

Pala M, Ryan J, Zhang, H, Singh M, Harris H.C. 2007. Water-use efficiency of wheat-based rotation systems in a Mediterranean environment. Agric Water Manag. 93:136–144.

Pinheiro J.C, Douglas M.B. 2000.Fitting Nonlinear Mixed-Effects Models. In: Mixed-Effects Models in S and S-PLUS. New York. Statistics and Computing. Springer.

Porter JR, Christensen S. 2013. Deconstructing crop processes and models via identities. Plant Cell Envir. 36:1919–1925.

Quemada M, Gabriel J.L. 2016. Approaches for increasing nitrogen and water use efficiency simultaneously. Glob Food Sec. 9:29–35.

Rahman M.M, Islam A.M, Azirun S.M, Boyce A.N. 2014. Tropical legume crop rotation and nitrogen fertilizer effects on agronomic and nitrogen efficiency of rice. The Scientific World J. 2014:1-11.

Rezgui M, Zairi A, Bizid E, Ben Mechlia N. 2005. Consommation et efficacité d'utilisation de l'eau chez le blé dur (*Triticum durum* Desf.) cultivé en conditions pluviales et irriguées en Tunisie. [Consumption and water use efficiency of durum wheat (*Triticum durum* Desf.) grown in rainfed and irrigated conditions in Tunisia]. Cahiers Agricultures. 14 (4):391–397.

Ryan J, Pala M, Masri S, Singh M, Harris H. 2008a. Rainfed wheat-based rotations under Mediterranean conditions: Crop sequences, nitrogen fertilization, and stubble grazing in relation to grain and straw quality. Eur J Agron. 28:112–118.

Ryan J, Masri S, Singh M, Pala M, Ibrikci H, Rashid A. 2008b. Total and Mineral Nitrogen in a Wheat-Based Rotation Trial under Dryland Mediterranean Conditions. Basic Appl Dryland Res. 2:34–46.

Shatar T. M, Mc Bratney A. B.2004. Boundary-line analysis of field-scale yield response to soil properties. J Agric Sci. 142:553–560.

Singleton P, Thies J, Bohlool B.B.1992. Useful models to predict response to legume inoculation. In: Mulongo Y.K, Gueye M, Spencer S. editors, Biological Nitrogen Fixation and Sustainability of Tropical Agriculture. New York: John Wiley & Sons, 245–256.

Spiertz J.H.J, De Vos N.M. 1983. Agronomical and physiological aspects of the role of nitrogen in yield formation of cereals. Plant Soil. 75 (3):379–391.

van Ittersum M.K, Cassman K.G, Grassini P, Wolf J, Tittonell P, Hochman Z, 2013. Yield gap analysis with local to global relevance. A review. Field Crop Res. 143:4–17.

van Ittersum M.K, Rabbinge R. 1997. Concepts in production ecology for analysis and quantification of agricultural input-output combinations. Field Crop Res. 52 (3):197–208.

von Liebig J, 1855. Die Grundsätze der Agriculturchemie mit Rücksicht auf die in England angestellten Untersuchungen. [The principles of agricultural chemistry with regard to the investigations undertaken in England]. Braunschweig, Germany: Friedrich Vieweg und Sohn Publ Co.

Wallach D, Makowski D, Jones J.W, Brun F. 2014. Working with Dynamic Crop Models : Methods, Tools and Examples for Agriculture and Environment. London: Academic Press – Elsevier :504.

Wang D, Xu Z.Z, Zhao J.Y, Wang Y.F, Yu Z.W. 2011. Excessive nitrogen application decreases grain yield and increases nitrogen loss in a wheat soil system. Acta Agr Scand B-Soil and Plant Sci. 61 (8):681–692.

Zitouna-Chebbi R, Prévot L, Chakhar A, Marniche-Ben Abdallah M, Jacob F. 2018. Observing Actual Evapotranspiration from Flux Tower Eddy Covariance Measurements within a Hilly Watershed: Case Study of the Kamech Site, Cap Bon Peninsula, Tunisia. Atmosphere. 9 (2):1-17.

Table 1. Agronomic situations surveyed in durum wheat in Tunisia

Regions	Years	Annual rainfall (mm)	Agronomic situations	Soil texture	Organic matter (%)	
Fernena	2011/2012	590	115	C-LC	**Mean**	2.07
					CV (%)	22.50
Lebna	2012/2013	600	68	LC-SLC	**Mean**	0.88
	2013/2014	520	62		**CV (%)**	53.04

C: clay, LC: silty clay loam, SLC: sandy clay loam

Annual rainfall measured from September 1st to June 30th of each cropping season

Table 2. Soil Organic Matter content (%) across the preceding crop

	Preceding crop			
	CE	CM	LG	CP
Mean	1.45	1.51	1.25	1.01
CV (%)	53.78	53.13	52.09	50.82
Max	2.75	2.81	2.75	2.22
Min	0.48	0.49	0.47	0.45

CE: cereals, CM: vegetable crops, CP: chickpea, LG: other legumes (medic, faba bean, vetch)

Table 3. Description of published data from experimental results on durum wheat performance (dry matter, nitrogen content in grain and straw and harvest index) for different regions, years and treatments

Country	Number	Years	Treatment	Reference
Spain	12	1996 1997 and 1998	N-supply	López-Bellido and López-Bellido 2001
Tunisia	6	2009 and 2010	N-supply	Ayadi et al. 2014
Italy	6	1999 and 2000	N-supply	De Giorgio and Montemurro 2006
India	10	1975	Cultivar	Desai and Bhatia 1978
Mexico	18	1995 and 1996	N-supply Cultivar Irrigation	Ottman et al. 2000
California	10	1993	N-supply Cultivar	Ehdaie and Waines 2001
Tunisia	4	2013	N-splitting	Melki et al. 2015

Table 4. Average of dry matter. nitrogen concentration in grain and straw and harvest index in bibliographic and experimental data (2014-2015) on the four Tunisian varieties

Bibliographic data	**Grain**		**Straw**		**Harvest Index**	
Number=66	DM (kg ha^{-1})	Ngrain (%)	DM (kg ha^{-1})	Nstraw (%)	HI	NHI
Mean	4771	**2.17**	6949	0.48	0.43	**0.78**
CV (%)	42.9	13.2	43.1	37.9	20.7	11.1
Experimental data						
Number=16						
Mean	5039	2.06	3985	0.48	0.56	0.84
CV (%)	13.4	5.0	17.8	8.1	2.8	1.1

DM: Dry matter. HI: Harvest index. NHI: Nitrogen harvest index

Table 5. Boundary curve parameters of the relationship between N uptake and N-input in ICARDA's experimental station. as well as Akaike criterions (AIC) of a simple model (nls) and complex model (gnls) testing differences between boundary curve of each rotation and the highest boundary curve of all experimental fields from 1985/1986 to 1988/1989

	Preceding crop				
	Fallow	Watermelon	Legumes	Chickpea	Wheat
Nmax (kg ha^{-1})	179.79	153.57	178.99	161.17	48.85
k	1.9301	2.1339	1.484	2.251	0.9226
r	0.0196	0.0265	0.0236	0.0195	0.0275
AIC (gnls)	159.85	166.52	417.01	155.97	134.00
AIC (nls)	234.90	259.55	411.01	277.33	335.91
p-value	<0.0001	<0.0001	0.9999	<0.0001	<0.0001

Nmax: the maximum N uptake (kg/ha); k and r obtained by minimizing the root mean square error (RMSE)

Table 6. Comparison of models used to establish boundary curves of the relationship between N uptake and yield for each rotation based on Akaike criterion (AIC)

	Preceding				
	Fallow	Watermelon	Legumes	Chickpea	Wheat
AIC (ax)	11.838	-5.100	-4.113	-4.172	-21.552
AIC ($ax^2 + bx$)	-3.570	-4.291	-10.408	-4.381	-23.075

AIC: the Akaike information criterion

Table 7. Boundary curve parameters of the relationship between Yields and N-input in ICARDA's experimental station. as well as Akaike criterions (AIC) of a simple model (nls) and complex model (gnls) testing differences between boundary curve of each rotation and the highest boundary curve of all farmers' fields

	Preceding crop				
	Fallow	**Watermelon**	**Legumes**	**Chickpea**	**Wheat**
Ymax (t ha^{-1})	5.10	6.33	5.02	4.59	1.56
k	0.72	1.56	1.48	1.34	0.53
r	0.0300	0.0169	0.0236	0.0198	0.0509
AIC (gnls)	-47.14	-62.27	-225.41	-37.79	-63.39
AIC (nls)	-53.14	13.36	-176.49	66.76	119.48
p-value	0.9999	<0.0001	<0.0001	<0.0001	<0.0001

Ymax: the maximum grain yield (t ha^{-1}); k and r obtained by minimizing the root mean square error (RMSE)

Table 8. Boundary curve parameters of the relationship between N uptake and N–input in farmers' fields and Akaike criterion (AIC) comparing a simple model (nls) and complex model (gnls) testing differences between boundary curve of each rotation and the highest boundary curve of all farmers' fields

	Preceding crop			
	Cereals	Legumes	Vegetables	Chickpea
Nmax (kg ha^{-1})	98.7	165.1	123.5	119.5
k	1.280	2.699	8.006	2.059
r	0.027	0.037	0.069	0.025
AIC (gnls)	1077.6	903.2	509.2	360.6
AIC (nls)	1623.8	897.2	701.3	602.1
p-value	<.0001	0.9999	<.0001	<.0001

Nmax: the maximum N uptake (kg ha^{-1}); k and r obtained by minimizing the root mean square error (RMSE)

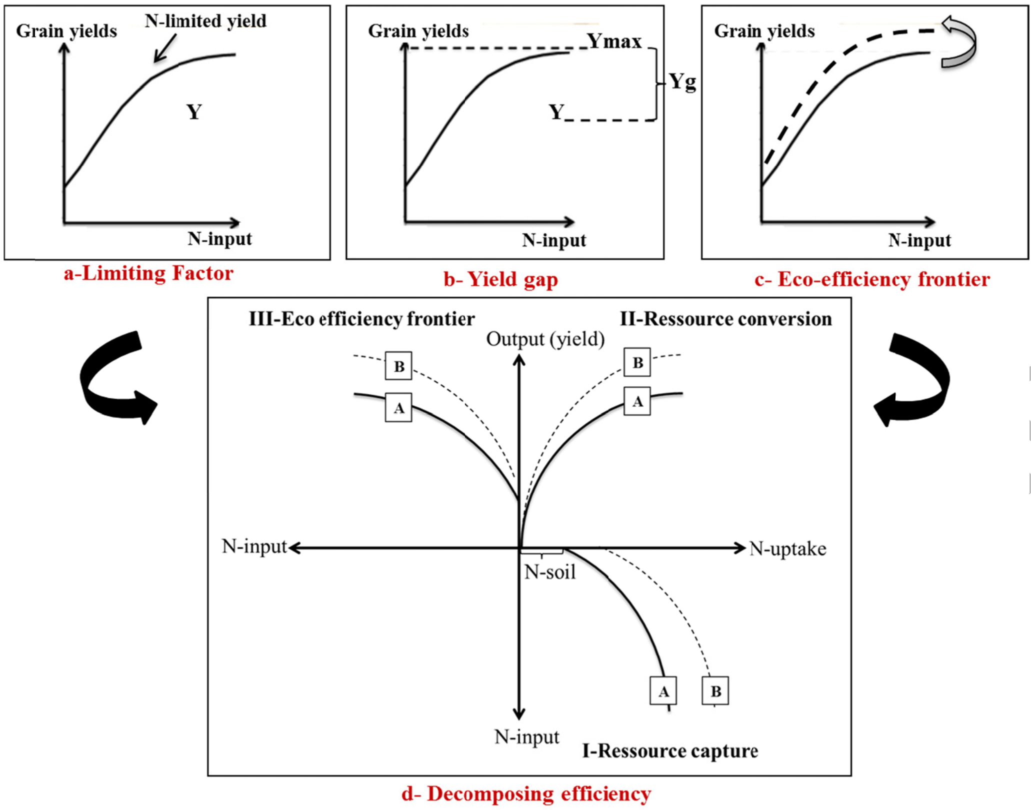

Figure 1. Conceptual framework based on concepts of limiting factors (a), yield gap (b), eco-efficiency frontier (c) and decomposition of resource efficiency (d) allowing to analyze the efficiency of resource capture and conversion. Ymax is the potential (maximum) performance respectively when the resource in the x axis (N-input) is not limiting for plant growth.

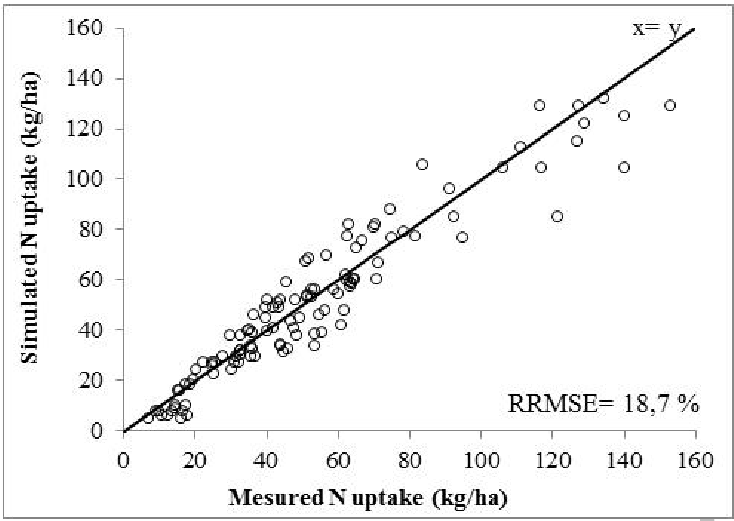

Figure 2. Simulated versus measured N uptake by durum wheat in ICARDA's experimental station at Tel Hadya from 1985/1986 to 1988/1989.

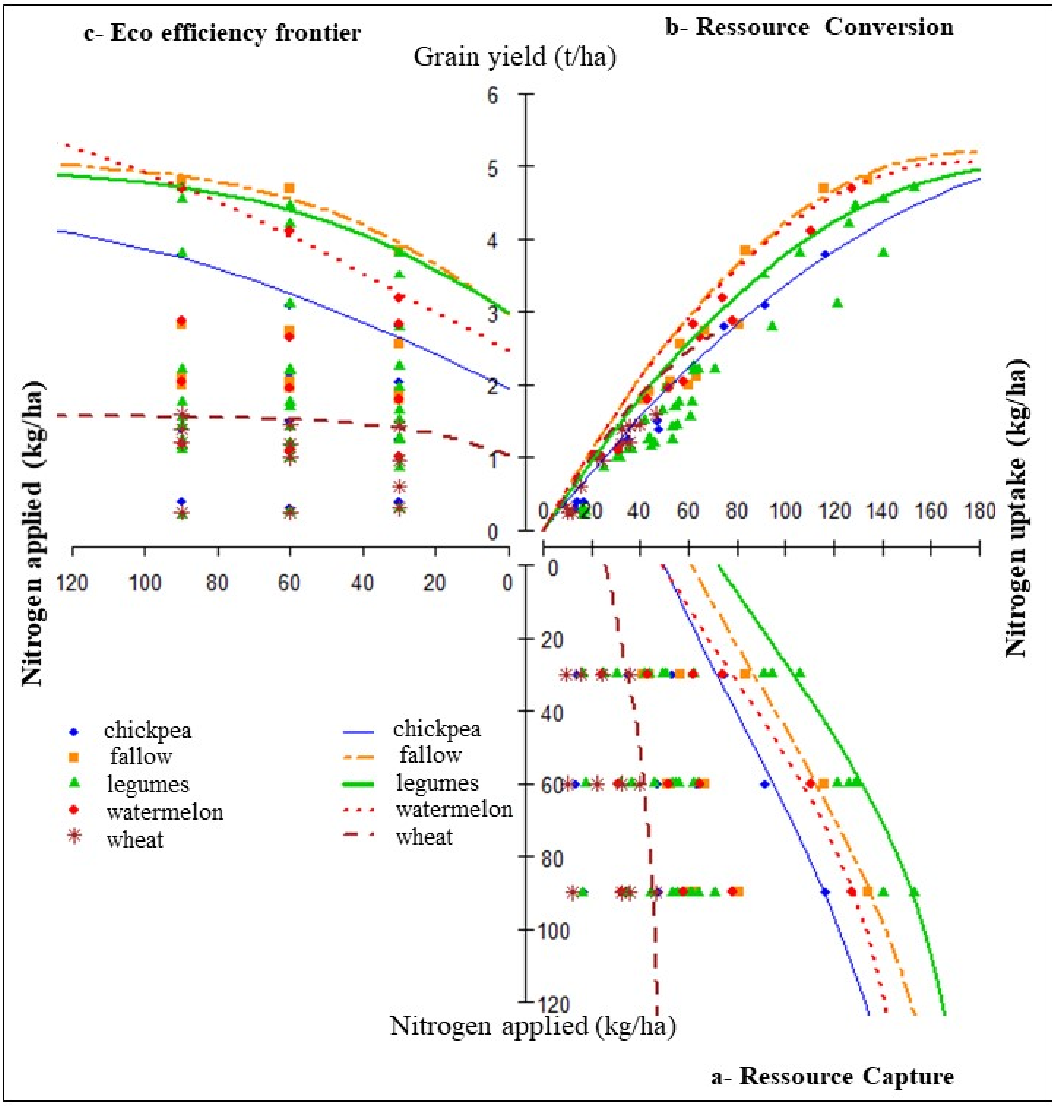

Figure 3. Three-quadrant diagram based on experimental data in ICARDA's experimental station at Tel Hadya, showing individual field measurements from 1985/1986 to 1988/1989 and boundary curves of the relationship between (a) nitrogen applied and nitrogen uptake (Resource Capture), (b) nitrogen uptake and grain yield (Resource conversion), and (c) yield and nitrogen applied (eco-efficiency frontier) for each preceding crop in the rotation: fallow, watermelon, legumes, chickpea and wheat.

(a) Resource Capture, (b) Resource conversion, and (c) eco-efficiency frontier

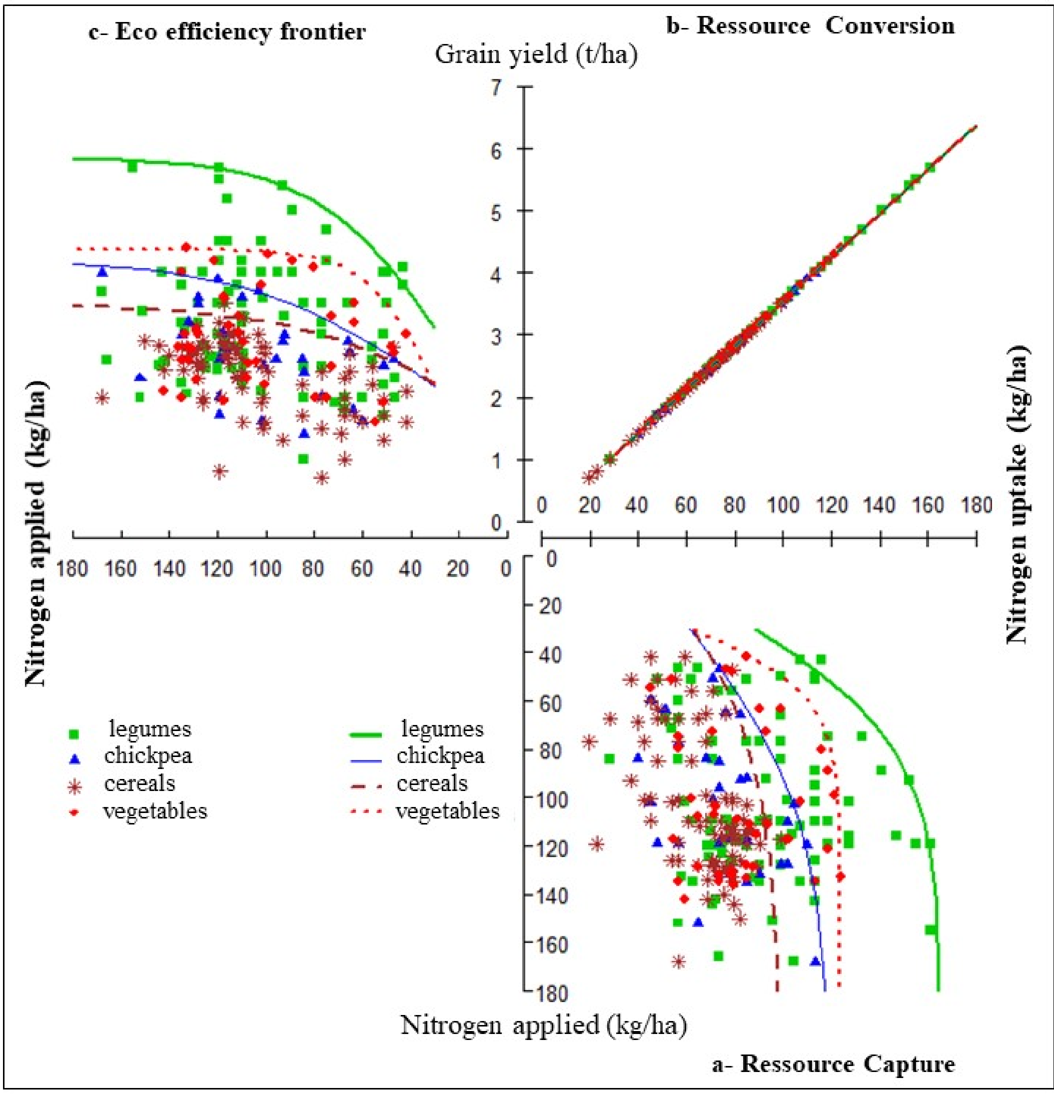

Figure 4. Three-quadrant diagram based on data collected across Tunisian farmers' fields at Fernena (2011/2012) and Lebna catchement (2012/2013 and 2013/2014) showing the relationship between (a) nitrogen applied and nitrogen uptake (Resource Capture), (b) nitrogen uptake and grain yield (Resource conversion), and (c) yield and nitrogen applied (eco-efficiency frontier) for each preceding crop in the rotation: cereals, vegetables, legumes and chickpea.

(a)Resource Capture, (b) Resource conversion, and (c) eco-efficiency frontier

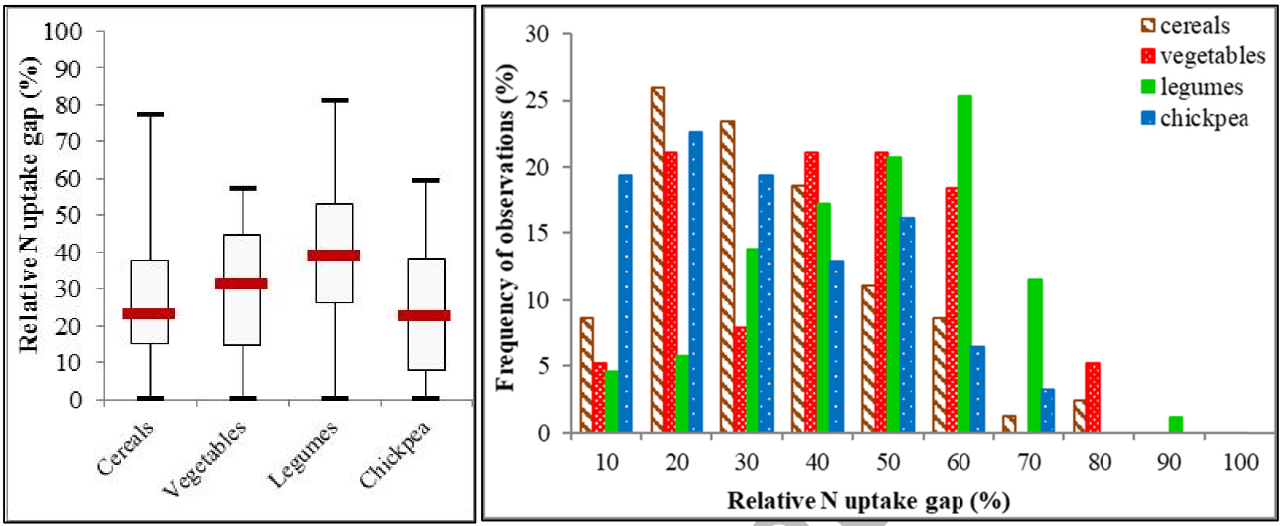

Figure 5. Boxplot of the relative gap of N uptake (i.e. relative distance to the boundary curve in quadrant a in Figure 4) and its frequency distribution for each preceding crop in the rotation: cereals, vegetables, legumes and chickpea.

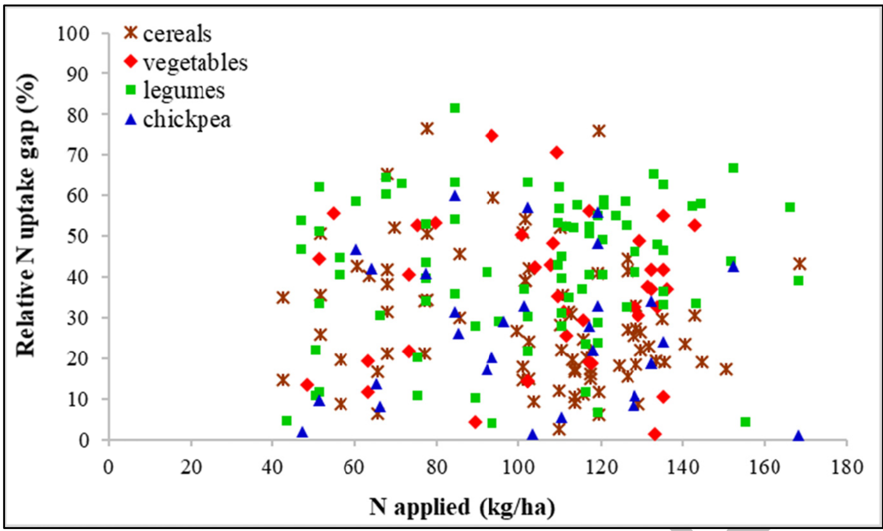

Figure 6. Relationship between the relative gap of N uptake and N applied for each preceding crop in the rotation: cereals, vegetables, legumes and chickpea.