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The CropSyst model to simulate the N balance of rice for alternative management

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Abstract – CropSyst is a mechanistic model developed for simulating the growth and development of potentially all herbaceous crops under potential and water/nitrogen (N)-limited conditions. Although the model has been widely used for many crops under different pedo-climatic and management conditions, studies on the simulation of water and N balance for flooded rice are lacking. We evaluated the CropSyst model for simulating the N balance of north-Italian rice fields for scatter-seeded rice grown under continuously flooded conditions. In order to calibrate and validate the model for the processes involved with soil N transformation, data collected in field experiments carried out in northern Italy between 2002 and 2004 were used. The results show the robustness of the model in reproducing the course of the measured soil mineral nitrogen content: the Modeling Efficiencies which describe the agreement between measured and simulated trends, are in most cases positive and the model error fell almost always within the experimental error on the measurements ($P = 0.95$). Moreover, the model showed the same level of reliability while simulating the nitrogen balances under different levels of nitrogen fertilization, thus depicting it as suitable for comparing N fertilization scenarios. This first attempt at using a model for simulating the nitrogen balance under flooded conditions encourages further studies because of the need of effective tools for optimizing the nitrogen management of flooded rice systems, considered significant sources of groundwater pollution and greenhouse gases in many European rice districts.

Oryza sativa L. / simulation model / flooded soil / submerged fields / nitrogen transformation / mineralization / denitrification

1. INTRODUCTION

Mechanistic models for simulating agroecosystems behavior were developed during the last few decades with the aim of providing tools for analyzing, understanding and manipulating the main processes characterizing those systems (Monteith, 1996; van Ittersum and Donatelli, 2003). Mechanistic models result from the mathematical representation of the bio-physical processes which explain the crop-soil interaction driven by weather dynamics and management (van Ittersum and Donatelli, 2003). Therefore, they are particularly suitable for testing hypotheses (Pannkuk et al., 1998; Seppelt and Richter, 2005), for evaluating the impact of alternative management (Acutis et al., 2000; Confalonieri and Bechini, 2004) and climate scenarios (Mahmood, 1998).

In spite of the large number of studies on model calibration and validation concerning crop growth and development, there are few papers in the literature about the evaluation of crop models for water and nutrient dynamics. Moreover, where simulations are carried out to evaluate variables related to soil water (Alaoui et al., 2003; Confalonieri and Bechini, 2004) or, less frequently, nutrients (e.g. Hansen et al., 1991; Blombäck

et al., 1995; Diekkrüger et al., 1995; Sierra et al., 2003), they are usually carried out under unflooded conditions.

Flooding irrigation is the main factor responsible for the peculiar features of paddy rice. It has a great influence on all the main processes related to crop growth and development, on those related to soil bio-chemistry and physics, and therefore on those concerning the environmental impact of these systems (Pirmoradian et al., 2004). The direct effects on crop growth are attributable to the floodwater effect on the vertical thermal profile (Confalonieri et al., 2005a), which also affects the bio-chemistry of soil nutrient transformations, as most of the processes involved are temperature-dependent (Confalonieri et al., 2005a). Nutrients transformations are also influenced by the anomalous oxygen distribution in paddy soils. Despite the transport of oxygen in the rhizosphere by a specialized plant apparatus (aerenchyma) which allows nitrification activity close to the roots, the redox status of paddy rice soils is usually characterized by reducing conditions because of the low solubility of oxygen in water (with respect to air). These reducing conditions are responsible for the high denitrification rates (Ghosh and Ravi Bhat, 1998) which represent one of the important factors leading to the low agronomic nitrogen-use efficiency (NUE) usually recorded in rice fields. NUE is here

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intended as the ratio between the N uptakes from fertilized and unfertilized plots and the amount of N distributed to those fertilized. Cassman et al. (1993) reported N fertilizer efficiencies ranging between 36 and 39% in two favorable irrigated rice domains in the Philippines. Stutterheim et al. (1994) found even lower values analyzing data from 35 experiments performed between 1981 and 1991 in several European countries. Singh et al. (1999) reported values between 12 and 42% for different fertilization levels. The emissions of nitrous oxide by denitrification from rice paddies are particularly relevant with respect to other cropping systems, like for other important greenhouse gases (IPCC, 2001). However, denitrification is not the only cause of the low NUE which characterizes these agroecosystems. In fact, high NO_3^- leaching rates are observed in many European rice districts, mainly because of the high saturated hydraulic conductivities. This is especially true in the case of not-puddled conditions, like those typical of delayed flooding, a management option increasingly adopted because of the conflicts in water use between countryside and city due to the increasing dimension of urban areas.

Simulation models are powerful tools for investigating the processes related to nitrogen movements and transformation in soils and, once calibrated and validated, they can be used to evaluate alternative management options. Therefore, they are suitable tools for detecting satisfactory solutions/compromises between high production levels and low environmental impact, thus providing helpful information for increasing the efficiency of the agroecosystem. A large number of models have been developed explicitly for rice simulation, e.g. CERES-Rice (Singh et al., 1993), ORYZA1 (Kropff et al., 1994), maNage Rice (Angus et al., 1996) and WARM (Confalonieri et al., 2005b). Each of these models has specific objective(s) and therefore is focused on particular aspects of rice modeling: some of them are more focused on physiological processes, others on the effects of management practices, etc. In this study, the simulation model CropSyst (Stöckle et al., 2003) was used. The main difference between this model and those previously cited is that CropSyst is a generic crop simulator and, for this reason, it is particularly suitable for the simulation of complex cropping systems. That is, it can be used for simulating a succession of different crops both in space and in time. Moreover, several tillage, irrigation and N fertilization options are implemented in this model, thus indicating CropSyst as a powerful model for evaluating alternative management scenarios. Its suitability for large-scale scenario simulations is also proved by the reduced number of inputs needed with respect to other approaches (Confalonieri and Bocchi, 2005) and by a direct link with a GIS software. CropSyst has been calibrated and tested for simulating crop productions, water and nitrogen balances for different cropping systems but this is the first time it has been used for flooded rice simulations.

CropSyst is a multi-year, multi-crop, mechanistic simulation model (Stöckle et al., 2003) developed to evaluate the effects of soil, weather and management on crop growth and environmental impact. CropSyst simulates the soil water budget, soil-plant N budget, crop growth and development, residue production and decomposition, soil erosion and salinity with a daily time step as influenced by weather, soil features, crop (or cultivar) morpho-physiological characteristics and cropping system management options. In a previous work, Confalonieri

Table I. Soil characteristics (topsoil: 0.00–0.30 m layer) for the data sets of Vignate (MI) 2002; Opera (MI) 2002; Opera 2004.

Data set	Vignate 2002	Opera 2002	Opera 2004
Sand (%)	48.6	35.5	39.1
Clay (%)	12.4	18.9	24.3
Silt (%)	39.0	45.6	36.5
pH	5.90	6.20	5.80
C.E.C. (meq 100 g ⁻¹)*	16.63	17.34	13.80
SOM (%)**	2.23	2.07	2.26
Organic C (%)	1.29	1.18	1.31
Organic N (%)	0.15	0.12	0.13
C N ⁻¹	8.77	10.30	9.80
K content (mg kg ⁻¹)	154.00	120.30	–
Available P (mg kg ⁻¹)	134.30	42.00	–
BD (g cm ⁻³ ***)	1.37	1.34	1.30
Ksat (m day ⁻¹ ****)	0.08	0.03	0.02

*: Cation exchange capacity; **: soil organic matter; ***: bulk density; ****: saturated hydraulic conductivity.

and Bocchi (2005) calibrated and validated CropSyst for simulating rice growth and development. The objective of this work is to evaluate the model for the simulation of the N balance of paddy rice fields in northern Italy, under direct seeding (scattered) and continuously flooded management conditions.

2. MATERIALS AND METHODS

2.1. Experimental data

Experimental data were collected in two locations near Milan (Italy): Vignate (latitude 45° 29' N, longitude 9° 22' E) and Opera (latitude 45° 22' N, longitude 9° 12' E); precisely, in both the locations in 2002, and only in Opera in 2004, in a field different from that of the 2002 experiment. The physical and chemical characteristics of the soils of the three experiments are shown in Table I.

During these studies, explicitly carried out to analyze nitrogen use in paddy rice fields, three Indica-type varieties were grown: Sillaro (Vignate 2002), Thaibonnet (Opera 2002) and Gladio (Opera 2004). Rice was scatter-seeded in all the experiments with a centrifugal spreader; the date of sowing was April 29 for both the locations in 2002 and May 24 for the 2004 experiment. In order to obtain 400 plants m⁻², about 135 kg ha⁻¹ of seed were distributed.

Water management was comparable in all the experiments: fields were flooded about two weeks before sowing to level and puddle the soil (except for Vignate 2002, where soil was flooded only one day before sowing). For all the vegetative cycle, the water level was maintained at about 10 cm; water height was reduced to about 5 cm for two weeks after emergence to favor root growth. Then, the water supply was also stopped one day before fertilizations and restored after one day. The soil was finally dried at physiological maturity. The experimental fields were flooded for the whole growing season, and

also when the water supply was stopped (the day before the top-dressing fertilizations), the soil always remained saturated and in anaerobic conditions.

During the 2002 experiments, three levels of N fertilizer (urea) were distributed, using a completely randomized block design with three replicates. For Vignate, the three levels corresponded to 0, 70 and 150 kg N ha⁻¹ (three N distributions: one pre-sowing and two topdressed: at the beginning of tillering [BBCH code 21; Lancashire et al., 1991] and at the panicle initiation [BBCH code 34]), while for Opera the three levels corresponded to 0, 50 and 110 kg N ha⁻¹ (two N distributions; BBCH codes 21 and 34). In Opera 2002 less N was applied because of an organic fertilization (liquid manure) received some months before sowing. Only two levels of N fertilizer (urea) were applied (completely randomized block design with four replicates) in the 2004 experiment: 0 and 140 kg N ha⁻¹, supplied in two topdressed distributions. Rice was harvested with an experimental combine-harvester on October 8 in both the 2002 experiments, and on October 3 in 2004. In all cases, the measured variables were: yield, aboveground biomass (AGB), leaf area index (LAI), specific leaf area (SLA), plant N concentration (PNC) and soil N concentration (SNC; N-NO₃ and N-NH₄). Soil samples were collected the day before fertilization and every two days after fertilization for a week. SNC was determined on an aggregated sample (three 125-cm³ subsamples per plot) for the soil layer 0.00–0.10 m by using a continuous-flow analyzer. Bulk density (BD, g cm⁻³) was measured by determining the weight of the soil contained in a cylinder with a known volume. The cylinder was delicately introduced into the soil and two blades were used to close the two extremities of the cylinder. The saturated hydraulic conductivity (K_{sat}, m day⁻¹) was estimated by measuring the rate of water infiltration with a water level recorder in periods in which there was neither inflow nor outflow of water in the field. K_{sat} was considered corresponding to the rate of water level decrease, because the calculated ET for the examined periods was always negligible compared with the high water infiltration rate characteristic of north-Italian paddy fields and, generally, of delayed-flooded fields. Moreover, by using this method, the resulting value can be surely considered as the mean of the whole field.

2.2. Simulation model

Crop development is simulated as a function of thermal time accumulated between a base temperature (T_{base}) and a maximum temperature (T_{cutoff}). Crop growth is simulated for the whole canopy by calculating unstressed biomass growth based on potential transpiration and on crop intercepted PAR, and by correcting with water and nitrogen limitations to simulate actual daily biomass accumulation. Leaf area development is calculated from daily accumulated biomass using a constant specific leaf area and an empiric parameter called the stem/leaf partition coefficient. Root depth is simulated as a function of leaf area development, and reaches its maximum when the plant flowers. Potential evapotranspiration is estimated with the Penman-Monteith equation or, if air humidity and/or wind speed data are missing, with the Priestley-Taylor equation. Stöckle et al. (2003) provide a detailed description of how CropSyst simulates the processes involved in crop growth and development.

Soil water redistribution can be simulated by a simple cascading approach or by a numerical solution (finite difference) of the Richards soil flow equation proposed by Campbell (1985). Boundary conditions allow for flux or a saturated upper boundary and for free drainage or saturated (water table) lower boundaries (Stöckle et al., 2003). For the cascading approach, only the water contents at field capacity and at permanent wilting point have to be specified. The finite difference method derives water potentials from the saturation water content, air entry potential and Campbell B values for water transport. These parameters have to be specified for all the soil layers and can be computed from texture by the model.

Crop nitrogen uptake is simulated using the dilution approach proposed by Justes et al. (1994). Details about the implementation of this approach in CropSyst are provided by Bechini et al. (2006).

CropSyst simulates nitrogen transformation (ammonification, nitrification and denitrification) using first-order kinetics. The model includes routines for soil temperature simulation, to consider the dependency of these transformations on temperature. The amount of organic nitrogen mineralized is calculated by:

$$\text{MIN} = \text{MIN}_{\text{pot}} [1 - \text{MF} \cdot e^{(-\text{MRATE} \cdot \Delta t)}] \quad (1)$$

where MIN (kg N ha⁻¹) is the amount of organic matter N mineralized into ammonium in time *t* (one day); MIN_{pot} (kg N ha⁻¹) is the potential amount of organic matter N available for mineralization; MRATE (day⁻¹) is the mineralization rate constant depending on soil temperature; MF is a soil moisture function dependent on the fraction of pores containing water. Bulk density is used in the computation of soil porosity.

The daily amount of nitrified ammonium is computed by:

$$\text{NIT} = \text{NH}_4 [1 - e^{(-\text{NRATE} \cdot \Delta t)}] \cdot \text{MF} \quad (2)$$

where NIT (kg NH₄ ha⁻¹) is the amount of ammonium nitrogen transformed into nitrate in time *t*; NH₄ is the amount of ammonium N available for nitrification; NRATE (day⁻¹) is the nitrification rate constant; MF is the soil moisture function. NRATE depends on NRATE₃₅ (nitrification rate constant at 35 °C = 0.8 day⁻¹) and on soil temperature. The daily amount of denitrification is calculated by:

$$\text{DEN} = \text{NO}_3 [1 - e^{(-\text{DRATE} \cdot \Delta t)}] \quad (3)$$

where DEN (kg NO₃ ha⁻¹) is the amount of nitrate nitrogen transformed into gaseous nitrogen in time *t*; NO₃ (kg NO₃ ha⁻¹) is the amount of nitrate available for denitrification; DRATE (day⁻¹) is the denitrification rate constant depending on the denitrification rate value at 15 °C modified by a soil temperature function and a soil water function.

For N transport in the soil CropSyst uses the approach of Corwin et al. (1991), a simple mass-balance approach, and simulates N transport when water infiltrates the soil. This approach includes a bypass coefficient (BC) to describe the fraction of water in a soil layer that is bypassed, while 1-BC represents the fraction of the soil water subject to a piston-type displacement. BC accounts for flow through cracks and macropores. The effect is the flow of a mobile water phase independent of the immobile phase of water. The fraction of soil water bypassed (and its solute content) is not mixed with new incoming water during infiltration.

Table II. Parameters involved in soil nitrogen transformation for the data sets of Vignate (MI) 2002; Opera (MI) 2002; Opera 2004.

Parameter	Vignate 2002	Opera 2002	Opera 2004	Units	Range
MRA*	1.30	1.30	1.95	/	0–2
NRA**	0.40	0.20	0.06	/	0–2
DRA***	1.90	1.90	1.90	/	0–2

*: Mineralization rate adjustment; **: nitrification rate adjustment; ***: denitrification rate adjustment.

Mineralization, nitrification and denitrification rate adjustments (MRA, NRA and DRA; adimensional; range: 0–2) are then applied to reproduce the behavior of different soil types. No specific processes for flooded soil simulations are considered, although the reduced oxygen availability for chemical transformation due to flooding water is indirectly considered through a function of degree of pore saturation. The diffusion of oxygen through the aerenchyma is not directly taken into account, although it is implicitly considered because CropSyst does not apply a limitation to crop growth when soil water content exceeds field capacity. The effect of the aerenchyma on soil nitrogen transformation is included in the parameterization of MRA, NRA and DRA. In fact, the possibility of calibrating the parameters MRA, NRA and DRA makes the model very adaptable to a wide range of situations.

2.3. Model parameterization and validation

CropSyst version 3.02.23 (January 8, 2002) was used. Potential evapotranspiration was calculated with the Priestley-Taylor equation. The default value of 1.26 was used for the Priestley-Taylor constant. Soil water redistribution was simulated with the Richards equation solved using a finite difference method. Soil physical and chemical analysis allowed the initialization of soil profiles at the beginning of the simulations. Crop model parameters calibrated and validated by Confalonieri and Bocchi (2005) were used.

For the 2002 experiments, data from plots not N-fertilized and from plots with optimal N fertilization were used for calibration; data from the intermediate N fertilization level were used for validation. For the experiment carried out in 2004, data from the optimal N fertilization level were used for calibration, unfertilized plots for validation. MRA, NRA and DRA were calibrated (Tab. II). BD and K_{sat} were measured; air entry potential and Campbell B were computed by the model starting from texture data.

The agreement between observed and predicted values was expressed by using the indices proposed by Loague and Green (1991): the relative root mean squared error (RRMSE, minimum and optimum = 0%), the coefficient of determination (CD, minimum = 0, optimum = 1, indicates whether the model reproduces the trend of measured values or not), the modeling efficiency (EF, $-\infty \div 1$, optimum = 1, if positive, indicates that the model is a better predictor than the average of measured values), the coefficient of residual mass (CRM, 0–1, optimum = 0, if positive indicates model underestimation) and the parameters of the linear regression equation between observed and predicted values.

Calibration of MRA, NRA and DRA was carried out following a trial-and-error optimization procedure by optimizing the values of the fitting indices above.

3. RESULTS AND DISCUSSION

3.1. Experimental results

The measured values of K_{sat} were 0.08, 0.03 and 0.02 m day⁻¹, respectively, for Vignate 2002, Opera 2002 and Opera 2004. The first value is high compared with those usually reported for north-Italian paddy fields because of the soil texture and the mechanical soil preparation (not puddled) but anyway is consistent with that reported by Liu et al. (2001) for the same soil type. Measured SNCs are shown in Figures 1 and 2. Figure 1 shows that soil N transformations and crop uptake lead to an equilibrium of N-NH₄ concentration of about 2 kg N-NH₄ ha⁻¹ for Vignate and 3–4 kg N-NH₄ ha⁻¹ for Opera. This equilibrium is relatively stable in time (from May to September).

The soil N-NH₄ content observed in Opera during 2004 is usually higher. Probably, this is the result of the combination of high soil organic matter (SOM) content, low cation exchange capacity (CEC) and low pH compared with the other two data sets. The high SOM increases the potential availability of substrate for ammonification and the low pH leads to low NH₃ volatilization rates and therefore, together with the low CEC, these keep the concentration of NH₄⁺ free ions high. When the soil-crop system receives N (topdress fertilizations), the soil N-NH₄ concentration immediately increases, reaching a maximum value, and comes back to the original value in about a week. The second value measured in Vignate for the N level 0 (Fig. 1a) and the two highest values observed in Opera during 2004 for the same N level (Fig. 1h) are probably influenced by N horizontal movements from the nearby fertilized plots. Figure 2 shows that the soil N-NO₃ concentration is very low when the field is submerged because of (i) low nitrification rates, (ii) leaching (high infiltration rates were measured for both the locations) and (iii) denitrification. The rapid decrease in soil nitrate content shown for Vignate soil between the first and the second sampling is mainly due to nitrate leaching occurring after the first real submersion (only the false sowing – related flooding before) of the not-puddled field.

3.2. Model results

3.2.1. Calibration

K_{sat} and BD were initialized with measured values. Calibrated parameters involved in the transformation of nitrogen in the soil are shown in Table II. The values of the parameters

Figure 1. Measured (circles) and simulated (lines) values of soil N-NH_4 content (soil layer 0.0–0.1 m). Figures a–e show the results of calibration; figures f–h show the results of the test of the calibrated parameters. Dates (day/month) on the X-axes; kg $\text{N-NH}_4 \text{ ha}^{-1}$ on the Y-axes. Error bars are the 95% confidence interval for the mean.

reflect the peculiar conditions, typical of paddy fields, caused by reduced oxygen availability: high and low values for, respectively, denitrification and nitrification rates (Focht, 1979). The higher NRA value for Vignate reflects the already mentioned different seedbed preparation (no puddling). In fact, in this location, water level was usually lower (about 0.05–0.08 m) than that normally observed in north-Italian paddy fields (about 0.20 m). This probably caused higher oxygen availability for the oxidation of N-NH_4 . Measured and simulated values of N-NH_4 and N-NO_3 will always refer to the 0.00–0.10 m soil layer in this section.

The agreement between measured and simulated values of N-NH_4 is shown in Figure 1 and in Table III. After the calibration, the model was shown to be able to simulate the evolution of soil N-NH_4 content (Fig. 1a–e) for the three data sets, reproducing (i) the effects of the pre-sowing (Vignate) and the top-dressing (all data sets) fertilizations and (ii) the almost constant low N-NH_4 content measured for the N level 0. CropSyst underestimates N-NH_4 concentration for the Vignate soil sampled at the second date – N level 2 (Fig. 1b), while the apparent underestimation reported in Figure 1a (N level 0) is probably due to horizontal movements of N from the fertilized plots.

Figure 2. Measured (circles) and simulated (lines) values of soil N-NO₃ content (soil layer 0.0–0.1 m). Figures a–e show the results of calibration; figures f–h show the results of the test of the calibrated parameters. Dates (day/month) on the X-axes; kg N-NO₃ ha⁻¹ on the Y-axes. Error bars are the 95% confidence interval for the mean.

Figure 2 and Table III show the agreement between measured and simulated values of N-NO₃. The values of the parameters at the end of the calibration (Fig. 2a–e) allow the model to correctly simulate the course of nitrate in the soil for all data sets, although the model overestimates the value of the last sample of Opera 2002 (Fig. 2c–d).

3.2.2. Validation

The results of the validation of model parameters (Figs. 1f–h, 2f–h and Tab. III) may also be considered satisfactory: the model correctly reproduced the courses of soil N-NO₃ and N-NH₄. The model underestimation shown in Figure 1h is due to

Table III. Indices of agreement between measured and simulated values of soil mineral nitrogen concentration.

	Data set	N level	RRME (%)	EF	CRM	CD	Slope	Intercept [#]	R ²
N-NH ₄	Vignate 2002	0*	36.75	0.67	-0.18	1.23	0.83	0.05	0.79
		2**	118.37	-0.66	-0.43	4.68	0.45	1.97	0.90
	Calibration Opera 2002	0	64.74	-5.18	-0.12	8.50	0.20	2.13	0.33
		2	47.27	0.76	0.02	0.98	0.89	1.10	0.77
	Opera 2004	2	32.31	0.30	-0.03	0.29	1.04	-2.70	0.31
		1***	75.21	0.53	-0.39	2.46	0.64	0.42	0.96
	Validation Vignate 2002	1	86.14	-0.27	0.17	0.41	0.20	5.21	0.01
		0	36.64	-0.88	0.29	1.29	1.98	-10.97	0.40
N-NO ₃	Opera 2004	0	32.81	0.97	0.05	0.86	1.06	-0.04	0.97
		2	80.52	0.66	0.38	0.77	1.03	1.56	0.73
	Calibration Vignate	0	75.62	0.49	-0.20	0.79	0.85	-0.03	0.54
		2	83.31	-0.06	0.31	0.54	0.61	1.59	0.15
	Opera 2004	2	26.75	-1.67	0.07	0.93	-0.48	2.76	0.18
		1	76.25	0.76	0.28	0.77	1.04	1.02	0.80
	Validation Vignate	1	70.07	0.58	-0.02	0.78	0.87	0.25	0.60
		0	51.45	-2.64	0.36	2.20	-0.47	2.40	0.10

*: No N fertilizer has been applied; **: optimal N availability; ***: intermediate N fertilization level; #: kg N-NH₄ ha⁻¹ for N-NH₄; kg N-NO₃ ha⁻¹ for N-NO₃.

the N-NH₄ horizontal movements already discussed and correctly not simulated by the model.

3.3. Discussion on model performances

The test of calibrated parameters confirmed the accuracy of model performances for the simulation of soil N-NO₃ content, although some of the values assumed by the fitting indices (above all RRMSE) may not always appear satisfactory (Tab. III). In fact, the means of the measured values of all data sets are low, with a minimum corresponding to 1.38 kg N-NO₃ ha⁻¹ (Opera 2002 – N level 0) and a maximum to 4.44 kg N-NO₃ ha⁻¹ (Vignate – N level 2). This is why RRMSE values are high (RRMSE is calculated by dividing RMSE by the observed mean), although the figure shows satisfactory correspondence between measured and simulated values. In fact, the average of the RMSE values for N-NO₃ simulations is only 2.06 kg N-NO₃ ha⁻¹, which may be considered relatively low thinking about a possible use of the model for management purposes or, for example, to evaluate groundwater pollution due to nitrate leaching. In fact, most of the values calculated for the other fitting indices are satisfactory (EF positive in most cases, CD almost always close to 1). The same considerations regarding the values of RRMSE may also be valid for the simulation of N-NH₄, although the values of the other indices confirm the lower precision of the model in simulating this variable.

Figures 1 and 2 show that simulated values are in most cases within the error bars (95% confidence interval for the mean), especially for N-NO₃. This is particularly important from the environmental point of view, because NO₃⁻ is the N chemical form subject to leaching and the direct precursor of nitrous oxide, one of the most significant greenhouse gases. Moreover, when leached, NO₃⁻ is one of the most feared groundwater pollutants because, under reducing conditions, it is converted into nitrite, exposing infants to risk of methemoglobinemia.

For five days after the first topdressing fertilization (optimal N), CropSyst simulated average nitrification rates of 2.49, 1.87 and 1.14 kg N ha⁻¹ day⁻¹, respectively, for the Vignate, Opera 2002 and Opera 2004 experiments. These values are coherent with those reported by Reddy (1982) (about 2.8 kg N ha⁻¹ day⁻¹). The average simulated denitrification rates after the first topdressing fertilization (0.07 kg N ha⁻¹ day⁻¹ for Vignate, 0.04 kg N ha⁻¹ day⁻¹ for Opera 2002 and 0.01 kg N ha⁻¹ day⁻¹ for Opera 2004) are low compared with those reported by Reddy (1982) (about 0.5–1.1 kg N ha⁻¹ day⁻¹) but consistent with the value measured by Majumdar et al. (2000) (0.06 kg N ha⁻¹ day⁻¹). A possible explanation for the low simulated denitrification rates is related to the high water infiltration rates observed in these experiments, which may have caused higher nitrate leaching and, therefore, low N-NO₃ availability for denitrification.

CropSyst simulated average ammonification rates of 0.34, 0.36 and 0.52 kg N ha⁻¹ day⁻¹ for the Vignate, Opera 2002 and Opera 2004 experiments. These values are coherent with those reported by Kushwaha et al. (2000) under similar conditions of bulk density, carbon and N soil content and C/N ratio. During the period flooding – harvest, simulated values of total N ammonified are 160, 190 and 105 kg N ha⁻¹ for Vignate and Opera 2002–2004. The value simulated for Opera 2004 is lower than the others, despite the higher simulated ammonification rate, because of the false sowing and therefore the short flooding period. Simulated amounts of N leached at Vignate are 106, 137 and 189 kg N ha⁻¹ for the N levels 0, 1 and 2. Slightly lower values were simulated for the other two experiments. These high values are due to the high saturated hydraulic conductivity which characterizes rice cultivation in northern Italy and to the related high level of water losses by percolation. Simulated crop N uptakes for Vignate are 113, 147 and 166 kg N ha⁻¹ for the N levels 0, 1 and 2. The model simulated similar values for Opera 2002 (122, 173 and 167 kg N ha⁻¹ for the three N levels)

and Opera 2004 (72 and 156 kg N ha⁻¹ for the two N levels). The comparison between measured and simulated values of plant nitrogen concentration was considered satisfactory: RRMSE ranged between 13% and 30%; EF between 0.69 and 0.91; CRM between -0.18 and 0.24; R² between 0.74 and 0.99.

For Vignate and Opera 2002, the calibration carried out on data from the N level implying no fertilization leads to a combination of the parameters MRA, NRA and DRA very similar to the combination obtained carrying out the calibration using data from the N level corresponding to optimal N fertilization. That is, the same values of the parameters were reached through a process of optimization of the values of fitting indices computed separately on simulated soil N concentration data (from both the locations) from the two N levels. During the validation, the model showed similar levels of accuracy in reproducing soil mineral N concentration: for the intermediate N level, the calibrated values of the three parameters were also shown to be suitable. For these considerations, it is possible to conclude that, if the data sets for calibration and for validation would have been differently split, the three parameters would have probably converged on the same values.

Especially at mid-latitudes, flooding water has a strong effect on the vertical thermal profile, influencing air, water and soil-water interface temperatures. Confalonieri et al. (2005a) have analyzed and modeled this important aspect of flooded rice systems. Because of the dependency of soil N transformation rates on temperature, the introduction of these procedures (TRIS module) in CropSyst would probably improve N balance simulation.

4. CONCLUSION

CropSyst was calibrated and tested for the simulation of the N balance of paddy rice in northern Italy. This cropping system is considered a high impact one because of the low N-use efficiency due to the high losses by N leaching and denitrification. The results obtained at the end of the calibration for the simulation of soil N-NH₄ and N-NO₃ content show that, for the analyzed soil types, the model was able to reproduce soil mineral nitrogen concentration for the studied period, and the simulated nitrification and denitrification rates are similar to those measured by other authors. In spite of that, it is necessary to underline that this first test was carried out only with data from three experiments, collected in two locations over two years, and that no other work is available in the literature about N balance simulations under flooded conditions. Moreover, measured leaching data were not available. For these reasons, it is impossible, at the moment, to make definitive considerations about the model suitability. Interest in low N-use efficiency in rice fields is justified by its economic and environmental impact, as the amount of N not taken up by the crop is a significant source of greenhouse gases and groundwater pollution. Therefore, further tests of the model for N balance simulation are needed and the collection of field-specific data is the sine qua non condition to reach this aim.

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