The PILOTE-N model for improving water and nitrogen management practices: Application in a Mediterranean context

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The PILOTE-N model for improving water and nitrogen management practices. Application in a Mediterranean context.

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Abstract

In this paper we present PILOTE-N, a crop model devoted to the calculation of crop production from the joint water and nitrogen soil status effects. It is the extension of PILOTE, for contexts in which water might not be the sole limiting factor for crop yield, but the same model structure and credo of parsimonious parameterisation have been kept, assuming simplified descriptions of the physical processes at play. One original aspect of PILOTE-N is the calculation of Leaf Area Index (LAI) and cumulative nitrogen plant demand from similar logistic-type functions. LAI is controlled by specific temperature sums, shape parameters and the occurrence of water and nitrogen stresses, while the time average of LAI values over critical phenological periods also affects the predicted harvest index and crop yield. As specific plant parameters are known from PILOTE, calibration was devoted to nitrogen parameters. Which governing the daily-averaged mineralization rate in a first step, then the two shape parameters of the potential nitrogen plant demand (from the dilution curve) in a second step and, at last, which allowing the link between nitrogen uptake and nitrogen of the soil. Model performance was evaluated using multiple initial soil conditions, irrigation and fertilization strategies for corn, durum wheat and sorghum, over a climatic series of 14 years, at the experimental plot of Lavalette (Montpellier, South-East of France), hence in a Mediterranean context characterized by severe, water stresses during summer, typically exceeding nitrogen stresses. Crop yield as well as the dynamics of nitrogen budget were correctly simulated (R^2>0.94 for grain yield, total dry matter and nitrogen in plant). The robustness of such a simple and easy-to-calibrate tool is expected to facilitate its use and implementation in other agro-pedoclimatic contexts, to decipher the effect of abiotic stresses and improve irrigation and fertilization scenarios when included in dedicated tools.

Key words: Crop model, Nitrogen budget, Soil water balance, Irrigation, Fertilization, abiotic stress

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Summary

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Glossary

a_N	Parameter for the nitrogen stress impact on HI	-
a_w	Parameter for the water stress impact on HI	
C1 and C2	fixed and progressive N soil compartments	
C_M	Calibration parameter for the potential mineralization	kg ha^{-1} d^{-1}
C_p	Partitioning coefficient	-
Es	Soil evaporation	mm
Et_a	Actual evapotranspiration	mm
ETM	Maximal evapotranspiration	mm
ET_o	Reference evapotranspiration	mm
GY	Grain Yield	Mg ha^{-1}
HI	Harvest index	-
HI_{pot}	Potential harvest index	-
K_a	Parameter controlling nitrogen plant uptake	-
K_c	Crop coefficient	-
$K_{c\ max}$	Maximal value of K_c	-
K_r	Ratio between easily usable soil water reserve and TAW	-
K_{soil}	Resistance of soil to evaporation	-
LAI	Leaf area index	m^2 m^{-2}
LAI_{av}	Average LAI values between Ts_1 and Ts_2	m^2 m^{-2}
LAI_{max}	Maximal leaf area index	m^2 m^{-2}
LAI_{st}	Threshold LAI_{av} value	m^2 m^{-2}
N_A	Applied nitrogen	kg ha^{-1}
N_D	Nitrogen lost by denitrification	kg ha^{-1}
N_F	Final nitrogen amount	kg ha^{-1}
N_I	Initial nitrogen amount	kg ha^{-1}
N_L	Nitrogen lost by lixiviation	kg ha^{-1}
N_M	Nitrogen amount obtained by mineralization	kg ha^{-1}
N_P	Nitrogen amount in the plant	kg ha^{-1}
N_{soil}	N soil storage	kg ha^{-1}
N_V	Nitrogen lost by volatilization	kg ha^{-1}
OM	Volumetric organic matter	%
PCND	Potential Cumulative N plant demand	kg ha^{-1}
$PCND_{max}$	Maximal cumulative N plant demand	kg ha^{-1}
pH	Soil pH	-
P_r	Root depth	m
P_s	Depth of the first reservoir	m
R1, R2, R3	Superficial, root zone and deep soil reservoirs	-
Rs	Solar radiation	J cm^{-2}
R_{max}	Maximal root depth	m
RUE	Radiation use efficiency	-
T	Daily average air temperature	°C
TAW	Total available water in soil	mm m^{-1}
T_b	Base temperature	°C
T_D	Threshold temperature for denitrification	°C
TDM	Total Dry Matter	Mg ha^{-1}
T_e	Temperature for crop emergence	°C
T_{inst}	Temperature for root installation	°C

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TP_m	Maximal transpiration	mm
T_m	Temperature (in base Tb) to reach LAI_{max}	°C
T_{min}, T_{ms}	Temperature thresholds for mineralization	°C
T_{Mr}	Reference temperature for mineralization	°C
Tp	Transpiration	mm
Ts_1	Temperature of the 1st critical stage	°C
Ts_2	Temperature of the 2nd critical stage	°C
$V_{M\ pot}$	Potential permanent mineralization rate	kg ha^{-1} d^{-1}
V_r	Root growth rate	m d^{-1}
x_1, x_2	Shape parameters of the nitrogen plant demand curve	-
α, β	Shape parameters of the LAI curve	-
ε	Extinction coefficient	-
λ	Harmfulness of the water and nitrogen stresses	-
θ_{fc}	Soil water content at field capacity	cm^3 cm^{-3}
θ_{wp}	Soil water content at permanent wilting point	cm^3 cm^{-3}
θ_{R2}	Normalized water content of the R2 reservoir	-

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1. Introduction

Irrigation is necessary for ensuring crop growth under a wide range of climatic conditions going from Tropical Wet to Arid regions (FAO, 2013), allowing 40% of world crops over 20% of cropped lands (FAO, 2015). Water availability for irrigation is however increasingly constrained by prolonged rainfall deficits induced by climate change and the increasing competition among agriculture, industry, tourism and urban areas, urging the agricultural sector to improve water productivity (Molden and Oweis, 2007. More precisely, the optimization of water and nitrogen use efficiencies is most often deemed to achieve sustainable crop production while preserving the environment. This requires a change of paradigm in the numerous cases in which fertilisation practices were largely established under non-limiting water and nitrogen availability conditions: the merits and drawbacks of these irrigation and fertilisation strategies should plausibly be re-evaluated from wider perspectives. For example, Nitrogen (N) is necessary to crop growth and to obtain a good yield but excessive N applications with respect to plant N requirements can have substantial negative impacts on the surface waters, the water table and the farmer's income.

The optimal management of the water-nitrogen couple is a serious challenge today in agricultural contexts concerned by strong input reductions (Agostini et al., 2010). By contrast, Quemada et al. (2013) have recently conducted a review on existing strategies to reduce nitrate leaching from cropped lands. The authors highlighted that tailoring irrigation supply to crop requirements is the most efficient method for reducing nitrate leaching with reductions reaching as much as 78% of nitrate leaching from fields with poorly-managed irrigation calendars. Modelling appears as an appropriate tool to tackle this resources management optimization problem and a non-negligible number of efficient crop models have been developed for this purpose, but the use of most of these models is constrained by data availability. This pleads for the development of crop models requiring a limited number of parameters that may be calibrated from an affordable observation effort.

Some models are crop-specific such as CERES-Wheat (Richie et al., 1984), CERES-Maize (Jones et al., 1986) or ARCWHEAT (Weir et al., 1984). This crop specificity allows sometimes the introduction of several adaptive mechanisms, drawn from genetics, to mitigate water stresses (Casals 1996). Other models are more generic such as EPIC (Williams et al., 1989), DAISY (Hansen et al., 1990) and STICS (Brisson et al., 1998, 2003). Although such models are renowned scientific tools, their lack of flexibility (Affholder and al. 2012) and especially their typically high parameterisation costs limit their application for operational field management purposes. This again

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legitimates the development of lighter crop models, characterized by a limited number of sensitive parameters, while acknowledging limited objectives compared to these of the full physical basis approaches. Then the minimal expectations for models designed from the principle of parsimony could be to describe first-order physicochemical processes "well enough" to provide the correct temporal dynamics for the main observable quantities involved in the water and N budgets (e.g. soil water reserve, N amount in soil solution, mineralization rate, nitrogen uptake by plant roots).
Regarding N fate, most of the cited models calculate the plant N demand according to the critical N concentration required for the accumulation of biomass to start while STICS or DAISY rely on an optimum N concentration curve. Whatever the degree of sophistication of the N mineralization module, the process needs knowledge of soil organic matter and it is governed by soil temperature and humidity. Most models use a capacitive approach for the soil water balance, in which solute or nutrient leaching is based on the convection-dispersion equation involving mixing between two successive reservoirs, as for example in STICS that appeals to the Burns (1974) solute transfer approach. In PILOTE-N as in STICS, soil-related processes are simulated using a capacitive approach while plant-related processes are process-based. However, PILOTE-N has more limited objectives regarding yield components (and some aspects of nitrogen management) compared to STICS, resorting to a limited number of parameters.

In the world of crop models, the PILOTE model (Mailhol et al., 1997; Khaledian et al., 2009; Mailhol et al., 2011) is one irrigation management tool that has been built for operational field management objectives. It is the agronomic and the hydrological core of the Optirrig software (Cheviron et al., 2016) turned towards the generation, analysis and optimization of irrigation scenarios, and the coupling between both tools was made easier and more efficient by the relatively simple nature of PILOTE.
The objective of this paper is to describe the development of a new nitrogen management component of PILOTE. The latter has been widely used in different regions of France and Maghreb assuming that water was the sole limiting factor for crop yield. Satisfactory results were generally obtained. However, under peculiar conditions, some gaps between measured and simulated yields have suggested to add a nitrogen component to PILOTE in order to reach a more comprehensive description of abiotic stresses. More into details, the opportunity to connect or disconnect the nitrogen module, thus to use PILOTE or PILOTE-N, is a convenient method for understanding the origin of possible gaps and to decipher the relative magnitude of the abiotic stresses. This study therefore exposes the choice of new model components in coherence with the structure and the simplicity level of the pre-existing PILOTE model. To our knowledge, no similar research was

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conducted in a Mediterranean context where the plant can suffer from high water stress during summer, and where the dynamics of N uptake appear rather specific (Nemeth, 2001; Poch Massegù, 2012). The strength of the followed approach is also reinforced by the diversity of the experimental conditions over the 14 years of the climatic series. Some treatments are fully irrigated, little irrigated or conducted under rain-fed conditions. Regarding nitrogen, the initial N soil storage is sometimes high or low associated with different N applications, in addition combined with different climatic conditions. By contrast, it is not unusual that similar research relies on two years only, one for calibration, the other for validation. This is the case for instance of the study conducted by Salo and al., 2016) devoted to the comparison of 11 crop models which highlights the great variability of the model results. This may encourage the development of one's own model.

2. Materials and methods

2.1. *In the following sections, we will first briefly describe the structure of the existing PILOTE model. The description of the new nitrogen-based processes follows then.* The existing PILOTE model

2.1.1. Climatic forcing

PILOTE simulates soil water balance and crop yield at a daily time step, from daily climatic forcings, by associating a soil module to a crop module and considering water as the unique limiting factor. The required climatic data are the daily precipitation (P), reference evapotranspiration (ET_0), global radiation (R_g) and the daily-averaged air temperature (T).

2.1.2. Soil module

The soil module is built according to a capacitive approach: the soil profile is considered as a cascade of water reservoirs that only communicate through drainage. The holding capacity of each reservoir is calculated as the product of its field capacity (θ_{fc}) and depth. PILOTE assumes a three-reservoir system (Mailhol et al., 1996): a shallow reservoir (R1) of fixed depth (P_s=0.1 m) and two subsequent reservoirs (R2 and R3) whose depths vary with time. Once the root "installation temperature" (T_{inst}) is reached, the roots grow deeper at a rate V_r and so do R2, while R3 is located between the current and the maximal rooting depths (R_{max}), thus progressively vanishes as root deepening ceases. Drainage is assumed to occur when the water content of a given reservoir exceeds its holding capacity. Drainage from the first and second reservoirs (d_1 and d_2) supplies thus the R2

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and R3 reservoirs, respectively. Finally, drainage out of the third reservoir (d_3) accounts for deep drainage, i.e. water definitely lost out of the soil profile.

2.1.3. **Plant module**

The key variable of the plant module is the leaf area index (LAI), calculated as a function of the cumulative degree-day temperatures:

$$LAI_d = \left\{ \left(\frac{\sum_{k=1}^{d} (T_d - T_b) - T_e}{T_m} \right)^{\beta} \exp\left[\frac{\beta}{\alpha} \left(1 - \left(\frac{\sum_{k=1}^{d} (T_d - T_b) - T_e}{T_m} \right)^{\alpha} \right) \right] - \left[1 - \left(\frac{\sum_{day=d-w}^{d} Tp_d}{\sum_{day=d-w}^{d} Tp_{d\max}} \right)^{\lambda} \right] \right\} LAI_{\max} \quad (1)$$

where LAI_d and LAI_{max} are the daily and maximal LAI values, T_d is the daily average air temperature, T_b is crop-specific base temperature, T_e is the crop emergence temperature, T_m is the temperature to reach the maximum LAI value ($LAI=LAI_{max}$), Tp_d and Tp_{dmax} are the daily and maximum plant transpiration, w is the temporal window over which water stress is calculated as a transpiration ratio (over w=10 days, backwards from the current d day), α and β are the shape parameters of the logistic-type LAI curve and λ is a parameter which accounts for the harmfulness of the water stress.

The maximum crop water requirement, i.e., maximum crop evapotranspiration (ETM) is calculated according to Allen et al. (1998):

$$ETM = K_c ET_0 \quad (2)$$

,where K_c is the crop coefficient and ET_0 is the reference crop evapotranspiration. K_c is calculated as a function of LAI according to:

$$K_c = K_{c\max}(1 - \exp(-LAI)) \quad (3)$$

,where $K_{c\,max}$ is the maximum crop coefficient.

LAI is used to separate the maximum plant transpiration (T_p) from the maximum soil evaporation (E_s) using an empirical "partition" coefficient C_p:

$$C_p = 1 - \exp(-0.7LAI) \quad (4)$$

Hence:

$$T_P = C_p \, ETM \quad (5)$$

$$E_s = (1-C_p) \, ET_0 \quad (6)$$

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Alternatively, when water reserve in R1 is enough to satisfy the water demand of the crop, water is assumed to be only drawn from R1 (i.e. no root water uptake from R2) and it is also assumed that evaporation prevails over transpiration in the competition between processes to extract water from R1. Alternatively when R1 water reserve does not fulfil plant needs, the complement is drawn from R2. It is assumed that the actual evapotranspiration (ET_a) matches the maximal evapotranspiration (ETM) as long as the readily available water reserve (RAW) is not depleted. Otherwise, ET_a is supposed to decrease linearly from ETM to 0 as the content of R2 decreases from RAW to 0.

Under bare soil conditions, the evaporation rate is that of the climatic demand ET_0 until total depletion of R1. This shallow reservoir protects the subsequent layers against evaporation (somehow producing a mulch effect) so that evaporation drawn from R2 (E_{s2}) writes:

$$E_{s2} = K_{soil} \exp\left(-\left(1-\theta_{R2}\right)\right) ET_0 \quad (7)$$

,where K_{soil} is an empirical dimensionless parameter accounting for soil resistance to evaporation and θ_{R2} is a normalized volumetric water content in R2.

Grain yield is calculated as the product of the harvest index by the total dry matter (GY=HI*TDM). The harvest index is estimated as:

$$HI = HI_{pot} - a_w \left(LAI_{opt} - LAI_{av}\right) \quad (8)$$

,where HI_{pot} is a potential harvest index, a_w is an empirical reduction (or penalty) coefficient that accounts for eventual impact of suboptimal LAI during grain formation (LAI_{av}) on HI. LAI_{av} is a time-averaged LAI value over the thermal time interval Ts_1 and Ts_2 which delimits sensible grain formation stages (e.g. from the onset of grain filling to the pasty grain stage for corn).

Finally, the total dry matter TDM is updated on a daily basis:

$$TDM_d = TDM_{d-1} + RUE\, S_w^{\lambda}\, Rg_d \left(1-\exp\left(-\varepsilon\, LAI_d\right)\right) \quad (9)$$

where the d and d-1 subscripts indicate the current and previous day, RUE is the crop-specific radiation use efficiency, S_w is a water stress index taken as the ratio of actual to potential transpiration on the last day as expressed in Eq(1). Rg_d is global daily solar radiation and ε is the extinction coefficient. This formulation differs from that used in Mailhol et al. (1997) and Khaledian et al. (2009) by the formulation of the water stress term tested in Feng et al. (2014). It also differs by the fact that TDM can be simulated along the cropping cycle. One can notice that in Khaledian et al. (2009) and Mailhol et al. (2011), numerous examples attest that soil water balance and LAI are well simulated and that Eq.9 allows a satisfactory prediction of TDM along the cropping cycle (Li, 2012; Feng et al., 2014).

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2.2. The new Nitrogen module

2.2.1. Nitrogen balance equation

Nitrogen fluxes in soil are computed for a two-compartment system (C1, C2) in which C1 contains the root system and evolves with it (C1 encompasses R1 and R2), while C2 spreads out from the bottom of the root system to the maximal rooting depth (C2 is equivalent to R3). Plant Nitrogen uptake takes place only in C1, whose size grows with root depth, similarly to R2 (cf. section 2.1.2), with the difference that the initial depth of C1 is set to 30 cm (knowing that mineralization preferentially occurs in the 0-30 cm horizon). When drainage occurs out of R2, the nitrogen amount in C2 may be increased by lixiviation out of C1. Thus, the concept of soil water reserve evolving with root development, which was present in PILOTE, is now extended to nitrogen in PILOTE-N.

Under bare soil conditions (i.e., before a cropping season or between two cropping seasons), the nitrogen balance is calculated in the two-compartment system, placing the bottom of C1 at 30 cm and that of C2 further 30 cm lower. Regardless of the simulated period, mineralization and denitrification are supposed to occur only in the C1 compartment.

The nitrogen balance in the root zone (compartment C1) is formulated as:

$$N_F = N_I + N_A - N_V - N_D - N_M - N_L - N_P \quad (10)$$

where N_F is the final N soil storage, N_I is the initial N soil storage, N_A is N supply by fertilization, N_V is N loss by volatilization, N_D is N loss by denitrification, N_M is N supply from mineralization, N_L is N loss by lixiviation and N_P is N loss by plant uptake.

2.2.2. Volatilization

Nitrogen loss by volatilization, in the form of ammonia (NH4), mainly concerns organic fertilizers applied on the soil surface (Hofman and van Cleemput, 2001) during both hot (Sainz-Rosas, 1997) and dry periods (Sigunga et al., 2002). Nitrogen loss by volatilization is relatively small compared to the other terms of the nitrogen balance. More precisely, an irrigation is advised after a N application to compensate for a lack of rain and avoid volatilization. However, volatilization rarely reaches a maximum of 20% of the total nitrogen fluxes in extremely favorable conditions (Mahmood et al., 1998; Hofman and van Cleemput, 2001; Sainz-Rosas et al., 2004). In PILOTE-N, N_V is thus suppressed from Eq.10 for the sake of simplicity and replaced by a coefficient of "fertilization application efficiency" which ranges from 1 (no volatilization) to 0 (the applied fertilizer is entirely lost by volatilization). We assume thus that N_V may be handled indirectly through more or less efficient applications of the N fertilizer.

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2.2.3. Denitrification

Denitrification occurs under combined conditions of high temperature and high soil-water content following a dry period (Nemeth, 2001; Dorge, 1994). Denitrification is simulated as:

$$N_D = N_{soil}\left(T_{7d}/T_D\right) \quad (11)$$

where N_{soil} is the N soil storage, T_{7d} is the average temperature over the last 7 days, and T_D is the empirical temperature threshold over which denitrification occurs.

This equation holds when (i) soil water content is very close to field capacity in R1 ($\theta > 0.95\ \theta_{fc}$), (ii) T_{7d} is greater than or equal to T_D (setting T_D=28 °C) and (iii) N_I is above a threshold value (100 kg N ha^{-1}).

2.2.4. Mineralization

Mineralization occurs either from the decomposition of soil organic matter which is a permanent process depending on soil structure and characteristics (calcareous content for instance), temperature, and moisture (e.g. Delphin, 1993 ; Barakat et al., 2016) or from the decomposition of organic crop residues by the microbial biomass. The decomposition process of additional crop residue is not considered here, assuming nitrogen balance mainly concerns a cropping cycle where the initial N soil content is known and where only mineral fertilizers are applied. As consequence, the eventuality of an immobilization process followed by mineralization cannot be accounted for by the model in its present version.

Mineralization during the cropping cycle is calculated as follows:

$$N_M = V_{M\,pot}\,\frac{T}{T_{Mr}}\,\frac{\theta}{\theta_{fc}} \quad (12)$$

where $V_{M\,pot}$ (kg ha^{-1} d^{-1}) is the potential mineralization rate and T_{Mr} is a reference temperature for mineralization, assumed to occur only above T_{min} = 5°C. Similar formulations involving both the air temperature and a normalized soil water content are commonly used to model the mineralization processes (e.g. Stroo et al., 1989; Mary et al., 1999).

$V_{M\,pot}$ is expressed as:

$$V_{M\,pot} = C_M\ pHOM \quad (13)$$

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,where C_M is a dimensionless parameter, pH simply is the pH of soil solution and OM is the volumetric percentage of organic matter content in the soil.

The use of only two measurable quantities (pH, OM) plus one degree of freedom (C_M, discarding the clay and calcium carbonate percentages for example) is an attempt to focus only on the most crucial triggers for mineralization. By contrast, mineralization is reduced in calcareous soils having generally also a low OM value, while the optimal pH for mineralization ranges from 7 to 8 (Nemeth, 2001), and therefore the model assumes no mineralization takes place for pH values above 8.

2.2.5. Lixiviation

Nitrogen lixiviation (kg ha^{-1}) is assumed to occur by convective processes through drainage :

$$N_L = 10\, d_i\, c_N \tag{14}$$

where the numerical pre-factor is required to retrieve the legal units of kg ha^{-1}, d_i is daily drainage out of the C1 or C2 compartment and c_N is the concentration of nitrogen in the soil solution:

$$c_N = 10^{-4}\, N_I\, \theta_i^{-1} \tag{15}$$

where the numerical pre-factor is required to retrieve the legal units of kg m^{-3} and θ_i is the average water content of the C1 or C2 compartment.

2.2.6. Nitrogen demand by the plant

The potential cumulative nitrogen demand (PCND) by the plant is driven by the total dry mater TDM. Its logistic is similar to that of LAI driven by temperature (Eq.1). The main reason for choosing PCND as a logistic-type curve of TDM is that it can be scaled. This allows adapting the N plant consumption and the optimal couple (Total dry matter, N in Plant) to local climatic conditions:

$$PCND_d = \left(\frac{TDM^*(d)}{TDMpot}\right)^{x_2} \exp\left\{\frac{x_2}{x_1}\left(1-\left(\frac{TDM^*(d)}{TDMpot}\right)^{x_1}\right)\right\} PCND_{\max} \tag{16}$$

where TDM* is the simulated daily potential total dry matter (e.g. under no stress conditions) and TDM_{pot} is the potential final value of TDM. The x_1 and x_2 parameters dictate the shape of the PCND logistic curve and $PCND_{max}$ is the maximal PCND value, providing the scaling factor.

Root density is not considered in PILOTE-N since the rooting pattern is dispatched between two reservoirs only (fixed-depth R1, variable-depth R2). Nitrogen availability and uptake depend on

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water content and movement in convection, not diffusion. Nitrogen uptake is supposed to depend on nitrogen concentration in the soil solution and on the transpiration rate, as suggested by Frere (1977). The available nitrogen amount (somehow the "nitrogen offer by the soil") writes:

$$N_{OF} = 10\, c_N\, Tp\, K_a \left[\frac{\theta_i}{\theta_{fc}} \right] \tag{17}$$

where the numerical pre-factor is required to retrieve the legal units of kg ha^{-1} and K_a is a calibration parameter that could be related to the specificity of the rooting pattern and its ability to extract nitrogen. The ratio of humidity in the root zone is used for considering the effect of decreasing N uptake for low soil water contents.

Considering that daily Nitrogen plant demand is lower under water stress conditions than the potential demand, one can write:

$$N_{DE}^{*} = N_{DE}\, S_w \tag{18}$$

,where N_{DE}^{*} is the corrected value of N_{DE} in presence of a water stress S_w.

From the above, Nitrogen uptake (N_P term in Eq.14), is described as:

$$\begin{cases} N_{OF} \geq N_{DE}^{*} \Rightarrow N_P = N_{DE}^{*} \\ N_{OF} < N_{DE}^{*} \Rightarrow N_P = N_{OF} \end{cases} \tag{19}$$

which simply reads "nitrogen uptake is the lesser of the nitrogen offer and nitrogen demand terms".

PILOTE-N considers a nitrogen stress index S_N that affects the harvest index (cf. next section). S_N is calculated from the ratio of the uptake to the demand:

$$S_N = N_P / N_{DE}^{*} \tag{20}$$

The production of dry matter described in (Eq.9) is affected by water stress through the index S_w, whose harmfulness appears in the λ coefficient. It is also possibly impacted by nitrogen stresses S_N. The simplest way to proceed (until further developments are achieved and experimental data are collected on purpose) is to adapt (Eq.1) and (Eq.9) by replacing S_w by S_{wN}, where S_{wN} designates "the most severe of the S_w and S_N stresses". The λ parameter is kept whereas the introduction of distinct values (say λ_w and λ_N) may offer an additional degree of freedom, to be supported by experimental evidences.

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2.2.7. Nitrogen impact on harvest index

The correction of HI_{pot} to account for simultaneous water and nitrogen stresses may be adapted from Eq.8. This correction depends on the most severe of the S_w and $S_{N\,av}$ stresses, the time-averaged value of S_N over the sensitive period delimited by Ts_1 and Ts_2. If the average value of water stress over the period delimited by Ts_1 and Ts_2 is less than the average value of the Nitrogen stress, then Eq.8 is left unchanged. Otherwise, Eq.8 becomes:

$$HI = \min\left[HI_{pot}, HI_{pot} - a_N\left(1 - S_{N\,av}\right)\right] \quad (21)$$

where a_N is a reduction (or penalty) coefficient when nitrogen stress prevails over water stress.

Accordingly, nitrogen stresses occurring at thermal times late in the critical period or even after crop maturity would neither affect the predictions of LAI nor these of HI. For most crops, HI significantly increases with the nitrogen content in the plant, thus with nitrogen applications (Cox et al., 1993). By contrast, for some crops such as sugar beet, HI may decrease with increased nitrogen content in the plant, which may be accounted for by using negative a_N values in Eq.21, which makes Eq.21 generic.

2.3. Field experiments and validation data

2.3.1. Field experiments

The experiments were carried out at the Lavalette agronomic station of Irstea, the French National Research Institute of Science and Technology for Environment and Agriculture (43°40'N, 3°50'E, altitude 30 m) near the city of Montpellier, Southeast of France. The experimental site of about 1 ha is characterized by a Mediterranean climate with an average annual rainfall of 780 mm. Annual evapotranspiration calculated according to the Penman-Monteith equation (Allen et al., 1998) is 870 mm. The soil at Lavalette is loamy, containing in average 18% of clay, 47% silt and 35% sand over an average depth of 2.0 m. The holding capacity is around 180 mm/m and the "initial soil water content" used to model the development of summer crops is generally close the field capacity at the end of winter. Soil pH is 7.5 and the percentage of organic matter MO is 1.45 in average (Nemeth, 2001).

2.3.2. Validation data

The validation of the PILOTE-N model was realized using data collected on three crops: corn (*Zea mays* L.), durum wheat (*Triticum aestivum* L.) and sorghum (*Sorghum bicolor* L.), grown between 1997 and 2013, under varied climatic conditions and for various strategies of water and Nitrogen

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management strategies, as summarized in Table 1. Except for 1997 and 1999 where the corn yields under rain-fed conditions overreached 8.5 $Mg.ha^{-1}$, the summer period was generally dry. The initial N soil conditions were very different between years. That impacted noticeably the yield components of the limited N treatments, while the rain-fed treatments having beneficiated of a low N application (RFC99, RFC11, RFC12) subject to different initial conditions deserve a special attention for the analysis of combined abiotic stresses. The incoming solar radiation generally allows reaching the potential crop yield, hence no radiation deficit effect should be sought, except for 1997. The cropping season of 1997 had a radiation deficit of around 50000 $J.cm^{-2}$, in comparison with a typical year in the climatic series. This deficit combined with a rainfall amount of only 256 mm makes it an exceptional year, gathering conditions for low corn yields.

Crops cultivars were as follows: for corn, SAMSARA (1997-1999, 2002) and PR35Y65 (2007, 2011-2014), for wheat, Artimond (2004-2005) and Dakter (2005-2006, 2008-2009, 2009-2010) and for sorghum, Argens (2003-2004).

The experiments were described in previous papers focusing on water (Mailhol et al, 1997; Khaledian et al., 2009; Mailhol et al, 2011) or nitrogen management (Mailhol et al., 2001; Khaledian et al., 2011). The experimental domain of Lavalette is divided in several plots with different designs between seasons (Fig. 1 shows an example for 2012), supporting dedicated treatments, the size of which may vary from a few hundreds to a few thousand square meters. The treatments are either irrigated by sprinklers, by a travelling rain gun system or by subsurface drip irrigation (SDI). Irrigation scheduling was based on tensiometer readings or some time using PILOTE itself. Water application depths ranged from 25 to 35 mm by the sprinkler systems and between 5 and15 mm by SDI. From 2011 the limited irrigation treatments consisted in stopping irrigation at the end of July.

A non-fertilized treatment (0N) has in most cases been conducted for the evaluation of soil mineralization and a rain-fed treatment (RF) to calculate the irrigation water productivity (Mailhol et al., 2011). Neutron probes were used to monitor soil water content in the middle of each plot, always complemented by a series of tensiometers. Manual rain gauges were also installed in the vicinity of neutron probes to accurately estimate the local rainfall and irrigation amounts. LAI measurements were performed, at least weekly, throughout the cropping seasons using the LAI probe (LAI-COR-2000 Plant Canopy Analyzor LAI-meter). Several sub-plots (most often, seven) of 2-3 m^2, located in the vicinity measurement sites, were harvested after maturity to assess grain yield and biomass production and to assess nitrogen content in plants (leaves, stems and grains) according to the Kjeldahl method.

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The experiments conducted on Lavalette were mainly devoted to irrigation management, which is the reason why N in plant is only known at harvest dates, to verify if the yield gap is not due to a lack of nitrogen. The corn season 1999 was essentially focused on the fate of nitrogen under different irrigation systems (Mailhol et al., 2001) but unfortunately only one couple of total dry matter and Nitrogen in plants (TDM, N_p) is available during the cropping season, in addition to that obtained at harvest.

The profiles of nitrogen concentration in the soil solution near the measurement sites were characterized before sowing and after harvesting from the soil to surface to 1.5 m depth, with step of 30 cm.. The technique of the averaged soil sample consisting in mixing 3 or 4 soil samples collected with an auger at each step is explained in detail in Khaledian et al. (2011). The N applications were only measured with precision from 1999 to 2007, using plastic bowls around the measurements sites. Outside this period the precision on the N amounts depends on the performance of the spreading machine.

By the end of each growing season, crop residues were buried at shallow depths during tillage. Note that oat was sown on DOY285 in 2012, as a cover-crop for FIC13. For the summer crops, the nitrogen applications were immediately followed by irrigation, which was not the case for winter crops (durum wheat). Finally, it is noteworthy that drainage is most likely to occur during autumn as a result of typical strong rainfall events during this period of the year in Montpellier, with occasional nitrogen losses by lixiviation.

3. Model calibration

The first step of the calibration is devoted to C_M, the parameter involved in the mineralization process. Then calibration will be detailed for the parameters involved in the N plant uptake process and for those that control crop yield.

3.1. Calibration and validation of the mineralization module

The nitrogen amount resulting from the soil mineralization was obtained as proposed by Khaledian et al. (2011) from the 0N treatments. During each experiment, the tensiometers (not shown here) indicated no drainage, thus no lixiviation, and the conditions were not favorable for denitrification. C_M was thus (Section 2.2.4, Eqs.12-13) the only parameter to calibrate. The volumetric organic matter content OM of about 1.5 % and soil pH of 7.5 are the soil characteristic values considered for our experimental site. Consequently a C_M value of 0.075 yields a mineralization rate of 0.75 kg ha^{-1}

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d^{-1}, in agreement with that found by Nemeth (2001) at Lavalette. The reference and minimum temperatures for mineralization were respectively 20°C and 5°C. This parameter set (C_M=0.075, T_{Mr} = 20°C and T_{min} = 5°C) yields in average 100 kg ha^{-1} of total mineralization, a value generally found in literature (e.g. Desvigne, 1993; Mary and Recous, 1994; Campbell et al., 1984; Quemada and Cabrera, 1997).

The validation of this parameter value can be performed independently from PILOTE-N and thus may immediately follow calibration.

Since plant transpiration Tp is required to derive θ in Eq.12, PILOTE can be used with the daily values of rainfall, irrigation. Tp is calculated using Eqs. 1 to 5 and the measured LAI values for a given "light nitrogen" LN (or "zero-nitrogen" 0N) treatment. Note that irrigation was not limited and consequently one can assume that there was no water stress.

Mineralization was reasonably simulated as shown in Fig.2, except in 2007 where it is noticeably underestimated (95 vs. 110 kg ha^{-1}). It will be further strengthened by model simulations conducted during the inter-cropping season.

3.2. **Calibration of the plant nitrogen uptake and grain yield**

The calibration process in this case concerns x_1 and x_2, the shape parameters for the N plant demand (Eq.16), then K_a of Eq.17, and finally a_N involved in the estimation of the HI harvest index required for the grain yield calculation when the N stress is higher than the water stress.

3.2.1. Calibration for corn

The process starts with the calibration of x_1 and x_2. The plant nitrogen content was not monitored during the cropping cycle on any unstressed corn treatment, except for FIC99 (cf. Table 1) with only two measurements of (TDM, N_p) pairs. To overcome this limitation, the shape parameters x_1 and x_2 were calibrated based on the shape of the critical curve of the N plant demand formulated by Justes and al. (1994; 1997) and Plenet (1995). Using this critical curve ($\%N_p = a_{crit}TDM^{b\ crit}$, where a_{crit} and b_{crit} are dimensionless empirical parameters) allows generating a series of (TDM, N_p) pairs. Exploiting the analogy between Eq.1 and Eq.14, the fitting method used in Mailhol et al. (1997) and Khaledian et al. (2009) to obtain the shape parameters of the LAI curve vs. temperatures (Eq.1) was also used to obtain the x_1 and x_2 parameters. A distinction between corn cultivars is pointed out in this new formulation by specific values of $PCND_{max}$ and TDM_{pot} (Eq.14), assuming the values of x_1

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and x_2 depend on the crop, not on the cultivar. The values of x_1 and x_2 were 0.45 and 1.5 respectively.

The values of $PCND_{max}$ and TDMpot were set to 300 kg ha^{-1} and 23 Mg ha^{-1} for the SAMSARA cultivar. For the other late corn cultivar (PR35Y65) the potential TDM value is set to 30 Mg ha^{-1} (e.g. Lamm and Trooien, 2005; Couto et al., 2013) and that of $PCND_{max}$ to 380 kg ha^{-1}, for a grain yield of GY=17.5 Mg ha^{-1} (see Table 1). In absence of dedicated field experiments, the same harmfulness was assumed for the water and nitrogen stresses and $\lambda_\omega = \lambda_N = \lambda = 1.25$, as proposed by Khaledian et al. (2009) for field crops (corn, sorghum and wheat).

The parameter K_a (Eq.17) was calibrated from the FIC99 treatment, resulting in a value of 2.5, validated then on RFC99. It is shown in Fig.3a and b that this value allows a correct estimation of the N contents in both plant and soil. It is noteworthy that N soil storage is also reasonably simulated at the beginning of the cropping cycle and after the rainy periods from the end of September to the half of November (DOY= 313) for FIC99.

Parameter a_N was calibrated on the grain yield of 0NC99 because TDM (12 Mg ha^{-1}) of this treatment is perfectly simulated. Its value (0.15) was found slightly higher than that of a_N (a_N = 0.12 in Khaledian et al., 2009) used to account for the effect of water stress on the harvest index, then in turn on grain yield (Eq.21).

3.2.2. Calibration for durum wheat

The crop parameters for durum wheat were drawn from Khaledian et al. (2009) for the unstressed N treatment. Under our experimental layout the potential value of TDM was not reached. Consequently, the $PCND_{max}$ and TDM_{pot} values were drawn from literature and their values were assigned respectively to 280 kg ha^{-1} and 17 Mg ha^{-1} (Casals, 1996; ARVALIS, 2016). The calibration of the shape parameters was conducted similarly to the corn case, based on the N critical curve proposed by Justes et al. (1994), obtaining 0.8 and 1.4 for x_1 and x_2, respectively. Adopting the same assumption for λ, the value of K_a equal to 3 was found on DWLI05 to significantly improve both the prediction of N content in the plant and that of grain yield, with the same value of a_N for corn (0.10).

3.2.3. Calibration for Sorghum

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The $PCND_{max}$ value was set to 250 kg ha^{-1} associated to TDM_{pot} of 19 Mg ha^{-1}. These values are proposed by ARVALIS (ARVALIS 2012), a French institute which conducts studies on field crops and other plant species. Parameters x_1, x_2 and K_a were calibrated with the same method as for corn and durum wheat. The values for x_1, x_2 were found equal to 1 and 2, respectively and K_a was 4, from the FIS04 treatment. Nitrogen content in the plant was reasonably simulated. The highest gap between simulated and observed values was obtained for RFS03, respectively 110 vs. 95 kg ha^{-1} (not presented). N soil storage over the entire root zone (1.5 m deep as average depth for sorghum) at harvest was acceptably simulated for RFS03 (110 vs. 129 kg ha^{-1}) and for RFS04 (112 vs. 110 kg ha^{-1}), compared with the irrigated treatments LIS03 (67 vs. 99 kg ha^{-1}) and FIS04 (77 vs. 50 kg ha^{-1})

4. Model validation

4.1. LAI and Soil Water Reserve (SWR)

Many examples of model performance regarding LAI and the soil water reserve (SWR) simulations are presented in previous articles implying PILOTE where N is not a limiting factor. The ability of PILOTE-N to simulate not limited conditions both for water and nitrogen is thus little surprising. By contrast, the differences modeled between a full fertilized and a 0N treatment, both subject to the same irrigation strategy, should be pointed out (Fig. 4). Indeed, the SWR variation is substantially weak along the cropping cycle for 0N, with consequently, a lower Ce value (the coefficient of efficiency of Nash and Sutcliffe, 1970).

LAI for 0N and LN treatments which ranged from 1.6 to 3.1, are not very well simulated, with performance criteria of 0.595, 0.34 and -0.18 for R^2, the Root Mean Square Error (RMSE) and the Mean Biased Error (MBE), respectively. The negative value for MBE attests that LAI is somewhat underestimated by PILOTE-N. These same criteria are much better for the whole set of treatments (R^2 = 0.934 ; RMSE = 0,24 ; MBE = -0.01).

4.2. Mineralization and lixiviation during the intercropping period

The specificity of the lixiviation process adopted in PILOTE-N which could be considered as the weakest link in the model merits a peculiar attention. Because no parameter involved in this process required any calibration, this section is first dedicated to evaluating mineralization during the intercropping period. But overall, we focus on the lixiviation component of the model under different rainfall conditions. N leaching is assumed to only occur by convection, thus through drainage fluxes.

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The ability of PILOTE-N to correctly simulate N leaching implies thus the correct simulation of drainage, in addition to N plant uptake and soil mineralization processes. Generally, substantial drainage occurs during intercropping periods. We recognize that a specific protocol involving the installation of lysimeters for evaluating drainage and N leaching during intercropping period would have been necessary. However, one can attempt to show that leaching can be validated, on the basis of N soil storages (N_{soil}) leaning on a few plausible hypotheses regarding mineralization, described in the following.

4.2.1. Mineralization

We have to prove first that mineralization during intercropping periods is well simulated, before considering the leaching process itself. For that, we have to seek periods without rainfall that could induce drainage. When looking at Fig. 5, one can assume that mineralization during the intercropping period is satisfactorily simulated on the basis of simulated and measured N_{soil}. Mineralization is significantly lower for FIC13 (Fig.5b) than for 0NC13 (Fig.5a) because the soil water profile was much more depleted for FIC13 than for 0NC13 at the end of the cropping season (not presented), a consequence of the nitrogen deficit that reduces LAI and consequently transpiration, as shown in Fig.4b. Mineralization is low from DOY300 to DOY420 due the weakness of temperatures during winter.

4.2.2. Leaching

Some contrasted examples of N leaching during intercropping periods are presented in what follows, starting with heavy drainage conditions. Such conditions occurred for FIC97, FIC98, FIC12 and FIC13 for corn and also twice for durum wheat, for which experiments DWLI05 and DWLI06 are fairly well simulated. FIC97 and FIC98 received 613 mm of rainfall during the cropping season, resulting in a simulated drainage of 266 mm. FIC12-13 received 710 mm rainfall for a simulated drainage of 392 mm. Fig.6 shows that N_p and N_{soil} are correctly simulated, which implies that leaching also is reasonably simulated for the corn case.

Durum wheat, generally sown in autumn in South-East of France, can be affected by substantial rainfall periods inducing drainage and leaching risks, as presented in Fig.7. Rainfall during 2004-2005 and 2005-2006 experiments was 820 mm (from DOY320 to DOY720 e.g. end of 2005) and 366 mm from DOY320 to DOY570 e.g. end of July 2006), respectively, with a simulated drainage of 249 and 166 mm, respectively. Still hypothesizing that mineralization during the cropping cycle is well simulated, based on the fact that N_{soil} is correctly predicted, N leaching (occurring mainly outside the growing period) is then also well simulated.

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The intercropping periods 2002-2003 for corn and 2003-2004 for sorghum were particularly rainy. Indeed, rainfall and simulated drainage were 804 and 547 mm, respectively, for 2002-2003 and 1290 and 660 mm, respectively, for 2003-2004. PILOTE-N simulates N_{soil} and N_p reasonably under such heavy drainage conditions (Fig.8) hypothesizing that mineralization during intercropping season is correctly predicted.

Moderate drainage conditions were also observed during the experiments. The intercropping season 2011-2012 raises questions since N_{soil} measured at the end of March (DOY456) is substantially overestimated by the model as shown by Fig.9. For 2011-2012 the rainfall was 305 mm from DOY 273 to DOY 334, while simulated drainage, predicted to start on DOY 307 equals 174 mm for FIC11 and 260 mm for 0NC11. One can notice that N_{soil} at the end of the drainage period (around DOY 310) has the same value of that measured at the end of March 2012 (DOY 446). This overestimation of N_{soil} by the model on DOY 446 could result from the immobilization process probably more efficient or more noticeable under un-cropped soil with substantial crop residue conditions than under these previously presented. Indeed, the N amount (around 30 kg ha^{-1}) consumed by the microbial fauna during the assumed process seems a realistic value according to Mary et al. (1999). Under moderate drainage and leaching conditions, a possible failure of the simple mineralization module is thus highlighted. This example points out the difficulty of predicting the N balance even during the intercropping season on un-cropped soil without involving an efficient crop residue model. However, our main objective is the prediction of the N balance during the cropping season assuming that N_{soil} few days before sowing is required.

4.3. Model evaluation along the 14 years of experiments

Fig.10 and 11 refer to the soil N storage at the end of the cropping cycle, to N plant uptake and to crop yields. The N soil storage (Fig.10a) exhibits some discrepancies confirming that some phenomena are not always identified or captured. That is particularly the case when the N balance evaluated from measurements cannot be closed without any robust explanations (no drainage, no favorable conditions for volatilization or denitrification). The numerical criteria such as the coefficient of determination (R^2) and the root mean square error (RMSE) are satisfactory for N_p and yields, while the mean bias error (MBE) with values of 0.04 and 0.03, respectively, does not attest significant overestimation. R^2 and RMSE values are noticeably lower for N_{soil}, with MBE = 3.03. This can also be due to a lack of precision regarding N applications, as in 1998 for the rain-fed treatment where the N application were only estimated. But, as discussed above for the sorghum case, no explanation can be given for some gaps.

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N plant uptake (Fig.10b) is well enough simulated even for the 0N treatments such as for instance in 1999 (83 vs 90 kg ha^{-1}) or for the light N treatments, while this quantity is often overestimated by most of the crop models as shown in Nemeth (2001).

Total dry matter and grain yields are rather well simulated, as attested by Fig.11, even if the later also shows some overestimations of TDM on the 0N treatments, as for example for 2012 (12.8 vs. 14.3 Mg ha^{-1}) and 1998 (10.3 vs. 11.5 Mg ha^{-1}).

5. Discussion

In the present work, we did not intend to add another crop model to literature but rather to enhance and complement an existing one, PILOTE, which has been used for years for irrigation management and now tackles joint irrigation and N-fertilization management. The scientific interest of this work is in fulfilling the challenge to maintain the user-friendly and operational character of PILOTE, augmented with nitrogen management facilities. From the acceptability of the results obtained for a contrasted climatic series over 14 years, one can consider that our objective is reached. Indeed, we can say that "a good representation of reality" (Affholder and al., 2012) is proposed by this model since the predictions are performed with "acceptable accuracy and precision", as formulated by Loague et al. (1991).

PILOTE-N stands apart from most crop models by ruling the potential cumulative N plant demand by a logistic-like curve similar to that used for the increase of LAI with time. In addition, the shape parameters of this curve allow its application to different cultivars from the same species, as shown for the corn case. Although empirical, the role played by these parameters in the N plant uptake process is well identified. Indeed, the period where the N plant demand is the highest can easily be advanced or the delayed by decreasing or increasing x_1. A supplementary degree of freedom exists in the form of the required maximal N plant demand for the desired cultivar, a value generally proposed in literature, which serves as a scaling parameter for the curve.

The concept of successive soil water reservoirs of PILOTE is extended, in PILOTE-N, to nitrogen. As for water, N is taken up by plants according to a quasi-lumped model (using two variable-depth reservoirs) in which the soil is not multilayered, a true specificity amongst models developed to simulate the N fate. This quasi-lumped approach implicitly accounts for the compensated root water and nutrient uptake, a phenomenon not always well simulated by multilayered crop models (Simunek and Hopmans, 2009; Albasha et al., 2015). The allocation from the common pool to the different plant organs is not based on the source-sink principle as in some crop models. In PILOTE-N (as in PILOTE), LAI is not derived from TDM (the common pool for models based on the allocation

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principle) but simulated based on temperature accumulation (*i.e.* thermal time), before the current LAI value is used to calculate the TDM increase of the same day. Although not pointed out in the case of field crops, it is all the same possible to discriminate the impact of water or N stresses on the grain yield via the adequate harvest index formulations. Thus, despite its simplicity, our modeling approach offers some flexibility.

Some weaknesses of PILOTE-N are attested by occasional gaps between measured and predicted N soil storages after a rainy period during the inter-cropping season, could result from the fact that leaching is simulated based on a very rough approach. Indeed, the capacitive approach here used is very far from that used in LIXIM (Mary et al., 1999) in which N leaching is simulated according to the Burns (1980) model and where a peculiar attention is devoted to the role of crop residues. The authors recognize that a specific protocol should have been implemented for validating both mineralization and lixiviation during intercropping seasons, as proposed by Mary et al. (1999). Nevertheless, despite the assumption adopted regarding mineralization, the simulated N soil storages at the end of rainy periods (beginning of winter), associated with substantial drainage, do not differ a lot from the measured ones. The origin of the evoked gap between simulated and measured N soil storage at the end of the period 2011-2012 could result from losses by immobilization, a process requiring the use of an efficient crop residue model. The latter has been developed in the frame of this research. Because not validated yet it is not presented here. Under our experimental conditions, drainage rarely occurs during the cropping season more especially for summer crops. However, we compared simulations obtained with PILOTE-N and PILOTE (not shown here) to evaluate the added value of the N module. We noticed that PILOTE-N gave better yield predictions under drainage conditions than PILOTE. That could strengthen, in a way, the credibility of the nitrogen lixiviation simulated by the model as for the DW case 2008-2009 and that of corn in 2008 as further explained.
Note that the variable-depth compartments used for the N balance calculation may appear little justified due to the fact that, at the beginning of the cropping cycle, the N plant demand is low and can be compensated by mineralization. However, in case of heavy rain conditions, a substantial N amount can leach out of the first compartment to supply totally or partially the second one, which could impact the N plant uptake conditions: this is a process representation specific to the model.
Although the different mineralization models proposed in the literature use similar factors (mainly soil water content, temperature and soil properties) as those proposed in PILOTE-N, the latter is more simpler owing to its limited objectives (residue decomposition not taken into account yet) and still gives acceptable results by using air temperature instead of soil temperature. Mineralization is also satisfactorily simulated during the cropping season and during the inter-cropping season. The no

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drainage period from DOY 250 (2013) to DOY 90 (2014) due to the absence of heavy rainfall, confirms the ability of the model to properly simulate mineralization during the inter-season, the N soil storages being correctly predicted as shown by Fig.5.

LIC of 2007, 2011, 2012 and 2013 highlighted the pertinence of a reduction in N application for water-scarce conditions attesting that nitrogen savings are possible when the initial N soil storage before sowing is known. A case that deserves dedicated attention is the rain-fed treatment of 2008. This cropping season with corn, was not selected because N in the plant was not measured. But it was sufficiently rainy (235 mm on the cropping cycle) to point out the effect of a reduction in N inputs (37 kg N ha^{-1} only at sowing) responsible for the low final grain yield, unlike other rain-fed treatments analyzed in this article. The fact that PILOTE substantially overestimates the corn yield (7.3 vs. 4.0 Mg ha^{-1}) compared with PILOTE-N (4.3 vs. 4.0 Mg.ha^{-1}) highlights the difficulty to manage efficiently both water and nitrogen, since the rainfall forecast is not possible for a farmer. For the durum wheat case, the application of PILOTE-N allowed noticing that the low yield value for the 2008-2009 cropping season was due to N leaching, whereas PILOTE substantially overestimated the yields. This statement pleads in favor of the identification of an efficient N management strategy using a modeling approach such as that proposed by PILOTE-N.

Due to the absence of a treatment both full irrigated and full fertilized, and for which a series of (TDM, N_p) pairs would have been monitored along the cropping cycle, the shape parameters (x_1, x_2) for the cumulative nitrogen plant demand were calibrated on the N critical curve proposed by Justes et al., (1994). This should ensure a correct simulation of N_p along the cropping cycle (in adequacy with TDM) and not at harvest only. But we recognize that the lack of (TDM, N_p) pairs measured during the growing phase (except for FIC99 and RFC99) may raise criticisms. More precisely, a model run with an inadequate parameter set (x_1, x_2), can result in a good prediction of the (TDM, N_p) pair at harvest but the temporal coherence would be poor and significant gaps between predicted and observed values would appear during the cropping season, especially for N_p. It can be noticed that, in average, 85-90% of the final nitrogen plant consumption is reached few days after the maximal LAI value is reached, with the parameter set (x_1, x_2) calibrated by the proposed method.

As evoked in introduction, PILOTE-N is an interesting tool for analyzing abiotic stresses. That is especially obvious when comparing treatments both fully irrigated and little fertilized (LN11, LNC12) with rain-fed treatments (RFC11, RFC12) also little fertilized, with similar moderate initial N soil storage. As shown on Table 1, the corn yields of the rain-fed treatment are noticeably lower than the little fertilized ones attesting thus the preponderance of water stress on N stress. When disconnecting the N module (passing from PILOTE-N to PILOTE) the yields of the rain-fed treatments were very well simulated which means that water stress is responsible of the weakness of

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the yields despite a very light fertilization. The condition to correctly account for such situations is that N stress should not appear before water stress in time. This condition is met due to the shape of the N plant demand and by the fact that the latter is reduced within the water stress period. The necessity to reduce fertilization under limited water conditions is clearly shown by this analysis, and the water management under such conditions could be performed using PILOTE only.

There is no question that a sound sensitivity analysis would merit to be performed. It was conducted by Khaledian et al. (2009). It revealed that PILOTE was sensitive to initial soil water content more especially for the rain-fed and the little irrigated treatments. A similar statement can also be proposed to PILOTE-N regarding the initial N soil storage for the limited N treatment. Nitrogen plant uptake and yields are little sensitive to K_a, in particular on the limited N treatments because plant cannot take up more N than offered by the soil. On the no limited N treatments, a 25% variation of Ka gives a variation of N in plant lower than 5% at harvest. N in the plant is little sensitive to the shape parameters ruling the curve of the potential N demand. For instance a 25% variation of the shape parameters results in variation of N in plant lower than 5% at harvest. The impact on TDM is higher on the N limited treatments. A 25% variation of the shape parameters results in a TDM variation at harvest lower than 7% in average and lower than 3% for moderate or full fertilized treatments. This sensitivity of TDM and that of N in plant to the shape parameters is a little higher at the beginning of the cropping cycle and more especially with respect to x_1 because this parameter allows to advance or to delay the period during which plant requires the highest N amount.

Of course the sensitivity of GY to a_N is essentially highlighted on the limited N treatments. This sensitivity can be considered moderate. For instance, when a_N decreases from 0.14 to 0.12, GY increases from 6.0 to 6.2 Mg $ha^{-1}$and decreases by 0.2 Mg ha^{-1} when a_N increases from 0.14 to 0.16 on treatment 0NC11. A similar model behavior can be observed on the other treatments.

At this stage, the convenience of using such a tool (written in FORTRAN), merits to be highlighted. As written in Khaledian et al. (2009) for PILOTE, most of the model parameters can be measured or derived from literature. Only the shape parameters (α,β) of LAI and λ, which is dedicated to simulate the impact of the water stress conditions on both on LAI and TDM, have to be calibrated for the case of a new crop. Regarding PILOTE-N, the only parameters to calibrate are x_1, x_2 and K_a. Finally, specific treatments are needed for the calibration of a_N, parameter dedicated to the harvest index, for crops having a same sensitivity to water and to N stress.

In order to correctly simulate N_p for the full fertilized N treatment Nemeth (2001) and Poch-Massegù (2012) have modified the initial parameters governing the N plant uptake of STICS in the Mediterranean context. Since highly predictive crop models do not exist, it is advantageous to have a

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model easy to calibrate, to run in optimization scenarios or to update within data assimilation techniques, which are forthcoming works with the PILOTE model (e.g. the Optirrig tool for the generation, analysis and optimisation of irrigation scenarios, possibly running with nitrogen management options, Cheviron et al., 2016). For instance, the SPAD-502 chlorophyll meter, (Bulloc et al. 1995) an apparatus allowing the N monitoring in the plant, can be used to update specific parameters (which involved in the N plant uptake process) of the N module. For analysing the nitrogen stress, it would probably be more interesting than an apparatus such as the LAI2000 based on the light interception, and which does not provide information about the percentage of photosynthetic active mater. This could initiate further researches for justifying the fact that LAI is little under estimated by PILOTE-N for the 0N treatments while SWR is rather well simulated for these treatments.

6. Conclusions

The objective of this work was to propose a convenient tool for predicting the impact of a reduction of nitrogen inputs on the crop production. It is reached since both N in the plant and crop yields are correctly simulated under both sub-optimal water and nitrogen applications, for a long climatic series (1997-2013). This performance merits to be pointed out for a model whose empirical concepts could be criticized for their simplicity and weak predictive abilities. Moreover, PILOTE-N stands apart from most crop models by its originality, since its main components or equations are not derived from existing models, unlike most recent crop models.

This PILOTE version is not a research tool compared with more sophisticated crop models such as STICS (Brisson et al. 1998), developed by a group of agronomists supported by modellers, each one being a specialist of one of the processes embedded in the whole model. Instead, PILOTE is a convenient tool with limited objectives, which allows easier identification of the different sources of uncertainties that affect the nitrogen balance along a cropping cycle.

This paper is mainly focused on the application of PILOTE-N on the experimental site of Lavalette (Montpellier SE of France). The results obtained in this context encourage testing it under other agro-climatic conditions.

A substantial database as that of Lavalette, makes possible the validation of different modelling approaches. The present development of PILOTE-N should initiate studies devoted to the comparison of different modelling approaches in the domain of crop modelling. In the frame of such a work, the pertinence of a given formulation rather than another one for solving a specific question would be soundly analysed.

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For a variety of reasons, this PILOTE version can be more especially useful for practitioners or economists for evaluating the impact of input reductions such as water and fertilizers under contexts where the accessibility to data is generally limited.

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Table 1. A summary of data extracted from agricultural experiments on maize (*Zea mays* L.), durum wheat (*Triticum aestivum* L.) and sorghum (*Sorghum bicolor* L.) at Lavalette experimental station. Crops were references as C for maize, S for sorghum, DW for durum wheat. Irrigation treatments were full irrigated using sprinkler irrigation (FI), light irrigated using sprinkler irrigation (LI), subsurface drip irrigation (SDI) and rain-fed (RF). All experiments received full or moderate Nitrogen applications unless light Nitrogen (LN). 0N is referenced which indicates zero N applied. Collected data were initial soil N storage at sowing (N_{SI}), final soil N storage at harvest (N_{SF}) on the maximal root depth, applied N fertilizer (N_A), N uptake by the plant (N_p), N issued from mineralization (N_M:), water delivery (WAD), rainfall (RAIN), total dry matter (TDM), grain yield at 15% of humidity (GY). Sowing date is indicated by SD (day/month) and harvest date is indicated by HD (day/month). Finally, experimental seasons are indicated by two digits representing the decade and the year.

Treatment	N_{SI}	N_{SF}	N_A	N_P	N_M	WAD	RAIN	TDM	GY	SD	HD
	kg ha^{-1}					mm		Mg ha^{-1}			
FIC97	175	70	135	210	-	221	266	18.9	11.9		
LIC97	175	75	135	208	-	87	266	16.8	9.6	5/3	10/1
RFC97	190	95	135	185	-	10	266	15.2	8.5		
FIC98	106	120	200	265	-	323	94	21.3	12.5		
RFC98	102	260	200	115	-	36	94	10.3	4.6	5/2	9/25
0NC98	80	60	0	91	85	284	94	10.5	4.6		
FIC99	156	135	150	262	-	226	239	23.1	14.2		
RFC99	186	202	88	177	-	29	239	15.5	9.4	5/27	9/30
0NC99	95	80	0	81	95	272	239	12	5.8		

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FIC02	73	60	189	236	-	346	229	20	11.9	5/17	9/18
LIC02	79	52	186	215	-	285	229	18	10.4		
RFC02	151	130	180	163	-	0	229	10.8	5.0		
0NC02	93	57	0	120	84	235	229	12.8	6.5		
LIS03	80	50	64	185	-	107	61	11.2	7.1	5/10	9/17
RFS03	90	110	74	110	-	0	61	6.6	4.8		
FIS04	92	-	137	230	-	291	102	18.4	8.1	5/9	9/13
RFS04	80	112	70	200	-	0	102	12.4	5.8		
DWLI05	73	77	151	134	-	88	226	12.5	6.3	11/17	6/28
0NDW05	35	55	0	64	84	97	226	6.8	3.8		
DWLI06	57	85	160	143	-	92	271	9.7	6.0	11/23	6/28
0NDW06	38	46	0	85	93	92	271	7.5	4.2		
LIC07	135	150	180	240	-	217	171	22	14.0	4/24	9/28
LNC07	130	59	27	150	110	217	171	19	10.0		
DWRF09	70	-	230	150	-	0	736	9.7	5.0	11/2	6/5
DWLIT10	42	-	190	175	-	66	523	13	6.5	9/11	6/1
FIC11	82	45	250	350	-	343	179	26	16.1	4/20	9/29
LIC11	82	170	250	229	-	124	179	16.5	10.1		
RFC11	59	60	40	102	-	27	179	12.5	5.4		
LNC11	40	60	35	100	85	343	179	12	6.4		
SDIC11	64	83	232	292	-	214	179	22.1	13.8		
FIC12	57	99	358	380	-	330	232	30	18.0	4/27	9/30
LIC12	62	125	160	158	-	135	232	16	8.9		
RFC12	25	91	40	79	-	36	232	12.4	5.4		
LNC12	32	35	40	124	100	330	232	14	7.5		
FIC13	38	110	346	335	-	296	135	23.5	16.0	04/24	09/26
LIC13	26	55	135	217	-	177	-	17	9.1		
0NC13	38	29	0	96	96	296	-	10.5	4.7		

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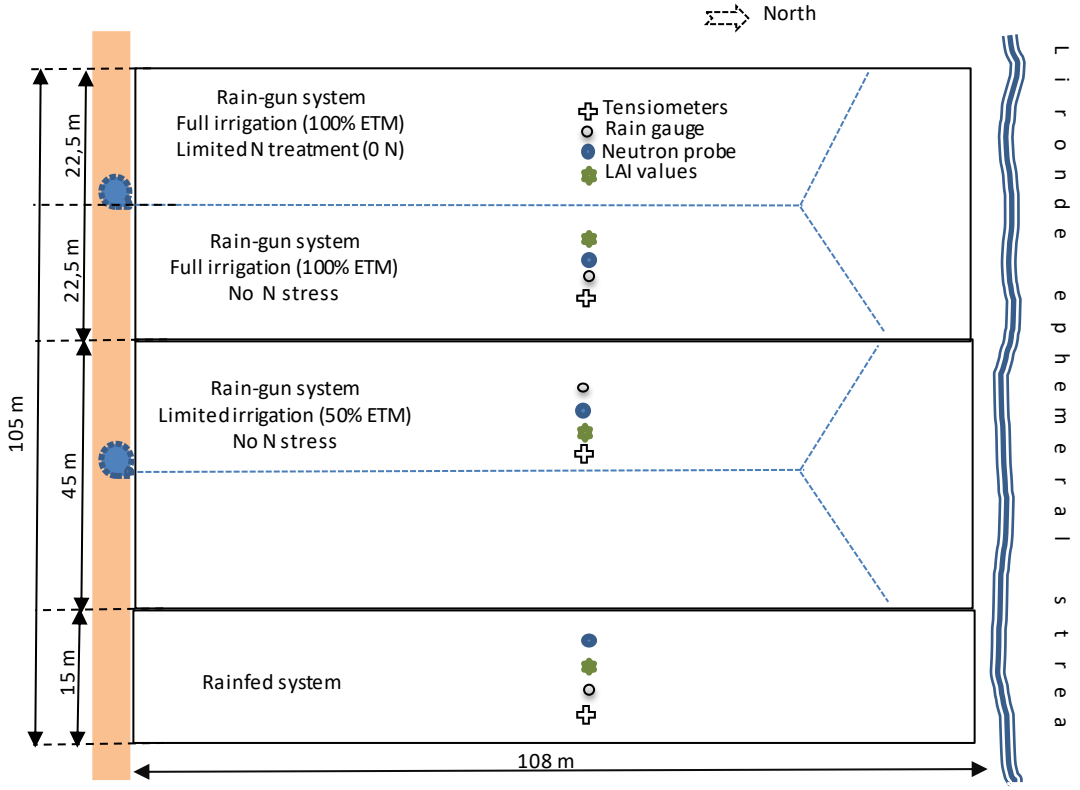

Figure 1. Plot layout at the experimental Lavalette station (Montpellier, France) where corn was cultivated in 2012

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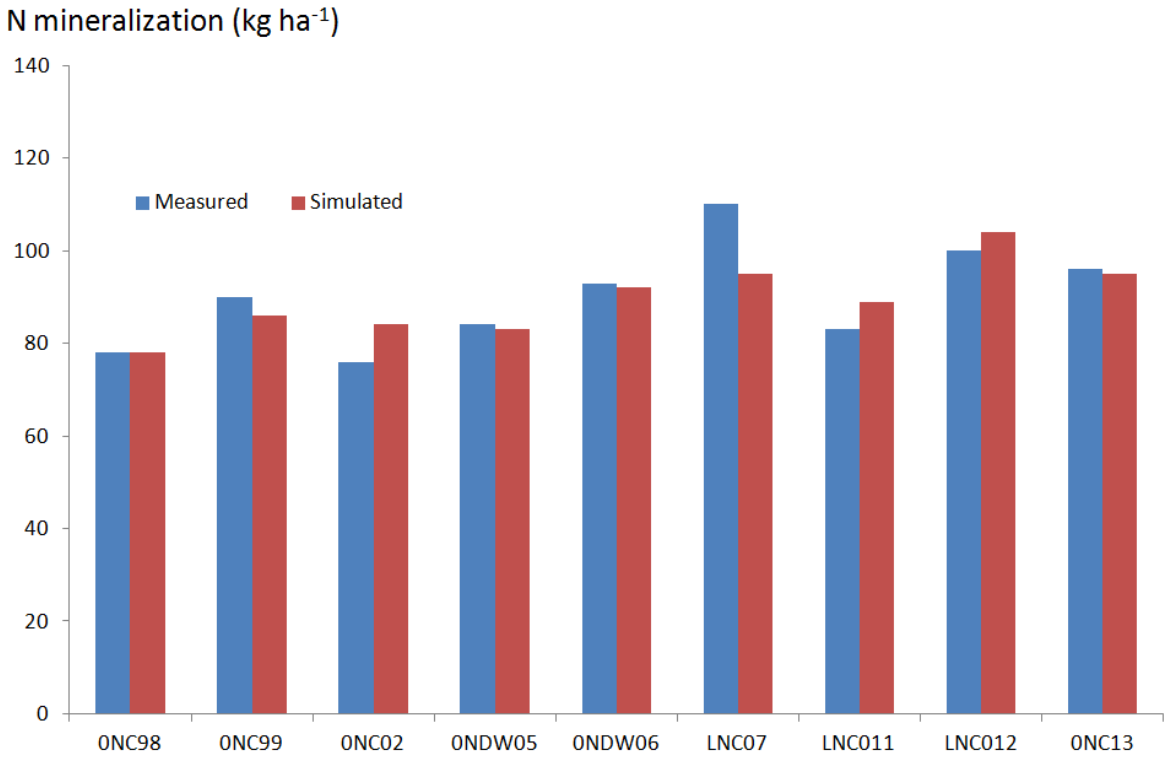
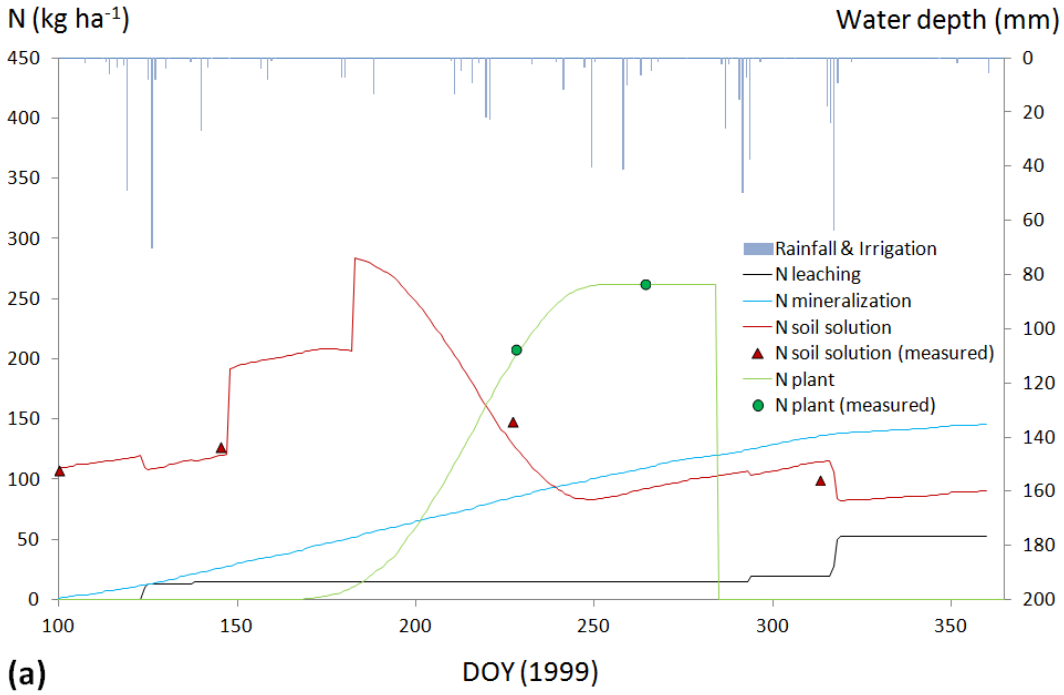


Figure 2 – Comparison between the measured and simulated mineralization rates for nine cropping cycles (see details in Table 1).



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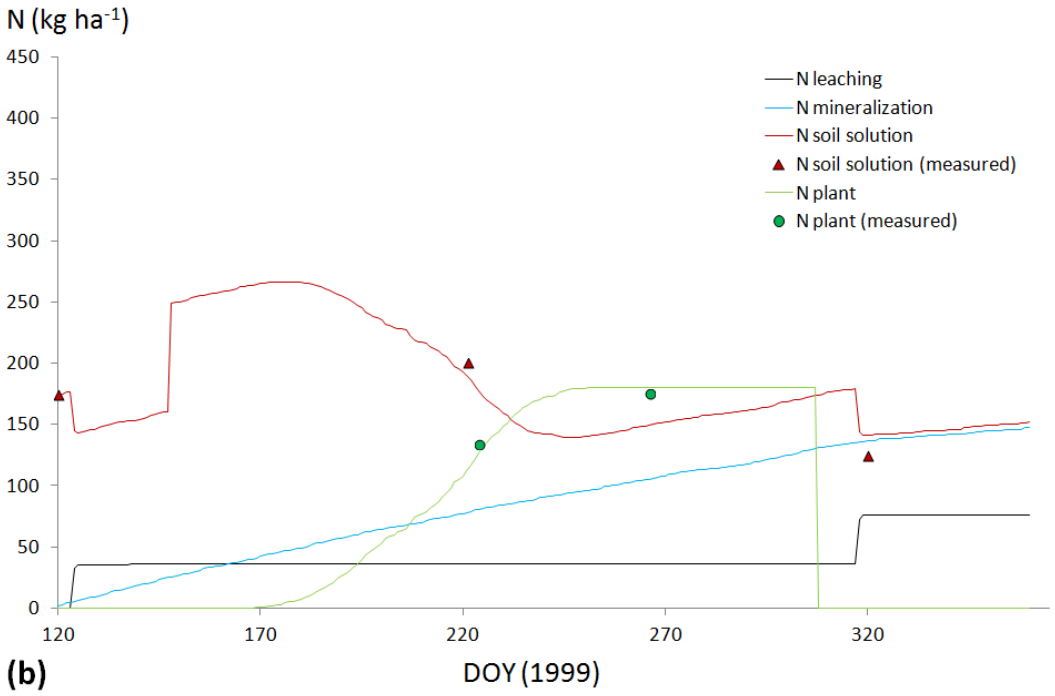
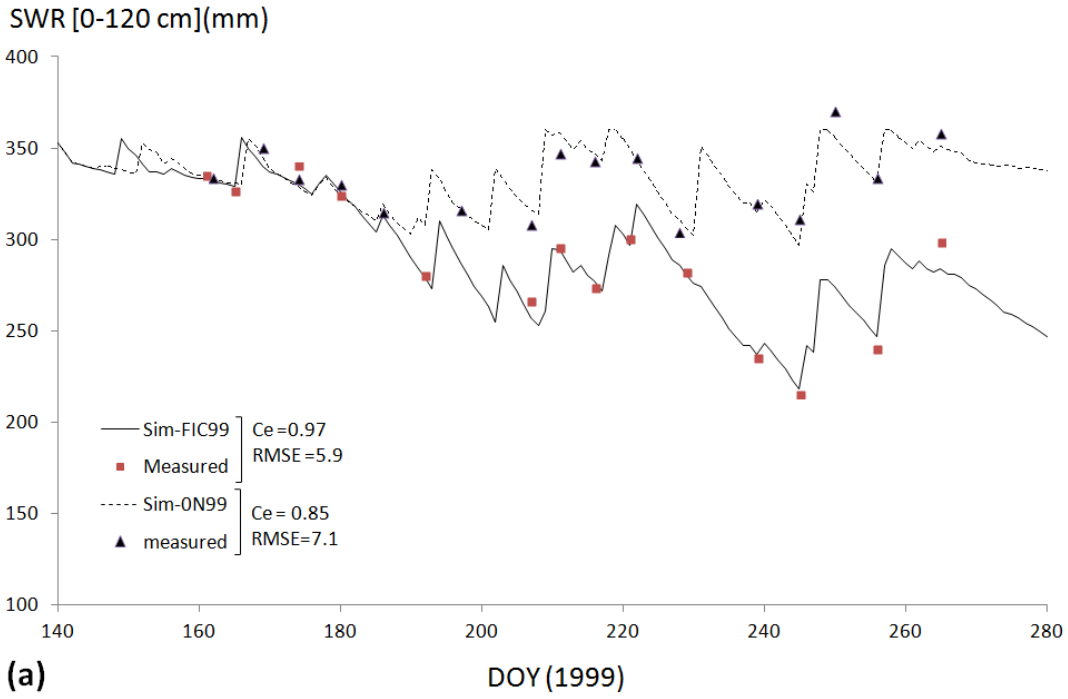


Figure 3. Simulation of the nitrogen budget on the fully irrigated FIC99 treatment for corn (a) and on the rainfed RFC99 treatment for corn (b). See Table 1 for details.



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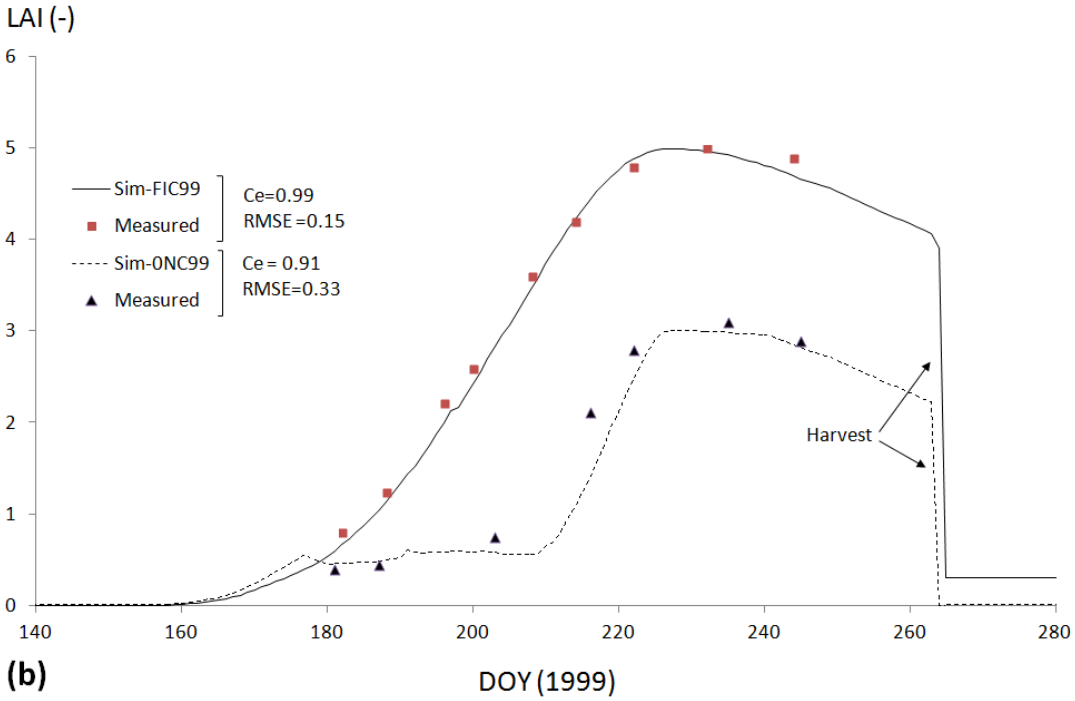
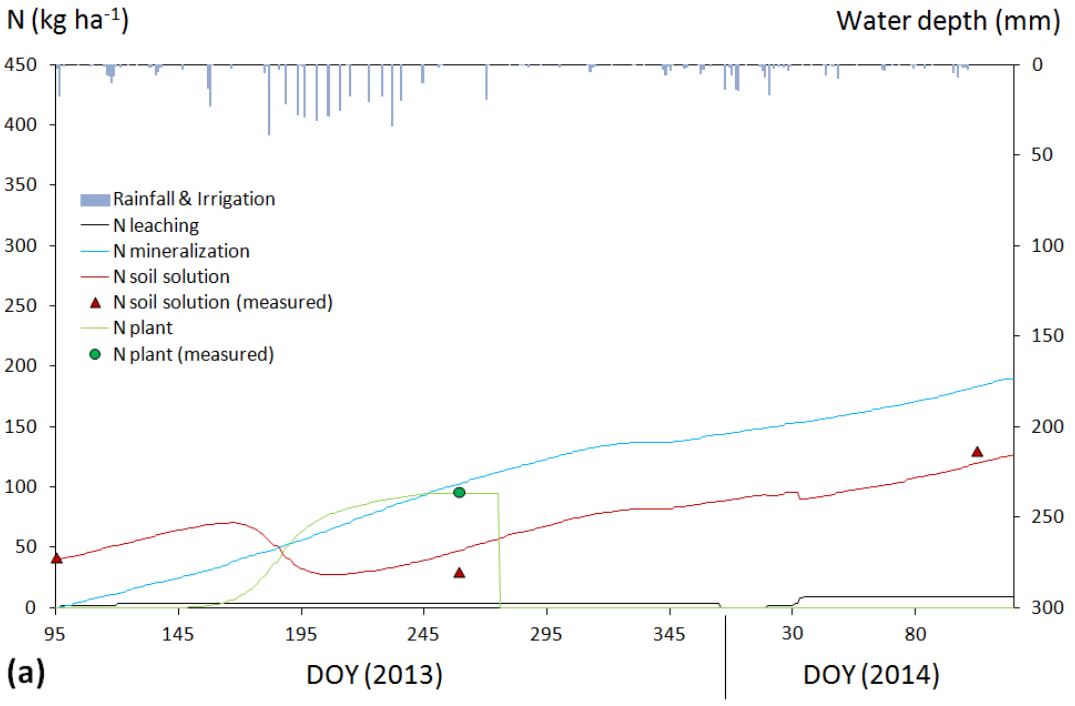


Figure 4. Simulations of Soil Water Reserve SWR (a) and Leaf Area Index LAI (b) for the fully irrigated FIC99 treatment for corn and the "zero-N" 0NC99 treatment for corn.



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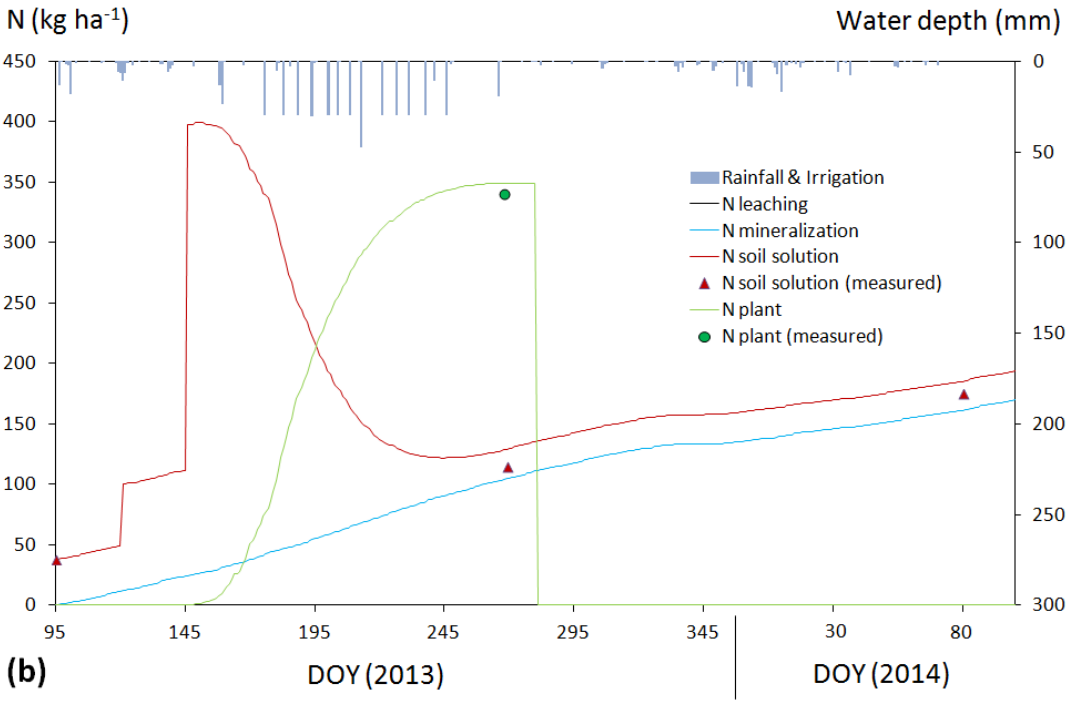
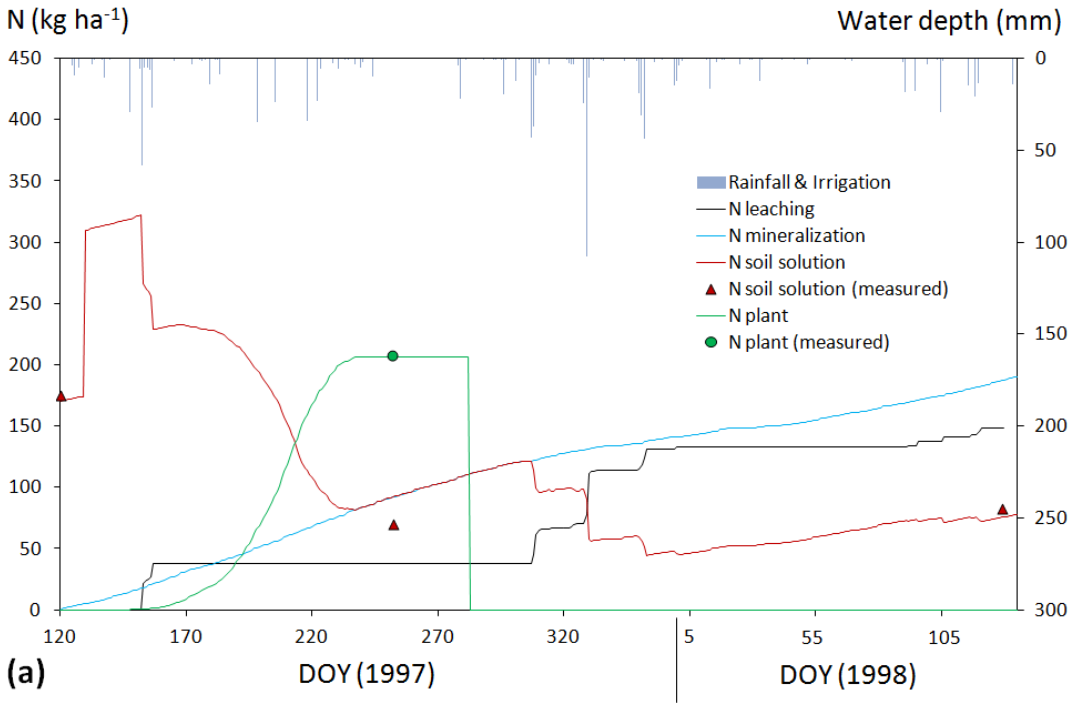


Figure 5 - Simulations for the "zero-N" 0NC13 treatment for corn (a) and the fully irrigated FIC13 treatment for corn (b). See Table 1 for details.



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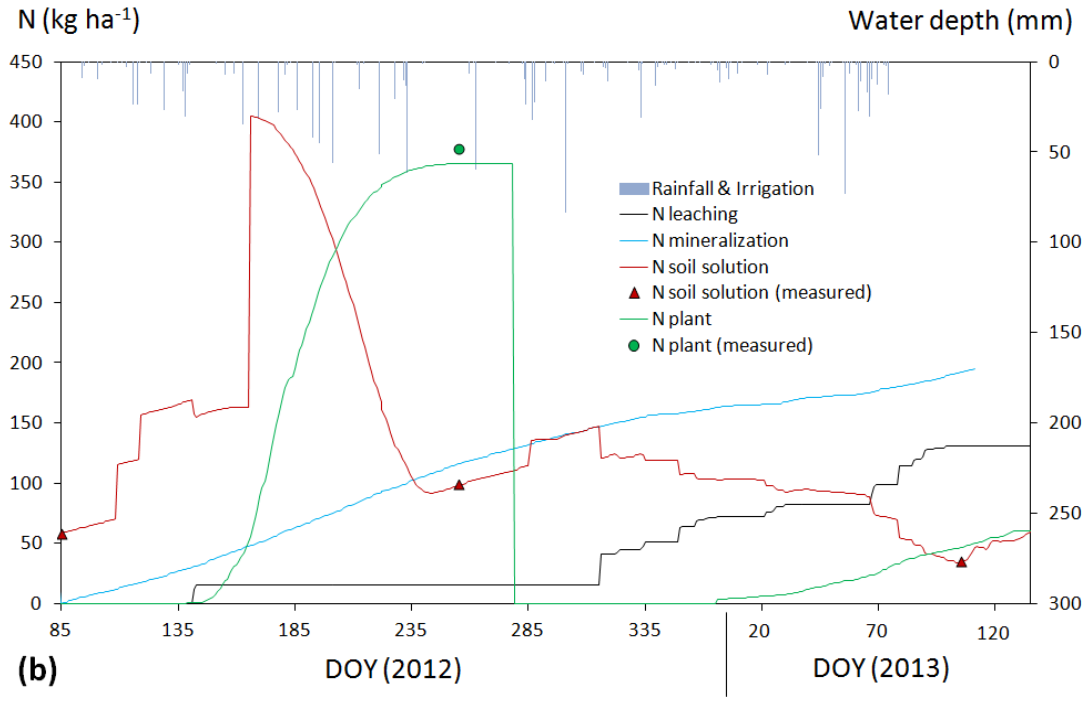
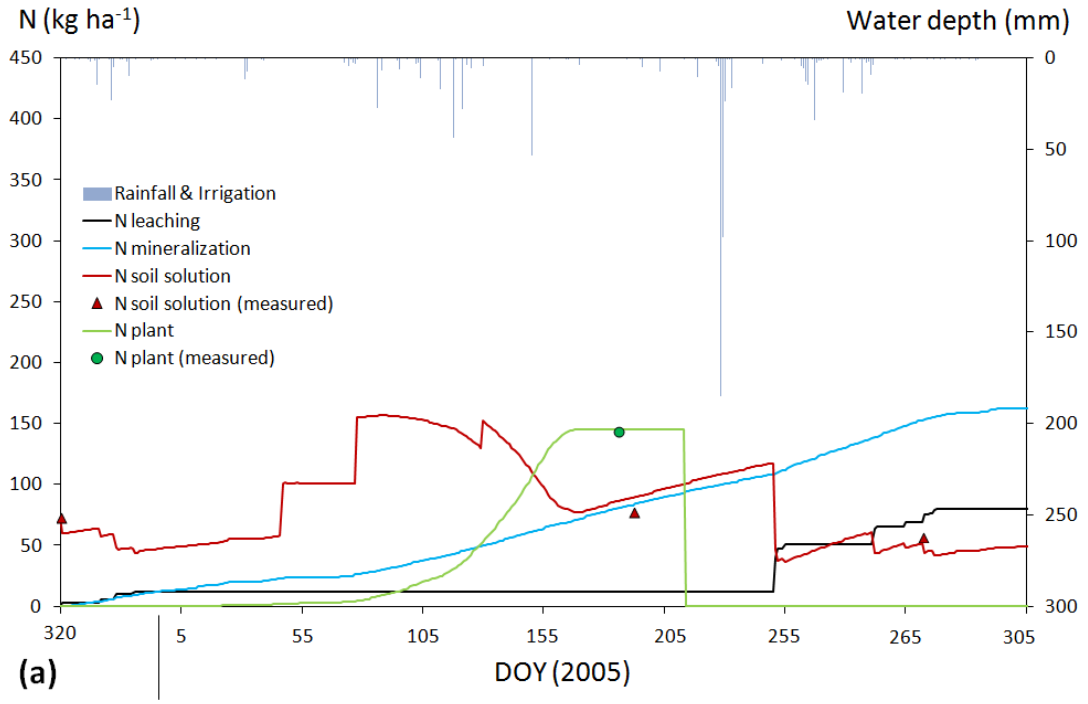


Figure 6 - Simulations for the fully irrigated FIC97-98 treatment for corn (a) and the fully irrigated FIC12-13 treatment for corn (b). See details in Table 1.



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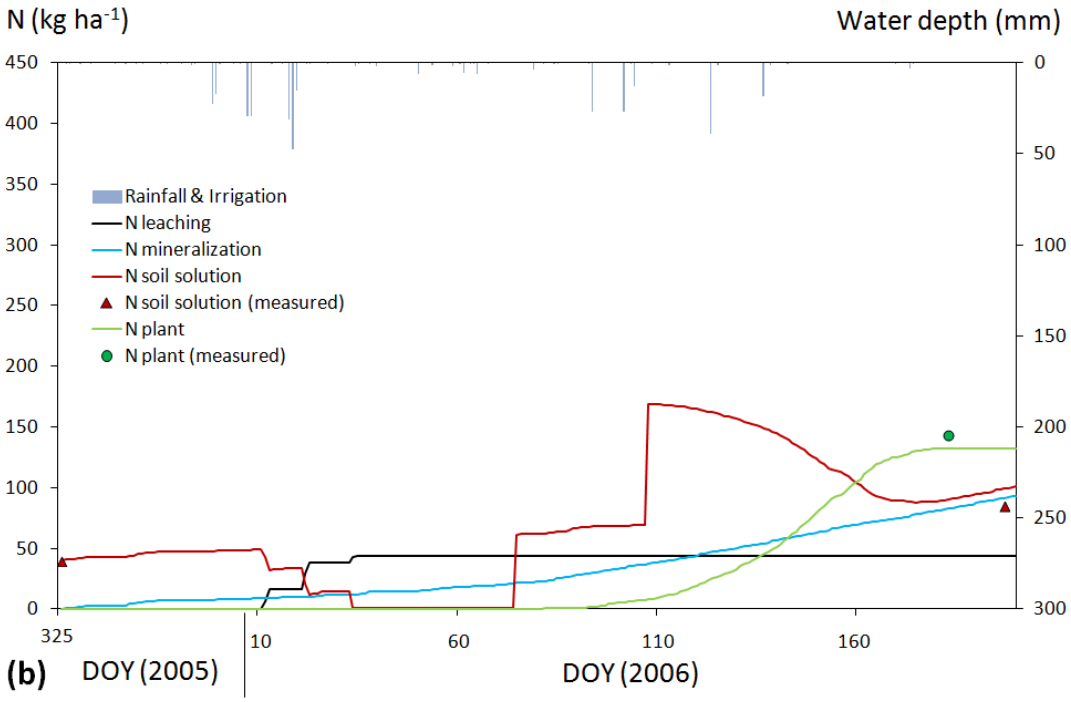
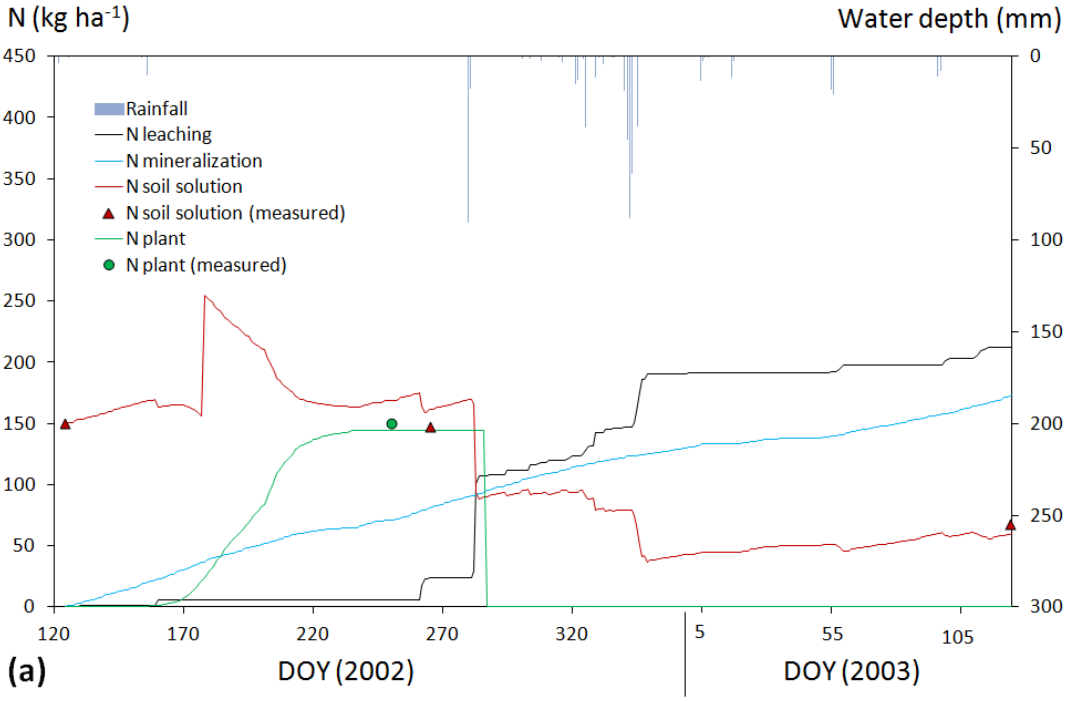


Figure 7 - Simulation for the light irrigation DWLI05 treatment for durum wheat (a) and the light irrigation DWLI06 treatment for durum wheat (b). See Table 1 for details.



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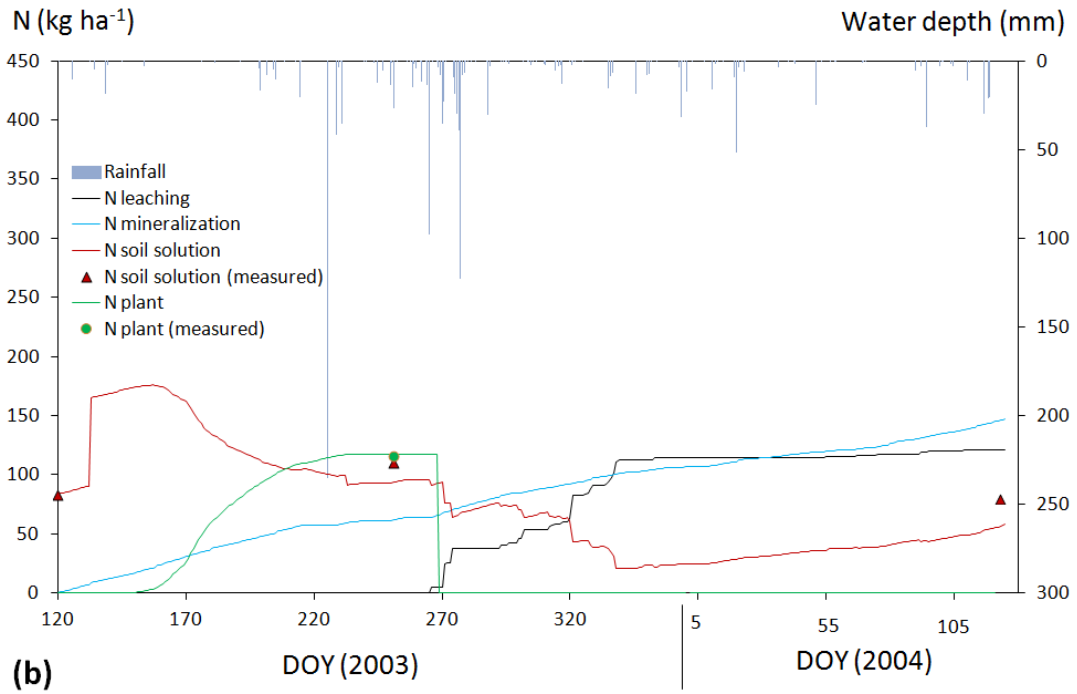
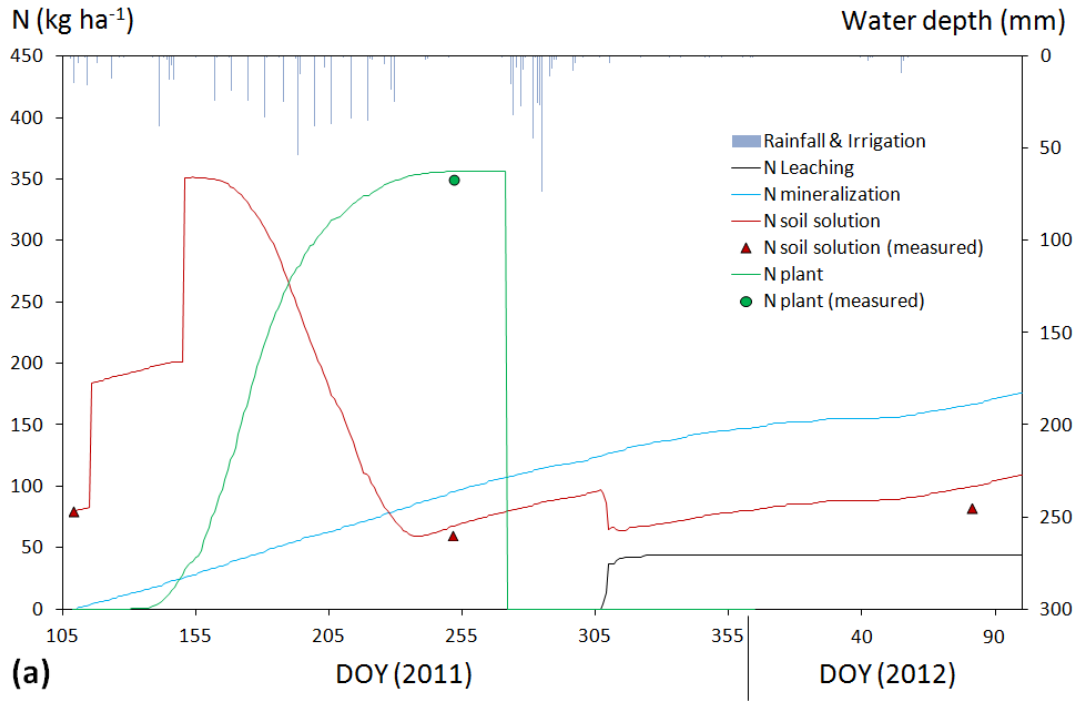


Figure 8. Simulations for the RFC02-RFS03 treatments for corn then sorghum (a) and for the RFS03-RFS04 treatments for sorghum then corn (b). The total rainfall amounts were 887 and 1308 mm, respectively. See Table 1 for details.



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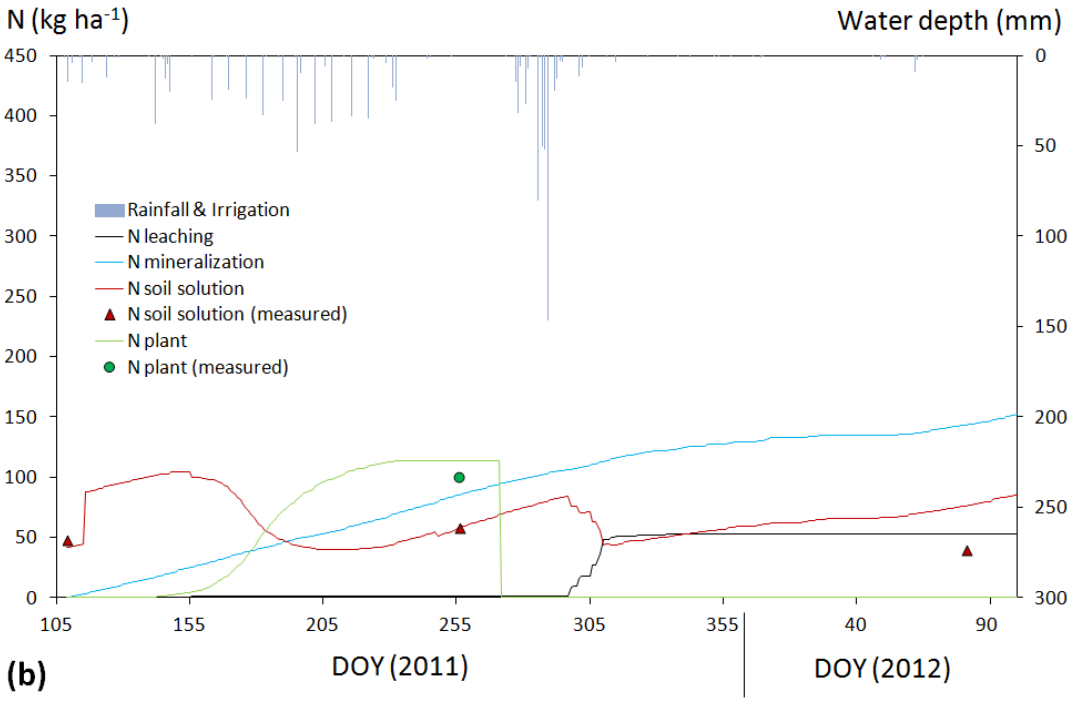
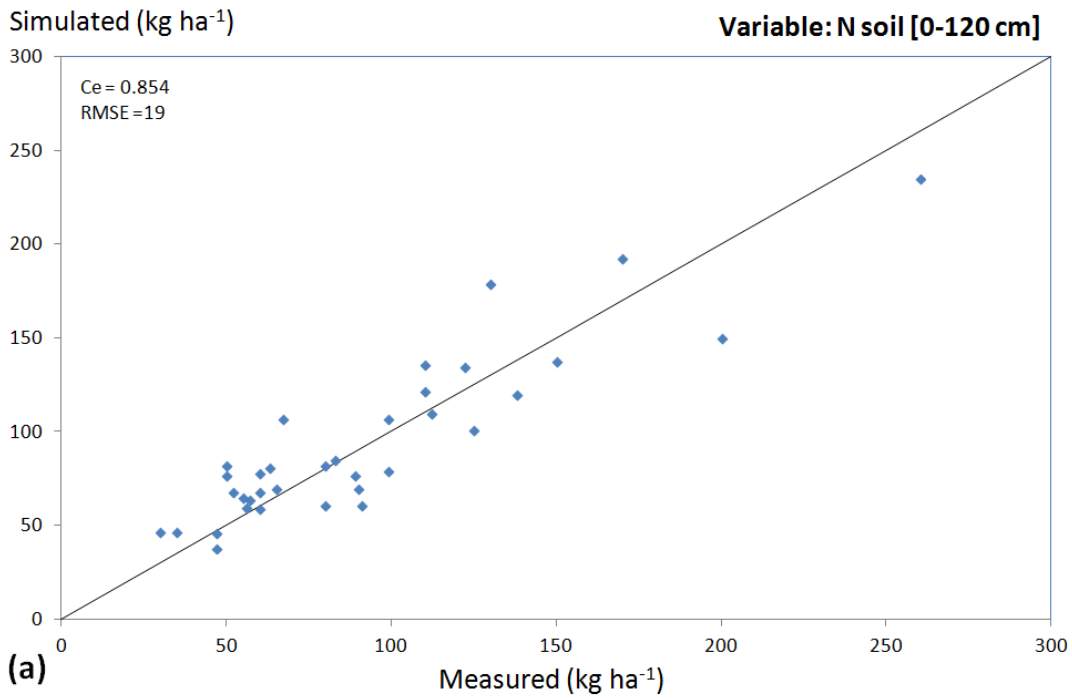


Figure 9. Simulations of the fully irrigated FIC11-12 treatment for corn (a) and the "zero-N" 0NC11-12 treatment for corn (b). See Table 1 for details.



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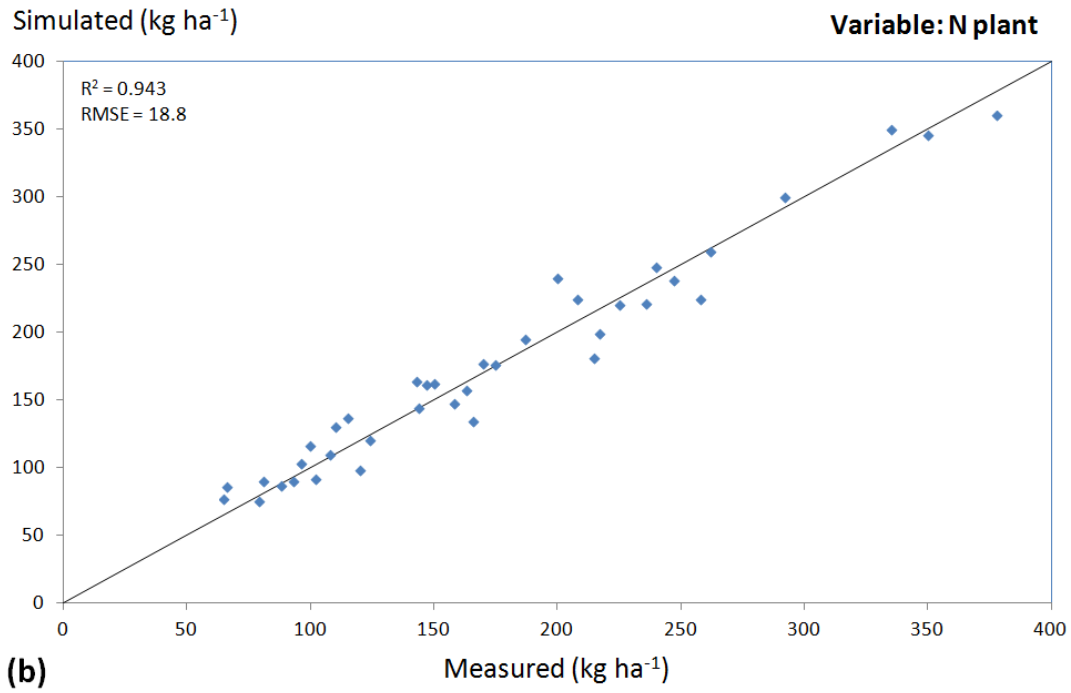
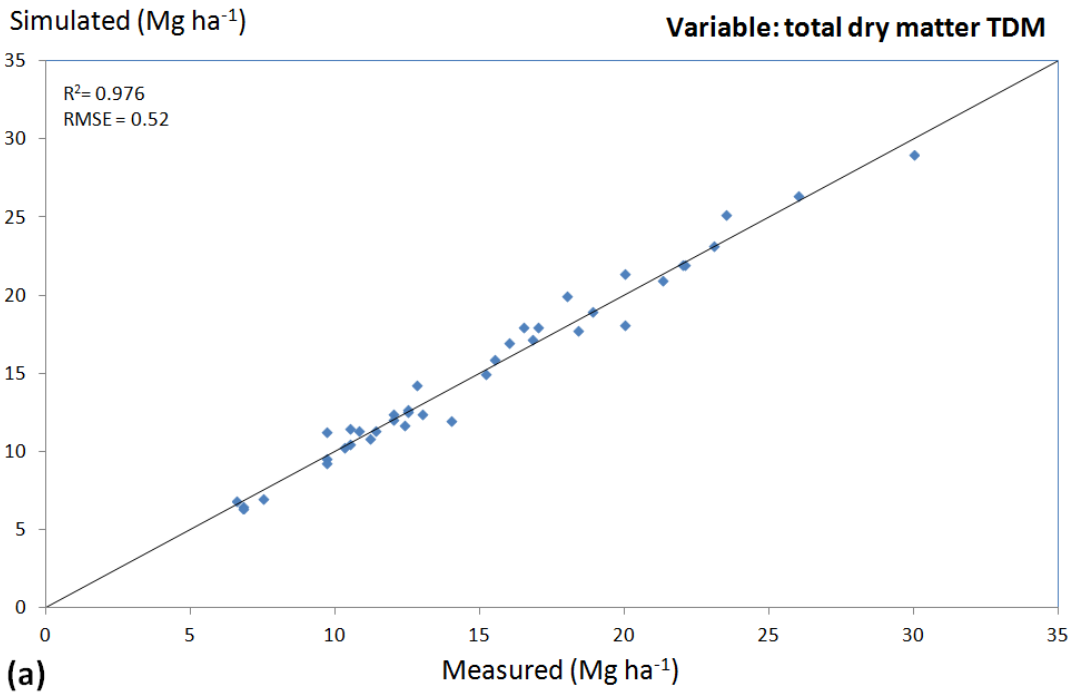


Figure 10. Comparisons between the measured and simulated Nitrogen amounts in the soil solution after harvest (a) and in the plant after harvest (b) for experiments on corn (1997-1998-1999-2007-2011-2013), durum wheat (2004-2006) and sorghum (2003-2004).



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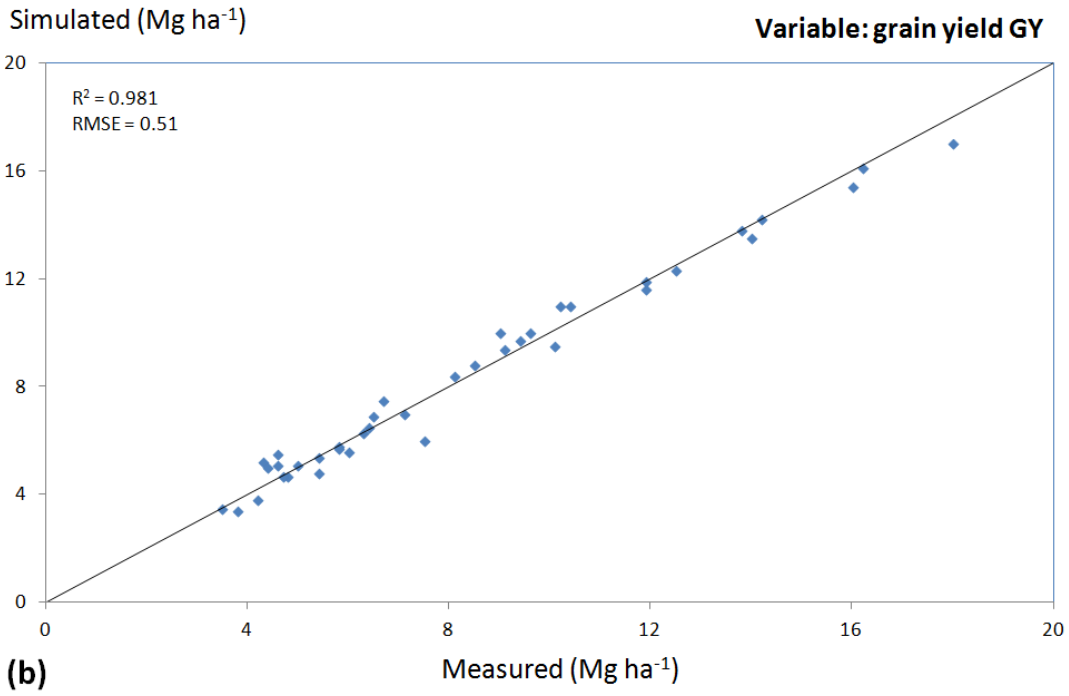

Figure 11. Comparisons between the measured and simulated Total Dry Matter TDM (a) and Grain Yield GY (b) for corn (1997-1998-1999-2007-2011-2012), durum wheat (2004-2006; 2008-2009; 2009-2010), and sorghum (2003-2004).