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Chapter

Modeling of Nitrogen Use Efficiency in Lettuce Culture (*Lactuca sativa*): Isotopic Nitrogen (15 N) and AquaCrop

Mawhoub Amirouche, Dalila Smadhi and Lakhdar Zella

Abstract

The present study is highlighted through an experiment carried out over two consecutive years 2014–2016, in the sub humid region of Algiers. The methodology adopted concerns the variation of optimal nitrogen doses and their effects on the evolution of lettuce (*Lactuca sativa* L.) cultivation, whose socio-economic impact is proven, using isotopic nitrogen (15 N) and the AquaCrop model. The experimental design adopted is of the complete randomized block type, with four (04) levels: 0 (control), 60, 120, and 180 kg N/ha with four (04) replicates. The results obtained showed that the 120 kg N/ha dose is the efficient dose to cover the nitrogen requirements of lettuce with an efficiency of 74.48%. The accuracy of the model in calibration was tested using the following statistical indicators: R2, nRMSE, and d, which are, respectively, $0.64 < R^2 < 0.81$; $18 < nRMSE < 46.3$ and $0.78 < d < 0.94$ for canopy coverage and $0.92 < R^2 < 0.98$; $21.6 < nRMSE < 34.5$ and $0.91 < d < 0.96$ for dry biomass. The AquaCrop model could be recommended as a practical tool to better manage agricultural practices including fertilization.

Keywords: lettuce, AquaCrop, isotopic nitrogen 15 N, nitrogen use efficiency, fertility stress

1. Introduction

In the coming years, agricultural production will have to face a double challenge, meeting the growing needs of the world's population while preserving the environment and natural resources. According to [1], the world's current population of about 6.3 billion people will reach nearly 8.6 billion in 2030. Agricultural production will then have to be significantly higher. This will be achieved by increasing yields. This has been achieved mainly through varietal improvement and associated cultivation techniques, including nitrogen fertilization.

In Algeria, 20% of the agricultural potential is located in the north of the country, which is characterized by poorly fertile soils. These soils are low in nutrients and have a very low rate of organic matter. Fertilization has remained archaic in the country. According to [2], in Algeria, the use of fertilizers in agriculture is not under control, despite the efforts made by farmers in charge of the cereal intensification program and potato farmers.

According to [3], fertilizers are applied in the absence of technical standards, neglecting the initial soil content; consequently, inputs are often poorly fractioned, leading to waste, which is a source of soil and water pollution. As several researchers have shown in their work on Algerian soils. In this context, [4, 5] conducted trials in the same semi-arid climate, respectively, on durum wheat and barley seed production, obtained maximum yields with similar rates (150 kg N/ha). These yields reached the respective values of 33.82 and 33.25 q/ha, i.e. gains of 11.52 and 9.76 q/ha. Halilat [6] showed that the interaction of potassium (P) and nitrogen (N) fertilization significantly affects wheat grain yield in the Saharan zone. The maximum yield reached 6.780 Mt./ha with the N250 P180 dose. With regard to nitrogenous fertilization, the observation highlights the need to promote adapted and balanced fertilization. Since urea is the most widely used nitrogen fertilizer in the world [7], it is crucial to assess the nitrogen use efficiency (NUE) by crops, since it is always aimed at achieving higher yields with a minimum application of fertilizer. This indicator (NUE) has been widely studied by several researchers around the world on various crops, including cereals, e.g. rice [8], maize [9], durum wheat [10, 11]; leafy vegetables, e.g. lettuce [12–14], spinach [15], cabbage [16] and vegetable crops, e.g. Potato [17, 18]; beans [19], tomato [20, 21].

In this perspective, this study uses the isotope approach 15 N to evaluate the nitrogen use efficiency. This new method, used by [22], highlights 15 N isotopic nitrogen, which is the most commonly used stable isotope in agriculture-related studies. It is the direct way to measure nitrogen uptake by applied fertilizer, and the most reliable way to monitor the flow and fate of nitrogen in the soil–plant system [23, 24]. To highlight the monitoring of this system, the chosen plant material is lettuce (*Lactuca sativa* L.), due to its short growing cycle. But also, because of the socio-economic impact that is beginning to dominate, at the national level. It is a source of wealth and income for producers. The search for decision support tools is essential in order to master agricultural practices and to plan for a sustainable agriculture that respects the environment. In this respect, the AquaCrop model, designed by the FAO, has been chosen as a decision support tool. The objective of this study is essentially oriented toward the search for optimum doses of nitrogenous fertilizers with the aim of contributing to the production of technical references for the efficient use of fertilizers.

2. Materials and methods

2.1 Study site

The study was conducted at the National Institute of Agronomic Research of Algiers (36°68′ N and 3°1′ E, at an altitude of 18 m), located south-west of Algiers in the eastern part of the Mitidja (**Figure 1**).

2.2 Climatic and soil data

Climatic conditions in the study area are characterized by pronounced seasonal variations with mild, wet winters and hot, dry summers. The meteorological data used are from the automatic weather station installed in the field. The measurements taken at daily time steps are: minimum and maximum temperatures (°C), rainfall (mm), wind speed (m/s) at 2 m above ground level, solar radiation (W/m^2) and relative humidity (%). The reference evapotranspiration (ET0) was calculated according to the FAO Penman-Monteith method [25]. A soil profile was carried out
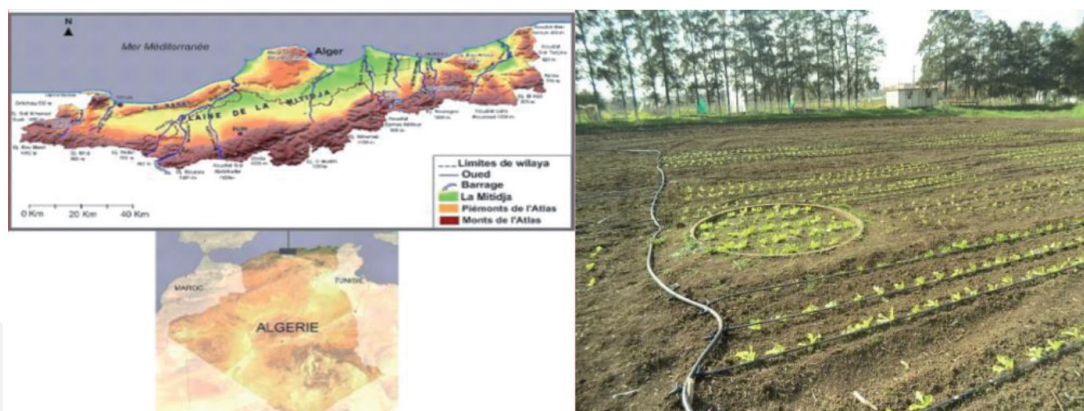
Figure 1.
Location of the study area.

over a depth of one meter, comprising three horizons. Soil samples were taken from each horizon with an auger for analysis physico-chemical.

2.3 Crop data

The crop taken into consideration is variety lettuce, stubborn from Nîmes, belonging to the lettuce to be applesauce class, which is eaten young, before it goes to seed. Lettuce seeds were sown in the honeycomb plates for 19–25 days in the nursery before being transplanted. The young lettuce plants were transplanted at the 3–4 leaf stage onto well plowed soil in the field.

2.4 Experimental protocol

The experiment was carried out in the open field using a complete randomized block experimental design with four levels of nitrogen, namely: T1 (0 N kg/ha), T2 (60 N kg/ha), T3 (120 N kg/ha) and T4 (180 N kg/ha) arranged in four blocks. Each block has four sub-plots. Each micro plot is 6 m long and 3 m wide, giving a total area of 18 m^2, of which 4.5 m^2 was used for the 15 N. The trial was repeated for two consecutive years (2014–2015) and (2015–2016). Isotopic nitrogen was used only in the first year because of its high cost. The amounts of nitrogen used were distributed along the crop development cycle, namely: 10% at 15 days after transplanting (DAT), 30% at 40 DAT, 40% at 60 DAT and 20% at 75 DAT. The growing season is from January to April for both companions, coinciding with the winter season, during which irrigation is not necessary.

2.5 Measured parameters

The parameters measured in the field are essentially the above-ground biomass (B), which represents a parameter that best allows verification of fertilizer efficiency in lettuce where the growth of the above-ground part is a determining factor in agricultural value [26]. Every 10 days, samples of 6 plants/subplot are taken and brought back to the laboratory where they are dried in the open air for 24 h and then in an oven for 48 h at 70 C°. In addition to this, the evolution of the green canopy (CC) cover is monitored by reference to photos taken vertically at a height of 1.8 m above the crop, using a photometric device. The photos were analyzed using ARCgis 10.1 software using the supervised classification by maximum likelihood method (**Figure 2**). Harvesting was done when the apples were tightly packed and full for each subplot of 1 m × 1 m.
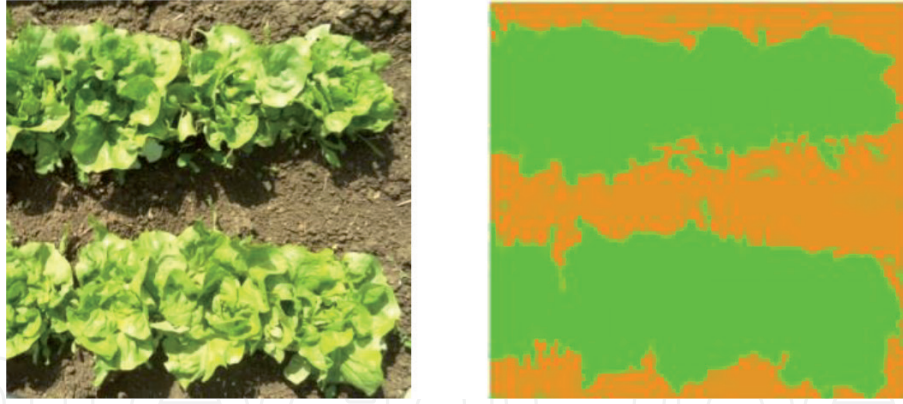
Figure 2.
Analyses of the fraction of the green canopy for the growth stage.

To determine the isotopic composition of lettuce plants, lettuce heads receivingan15N were divided into two parts (roots and leaves). Fresh weight was assessed for all parts of the crop. The samples were dried at 70°C for 24 hours, weighed for dry weight determination, ground into a fine powder using a 0.3 mm sieve and homogenized for total nitrogen and excess N15. The isotopic analysis of the lettuce culture samples was carried out at the National Centre for Energy, Science and Nuclear Techniques (CNESTEN-Morocco).

The quantification of fertilizer nitrogen was measured on the basis of the isotope dilution method from fertilizer nitrogen and the rate of nitrogen fertilizer applied, according to the following equation defined by [22]:

$$\% \text{ Fertilizer N utilization} = \frac{Fertilizer\ N\ yield}{Rate of N application} * 100 \tag{1}$$

2.6 Description and evaluation of the data by AquaCrop

AquaCrop requires five important components to be functional: climate, with its thermal regime, rainfall, evaporative demand (ETP) and carbon dioxide concentration; then crop characteristics, including development, growth and yield formation processes (**Table 1**); then soil, with its hydraulic characteristics (hydraulic conductivity at saturation, moisture at saturation, field capacity and permanent wilting point); and finally management practices, which are divided into two categories: plot management and irrigation practice management; and finally initial conditions.

2.7 Model calibration for soil fertility stress

Calibration of the model to fertility stress requires coverage of the green canopy (CC) and biomass production (B), recorded on the fertility stressed plot 'stressed plot' and the unstressed plot 'reference plot' (**Table 2**). The soil fertility stress in the AquaCrop model is given as follows:

$$\text{Stress} = 100 \left(1 - B_{rel} \right) \tag{2}$$

Where: B_{rel} is the ratio of total dry above-ground biomass at the end of the growing season in the reference plot (B_{ref}) to that under stress (Bstress). Soil fertility

Description	Units	2015–16	Source
Conservative crop parameters			
Base temperature	C°	7	Calibrated
Upper temperature	C°	30	Calibrated
Upper threshold for canopy expansion, Pexp,upper	—	0.25	Simulated
Lower threshold for canopy expansion, Pexp,lower	—	0.55	Simulated
Shape factor for the stress coefficient for canopy expansion	—	3	Calibrated
Upper threshold for stomatal closure, Psto,upper	-	0.50	Calibrated
Shape factor for the stress coefficient for stomatal closure	—	3	Calibrated
Water productivity (WP)	$g\,m^{-2}$	19	Calibrated
Reference harvest index (HIo)	%	95	Measured
Crop coefficient when canopy is complete	—	0.85	Simulated
Non conservative parameters		2015–16	
Number of plants per m^2	$Plant\,m^{-2}$	15	Measured
CC0	%	2.25	Simulated
Maximum canopy cover CCx	%	81	Measured
Canopy size of the transplanted seedling	$cm^2\,plant^{-1}$	15	Measured
Time from transplantation to emergence	Days	7	Observed
Time from transplantation to senescence	Days	80	Observed
Time from transplantation to maximum (CCx)	Days	50	Observed
Time from transplantation to maturity	Days	95	Observed
Minimum effective rooting depth	m	0.20	Measured
Maximum effective rooting depth	m	0.40	Measured
Transplantation time at maximum depth of rooting	Days	55	Observed
Date of transplantation		11/01/16	
Harvest date		14/04/2016	
Canopy growth coefficient (CGC)	$\%\,days^{-1}$	14.30	Simulated
Canopy decline coefficient (CDC)	$\%\,days^{-1}$	8.0	Simulated

Table 1.
Input culture parameters to calibrate the AquaCrop model.

Treatments	Brel (%)	CCx under fertility level (%)	Canopy Decline (-)
T1	51	51	Strong
T2	73	55	Medium
T3	100	61	Little
T4	100	58	Little

Table 2.
Input data to calibrate the AquaCrop model for soil fertility stress.

affects water productivity (WP), canopy growth coefficient (CGC), maximum cover (CCx) and canopy senescence.

The evolution of canopy cover, dry above-ground biomass and yield were taken into account in the evaluation of the AquaCrop model, while using the following statistical indicators: the coefficient of determination (R^2) of the linear fit, the square root of the normalized root mean square error (nRMSE) and the Willmott's agreement index (d).

3. Results and discussions

3.1 Analysis of climate data

Variations in rainfall and ETP are shown in **Figure 3**, which illustrates the rainfall distribution during the two years of experience 2014–2015 and 2015–2016. The cumulative rainfall received between September and August is, respectively, of the order of 552 and 551 mm. Those corresponding to the experimental seasons (January to April), they are close to the averages of 211.4 and 303.4 mm. The corresponding potential annual evapotranspiration is of the order of 744.3 and 782.6 mm. Those corresponding to the growing seasons are, respectively, 195.4 and 196.5 mm.

3.2 Physical and chemical characteristics of the soil

The study site is characterized by deep and heavy soils with high clay content. Soil analysis revealed the existence of 3 horizons with a silty-clay texture with high clay rates increasing with soil depth. At profiles of 0–25 cm, 25–55 cm and beyond 55 cm depth, these rates are 43, 49, and 52%, respectively. The pH of the station soils is generally slightly basic at 7.8, CEC varies between 17.9 and 15 meq/100 g and total limestone has a rate between 7.9 and 7.8%. The organic matter rate is 1.57% on the surface and 0.49% at depth.

3.3 Effect of fertilization on dry above-ground biomass

Figure 4 shows the evolution of the nitrogen doses applied at different phenological stages of the plant. This evolution is supported by the analysis of variance, which showed a very highly significant effect ($p < 0.001$), of the dry biomass, in relation to the increase in the doses of nitrogen supplied. A maximum of dry biomass is reached at the dose of 120 kg N/ha. Above this level, the increase in nitrogen rate is not significant. This result is consistent with that of [27], which showed that fertilization at high doses leads to a decrease in above-ground biomass. This is the case in the first year (2014–2015).

3.4 Effect of fertilization on yields

Figure 5 shows lettuce yields as a function of applied nitrogen rates. In fact, the graph shows that, during the two experimental campaigns, the highest lettuce yields (55.24 and 57.96 t/ha) were obtained by applying the 120 and 180 kg/ha rates. These doses are very highly significant ($p < 0.001$) compared to those obtained (30.19 and 45.49 t/ha) by applying the minimum doses of less than 60 kg/ha. This result is consistent with those of [28–30], who reported that increasing the N level from 0 to 120 kg N/ha had a positive effect on lettuce production. Nevertheless, in detail, the T4 treatment from the 2014–2015 trial shows a relatively lower yield of 50.25 t/ha
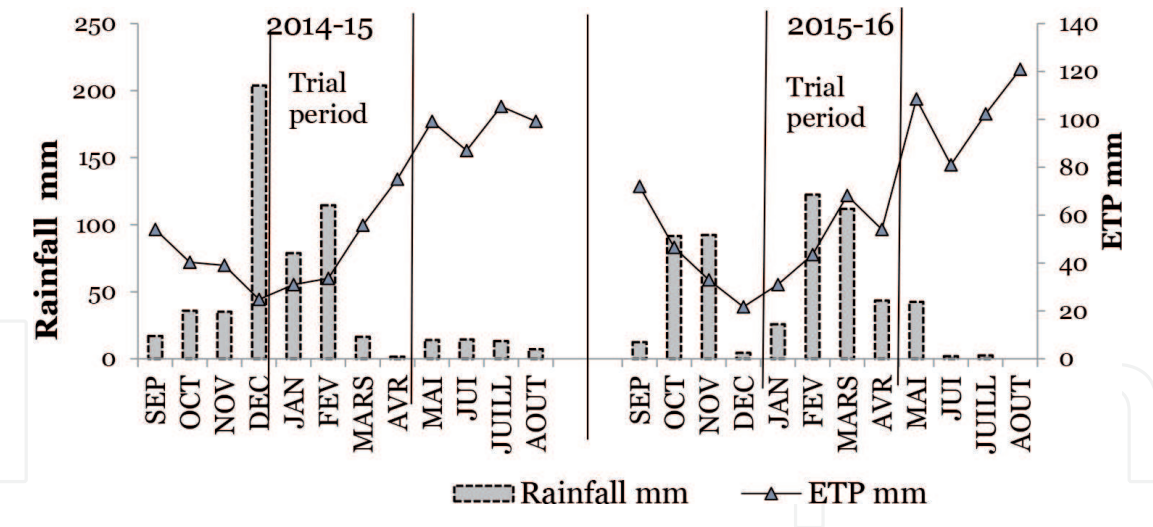
Figure 3.
Precipitation, potential evapotranspiration (ETP) on a monthly scale for test years 2014–2015 and 2015–2016.
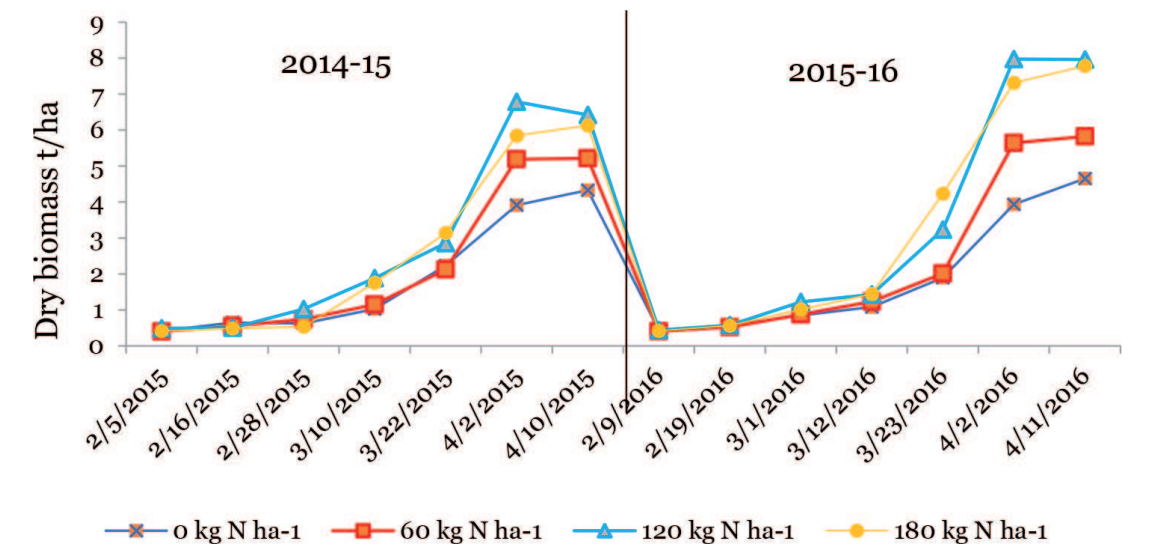

Figure 4.
Effect of different levels of fertilization on the evolution of dry above-ground biomass for the two growing seasons.

compared to the T3 treatment (54.25 t/ha) from the same year. The difference, evaluated at 3.08 t/ha, can be explained by the toxicity of the plants or by the nonattraction of nitrogen by the plants resulting from the consumption of excess nitrogen fertilizer, as pointed out by [31]. The response of lettuce for yields is considerably higher in 2016 than in 2015. This result is related to the higher rainfall amounts.

3.5 Nitrogen use efficiency

Nitrogen Use Efficiency (NUE) is an important indicator in the application of nitrogen fertilizers. Achieving a higher NUE always becomes a priority in agriculture [8]. In this context, **Figure 6** illustrates the variation in the percentage of NUE as a function of defined thresholds. For rates ranging from 60, 120 to 180 kg N/ha, the NUE varies from 65.42, 74.49 to 68.38%, respectively. The NUE decreased from 74.49% to 68.38% by increasing the rate from 120 to 180 kg N/ha. These results are similar to those reported by [32, 33]. The 120 kg N/ha rate provides the best efficiencies. This means that 74.48% of the fertilizer applied is consumed by the lettuce crop. The remaining 25.52% of N is either in the soil or lost through leaching. Lettuce is a short-cycle crop, making the best use of available nitrogen, as reported by [34].
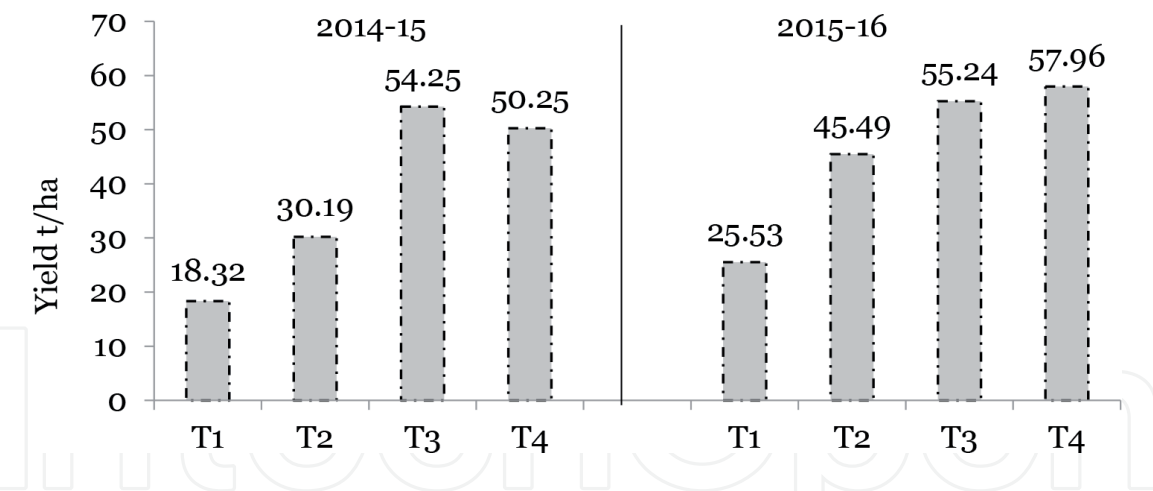
Figure 5.
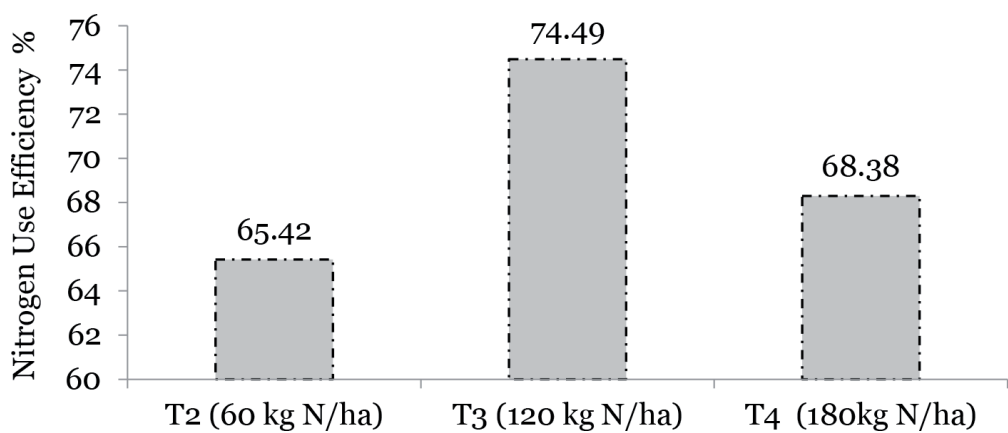*Effect of different levels of fertilization on yield for the two growing seasons.*

Figure 6.
Variation in nitrogen use efficiency by lettuce, expressed as a percentage (%).

3.6 Effect of fertilization on water productivity

Figure 7 shows the variation in water productivity (WP), soil evaporation (Es) and transpiration (Tr) of the lettuce crop under different levels of fertilization. This variation is supported by the analysis of variance, which showed a very highly significant effect ($p < 0.001$) of these parameters (WP, Es and Tr), in relation to the increase in the doses of nitrogen applied. The maximum values of WP and Tr are reached at the dose of 120 kg N/ha, for the two companions 2014–2015 (WP = 8.95 kg/m3; Tr =51.4 mm) and 2015–2016 (9.57 kg/m3; Tr = 55.80 mm). Above this level, the increase in the nitrogen rate is not significant.

3.7 Calibration of the AquaCrop model

3.7.1 Canopy cover and dry biomass

Experimental results of yield, canopy cover and dry above-ground biomass under different levels of fertilization are presented in **Table 3**. The AquaCrop model (V. 6.1) was calibrated using the crop data set obtained from the T3 treatment (120 kg N/ha). The lowest dry yield and dry aboveground biomass observed were 4.021 t/ha and 4.125 t/ha under the T1 treatment (0 kg N/ha), and the highest were 8.854 t/ha and 9.320 t/ha under the T3 treatment (120 kg N/ha), respectively. The AquaCrop model is capable of simulating these parameters. Overall, the agreement between simulated and observed vegetation cover and biomass
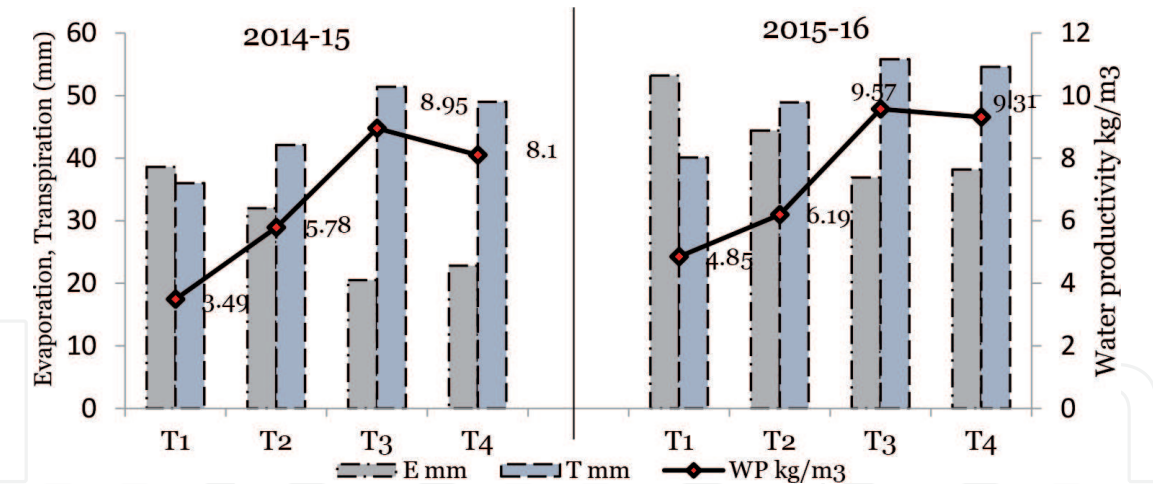
Figure 7.
Variation in water productivity of lettuce under different levels of fertilization.

Treatments	Biomass (t/ha)		Dry yield (t/ha)			CCx (%)		
	Obs	Sim	Obs	Sim	SD (±%)	Obs	Sim	SD (±%)
T1	4.125	4.785	4.021	4.546	(6.70)	51	44.80	(1.68)
T2	5.872	6.806	5.234	5.785	(11.68)	55	54.10	(5.76
T3	7.969	9.320	7.834	8.854	(8.27)	61	63.90	(2.67)
T4	7.788	9.100	7.626	8.645	(8.40)	58	63.70	(3.55)

Table 3.
Biomass calibration results, yield, and maximum canopy cover under different levels of fertilization in 2015–2016.

is satisfactory with 0.64 < R2 < 0.81, 18 < nRMSE > 46.3 and 0.78 < d < 0.94; 0.92 < R2 < 0.94, 21.6 < nRMSE <34.5, 0.91 < d < 0.96 (**Table 4**).

Figure 8 shows the comparison between simulated and observed canopy cover (CC) and dry above-ground biomass (B) for the calibration period (2015–2016). This figure shows that there is a close correspondence between observed and simulated CC and B. It is also important to note that the AquaCrop model correctly simulates CC from seeding to the maximum growth phase at which CCx is reached. This observation has been reported in several studies [35–37]. From **Figure 8**, it is clear that both parameters (CC) and B were overestimated by the AquaCrop model. In a recent study [38], it was shown that the AquaCrop model overestimated the cabbage canopy under different irrigation regimes. Nikolaus [39] also noted a slight (10%) but systematic overestimation of the amount of rice biomass conducted under different levels of irrigation and fertilization.

3.7.2 Yield

Observed and simulated lettuce yields are shown in **Figure 9**. The observed yields for treatments T1, T2, T3 and T4 are, respectively, 4.214; 5.187; 6.942 and 6.214 t/ha, while the simulated yields are 4.897; 5.981; 7.414 and 6.987 for the trial period (2014–2015), with a correlation coefficient R^2 = 0.92. On the other hand, the yields observed and simulated under the four treatments for the trial period (2015–2016) are of the order of 4.021; 5.234; 7.834 and 7.626 t/ha, while those simulated are of the order of 4.546; 5.785; 8.854 and 8.645, with a correlation coefficient R^2 = 0.99. Analysis of statistical tests and linear regression indicated that the values

Indicators	CC (%)				Dry biomass (t/ha)			
	T1	T2	T3	T4	T1	T2	T3	T4
R^2	0.81	0.71	0.66	0.64	0.92	0.98	0.94	0.94
NRMSE	18	35.5	41.4	46.3	34.5	21.6	25.6	25
EF	0.79	0.03	−0.13	−0.06	0.55	0.85	0.82	0.82
d	0.94	0.81	0.78	0.80	0.91	0.96	0.96	0.96

Table 4.
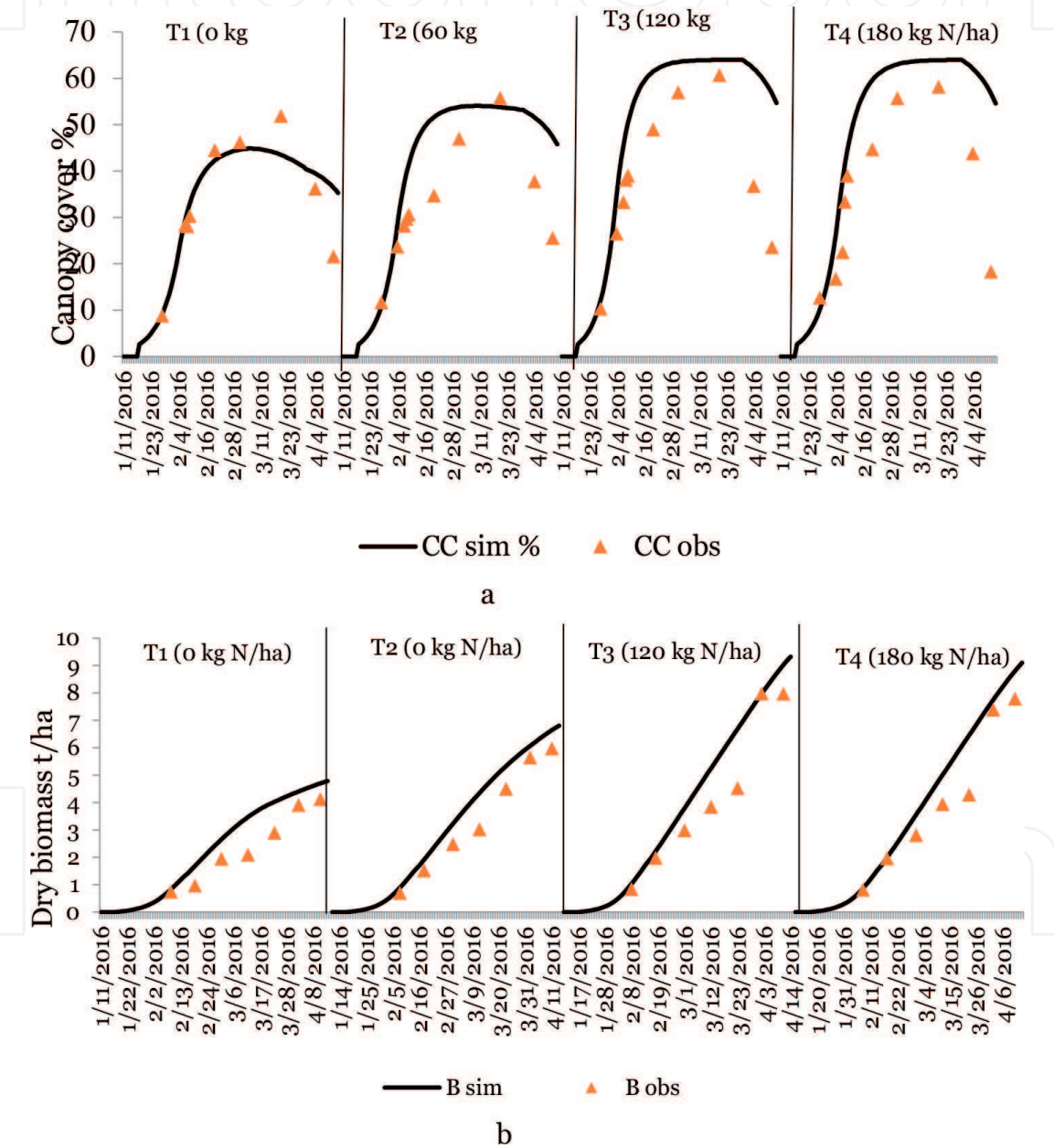*Indicators of goodness of fit in estimating canopy cover and dry biomass.*

Figure 8.
Canopy coverage (a) and dry biomass (b) simulated and measured for the calibration period (2015–2016) under different fertilization levels (T1, T2, T3, and T4).

simulated by the AquaCrop model are in good agreement with those observed. Araya et al. [40] reported R^2 values >0.80 when simulating above-ground biomass and barley grain yield using AquaCrop.
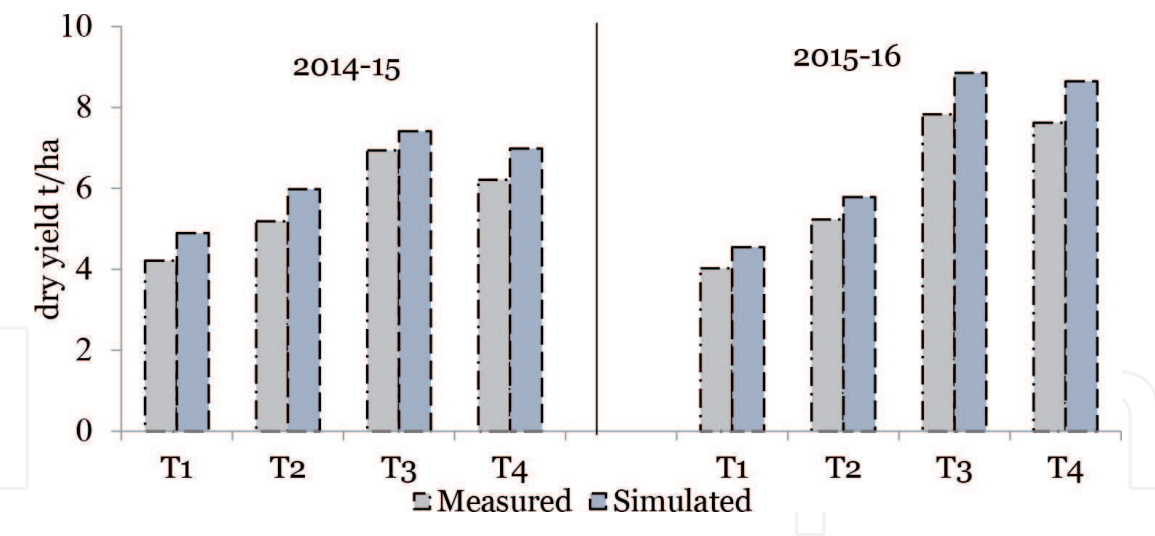
Figure 9.
Simulated and observed lettuce yields under different levels of fertilization.

4. Conclusion

The management of nitrogen fertilization is a major issue for agricultural production while contributing to water and soil pollution. In this situation, the adoption of fertilization management strategies aimed at using efficient doses and increasing the effectiveness of their use becomes necessary. Crop models simulating yield under such conditions could be important tools for fertilizer management planning. To this end, the parameterization of the AquaCrop model to estimate the effect of fertility constraints on lettuce yield under different levels of fertilization was investigated. The model tended to overestimate canopy coverage for T3 (120 kg N/ha) and T4 (180 kg N/ha) treatments, but with reasonable statistical indices (nRMSE: 14.80 for T3 and 12.50 for T4). AquaCrop has confirmed that it is a very useful tool that can be used to optimize the N rates applied to the crops, to play on the management of the plot in order to maximize yields.

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