Evaluating Nitrogen and Water Management in a Double-Cropping System Using RZWQM

C. Hu, S. A. Saseendran, T. R. Green,* L. Ma, X. Li, and L. R. Ahuja

ABSTRACT

Simulation of water and nutrient processes can enhance intensive agriculture to help feed the world's population in a sustainable manner. Due to excessive N application, environmental protection and agricultural sustainability have become major issues in agriculture. In this study, we calibrated and tested the RZWQM model to assess N management in a double-cropping system comprised of winter wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.) at Luancheng, in the North China Plain. Data, including biomass, grain yield, soil water, and soil and crop N, were used from 2001–2003 field trials applying 200 to 800 kg N ha^{-1} yr^{-1} for five cropping seasons. In general, soil water, biomass, and grain yields were predicted better than plant N uptake or soil residual N. Once it had been tested and used to improve the understanding of N processes in this cropping system, the model was further used to evaluate the effects of alternative water and N management scenarios on N leaching. Typical application rates of both water and N could be reduced by about half based on these results, which would have high economic, social, and environmental impacts in China. The results also demonstrate the potential of RZWQM for evaluating N and water management practices in other regions and climates of the world with intensive agriculture.

NITROGEN MANAGEMENT remains one of the most challenging tasks for sustainable agriculture, as it affects not only productivity and profit, but also other issues of importance to the environment such as NO_3 contamination of ground and surface waters, greenhouse gas emissions and global warming. Elevated NO_3 in groundwater has often been associated with overapplication of N fertilizers and irrigation water by producers anxious to achieve optimum yields (Schepers et al., 1991). Sexton et al. (1996) reported that NO_3 leaching from corn grown on a sandy loam soil in central Minnesota increased rapidly as the N application rate exceeded 100 kg N ha^{-1} yr^{-1}. As N rates increased to about 250 kg N ha^{-1} yr^{-1}, NO_3 leaching increased exponentially.

Population and economic pressures worldwide have driven a general intensification of crop production. Sustained agricultural production is a particularly important issue for China, with its huge population of 1.3 billion. Winter wheat and summer corn are the staple grain crops. The deficit of grain (demand minus supply) has been about 27 million Mg yr^{-1} recently in China (Zhou, 2004). In some high-yielding areas in the North China Plain (NCP), with great expansion of irrigated lands and large input of fertilizers (N application rates up to 450 kg N ha^{-1} yr^{-1}) since the late 1970s, total grain production has increased three times and annual yield is up to 14 Mg ha^{-1}. The NCP is one of the major agricultural areas in China (3×10^5 km^2) with a population of about 130 million people. It provides one-fifth of the nation's food supply. In the future, increased total grain production will be mainly dependent on the increase of grain yield per hectare, because urbanization is decreasing the area of arable land. Fertilizer application is one of the key factors contributing to increased grain yield. Using 1 Mg of fertilizer can cause an increase grain production by 8.84 Mg (Peng, 2000). Nitrogen fertilizer use is expected to rise continuously in China in the 21st century: 25 million Mg in 2005, 27 million Mg in 2010, and 30 million Mg in 2020 (Peng, 2000).

Water management issues are coupled with fertilizer management. The mean annual rainfall of the NCP is about 480 to 500 mm. About 70% of the total rainfall occurs from July to September, the growing season of corn. Rainfall during the winter wheat growing season (October–June) is about 60 to 150 mm. Supplemental irrigation is required to support wheat production, as the consumptive water use of winter wheat is about 430 to 470 mm. Farmers in this region generally irrigate winter wheat four to five times each season, and corn is irrigated once or twice per year.

Excess fertilizer application and overdraft of aquifers for irrigation have caused contamination and depletion of groundwater in the NCP (Zhang et al., 1995, 2003; Hu et al., 2005). Thus, for sustainable agriculture, it is necessary to develop comprehensive and improved N management recommendation tools to advise farmers. To maintain high yields while keeping adverse environmental impacts to a minimum, we need to effectively synthesize the knowledge accrued in various disciplines of agricultural research for timely solutions to practical problems in agriculture. Integration of information from field studies and processes through simulation modeling is recommended to identify solutions to such problems (Elliott and Cole, 1989; Peterson et al., 1993). Agricultural systems simulation models can help synthesize much of the information accumulated from various experiments at various locations (Mathews and Blackmore, 1997). In general, all the reported studies for determining fertilizer recommendations for a locality made use of field experiments that have been done periodically with limited multiyear, multilocation replications, and conclusions are extrapolated statistically or otherwise. Fertilizer responses, depending on the soil and climate (especially rainfall) at the location, vary a great deal among years and locations. Field

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Abbreviations: MRE, mean relative error; NCP, North China Plain; NUE, nitrogen use efficiency; OM, organic matter; RE, relative error; RMSE, root mean squared error; SD, standard deviation.

experiments to capture all the multiyear, multilocation variability are nearly impossible. In this context, dynamic cropping system simulation models, well calibrated and validated against field experimental data, hold the promise of extrapolating the short-duration field experimental results to other years and other locations (universal), making use of long-term weather and soil information (Mathews et al., 2002; Knisel and Turtola, 2000; Mathews and Blackmore, 1997; Godwin and Jones, 1991; Paz et al., 1998, 1999). Concepts from the present study using such simulation tools may be adapted to other locations, climates, and crops, such as other double-cropping systems in Australia (Bresson 1995), Japan (Nakamura et al., 2004), and Portugal (Trindade et al., 1997) where NO_3 leaching is a common issue.

The RZWQM model is a comprehensive, process-based, agricultural system model that can simulate the complex interactions in the soil–plant–atmosphere system as affected by irrigation, fertilization, tillage, and other management practices, and predict their effect on crop yield and water quality (Hanson et al., 1998; Ahuja et al., 2000). The generic crop model included in RZWQM can be parameterized to simulate specific crops (Hanson, 2000). The generic crop model of RZWQM has already been parameterized to simulate corn, wheat, and soybean [*Glycine max* (L.) Merr.], including validation with measured data (Farahani et al., 1999; Ghidey et al., 1999; Hanson et al., 1999; Jaynes and Miller, 1999; Landa et al., 1999; Martin and Watts, 1999; Ma et al., 2001, 2003; Saseendran et al., 2004; Wu et al., 1999). Furthermore, various N management strategies for rainfed winter wheat in eastern Colorado have been developed using RZWQM (Saseendran et al., 2004). The RZWQM model has not been tested for N management in double-cropping systems involving corn and winter wheat (two crops harvested in any single year). The objectives of this study were to: (i) calibrate and test the RZWQM for simulation of an irrigated wheat–corn double-cropping system in the NCP under a range of N application rates, and (ii) demonstrate the use of an agricultural simulation model for developing general nutrient and irrigation management recommendations that can balance negative environmental impacts with better agronomic yields. The model and methodology have potential for similar applications in other regions of the world.

MATERIALS AND METHODS

Site Description

Field experiments were conducted at Luancheng Agroecosystem Experimental Station (37°53′N, 114°41′E, elevation 50 m), Chinese Academy of Sciences, which is located at the piedmont of the Taihang Mountains, in the NCP. Daily meteorological data of air temperature, solar radiation, wind speed, humidity, and precipitation were collected from a weather station located about 300 m from the experimental site. Mean annual precipitation at the station is about 536 mm, 70% of which occurs during July to September. Annual average air temperature is 12.2°C. The soil type of the area is predominately silt loam (agric, rusty Ustic Cambisols; Zitong, 1999). The predominant cropping system in the region is a winter wheat–corn double-cropping system (two crops harvested in any single year) without a fallow period between the crops. Crops are generally flood irrigated with pumped groundwater.

The field experiment was conducted during a 5-yr period (1998–2003), but as the first 2 yr were used as “start up” to remove system memory effects, detailed data for the simulation study were available only from 2001 to 2003. A randomized block design was used, and there were four N treatments (200, 400, 600, and 800 kg N ha^{-1} yr^{-1}) with three replications each. These rates reflect feasible inputs (below average, average, high, and very high) currently used in the NCP. Each plot was 2.5 by 2.5 m, and was bordered by a concrete wall to the 2-m depth to prevent lateral flow of water and nutrients. A summary of the crop management details is shown in Table 1.

Table 1. Summary of crop management practices conducted for the experiment during 2001 to 2003.

	2001–2002		2002–2003		
Management events	**Corn**	**Winter wheat**	**Corn**	**Winter wheat**	**Corn**
Planting date	**12 June 01**	**12 Oct. 01**	**15 June 02**	**16 Oct. 02**	**15 June 03**
Planting density, plant ha^{-1}	**67200**	**2000000**	**67200**	**2000000**	**67500**
Row spacing, m	**0.80**	**0.15**	**0.80**	**0.15**	**0.80**
Tillage date		**10 Oct. 01**		**16 Oct. 02**	
Irrigation date and amount, cm	**5 July 01**	**6 Oct. 01**	**16 June 02**	**7 Oct. 02**	**23 June 03**
	7.5	**9.3**	**11.6**	**9.3**	**7.0**
	13 Aug. 01	**30 Nov. 01**	**17 July 02**	**16 Nov. 02**	**15 July 03**
	7.5	**7.0**	**11.6**	**7.0**	**7.0**
		15 Mar. 02	**20 Aug. 02**	**12 Apr. 03**	**14 Aug. 03**
		7.0	**9.3**	**7.0**	**4.7**
		25 Apr. 02			
		7.0			
		30 May 02			
		7.0			
First fertilizer application date and amount, kg ha^{-1}	**5 July 01**	**10 Oct. 01**	**16 June 02**	**16 Oct. 02**	**15 July 03**
(WC200N)†	**50**	**50**	**50**	**50**	**50**
(WC400N)†	**100**	**100**	**100**	**100**	**100**
(WC600N)†	**150**	**150**	**150**	**150**	**150**
(WC800N)†	**200**	**200**	**200**	**200**	**200**
Second fertilizer application date and amount, kg ha^{-1}	**13 Aug. 01**	**15 Mar. 02**	**17 July 02**	**12 Apr. 03**	**14 Aug. 03**
(WC200N)†	**50**	**50**	**50**	**50**	**50**
(WC400N)†	**100**	**100**	**100**	**100**	**100**
(WC600N)†	**150**	**150**	**150**	**150**	**150**
(WC800N)†	**200**	**200**	**200**	**200**	**200**
Harvest date	**28 Sept. 01**	**8 June 02**	**28 Sept. 02**	**10 June 03**	**2 Oct. 03**

† WC200N, 200 kg N ha^{-1} yr^{-1} experiment; WC400N, 400 kg N ha^{-1} yr^{-1} experiment; WC600N, 600 kg N ha^{-1} yr^{-1} experiment; WC800N, 800 kg N ha^{-1} yr^{-1} experiment. Note the split application rates (twice per crop).

A moldboard plow was used for tillage operations. Nitrogen was applied to the ground surface in the form of urea in four equal split doses at (i) preplanting of winter wheat, (ii) the jointing stage of winter wheat, (iii) the seedling stage of corn, and (iv) the tassel stage of corn. The crops were flood irrigated at a rate equivalent to a 70-mm depth of water after each N fertilizer application, i.e., four times a year. The actual irrigation amount applied to each plot every time (Table 1) was recorded with flow meters. Winter wheat was planted in late September or early October, and summer corn was planted in early June the following year after wheat harvest, with little or no fallow period in between the crops. The crop cultivars were Gaoyou 503 for winter wheat and Yedan24 for corn.

Soil water contents were monitored weekly at the center of each plot to 180 cm at intervals of 20 cm using a neutron probe. Soil samples for residual N analysis were collected down to 180 cm in 20-cm increments and three replications in June and September immediately after the harvests of winter wheat and summer corn. Nitrate N in the soil samples was determined by standard flow injection analysis of 2 *M* KCl extracts with fresh soil. Individual plots were harvested manually. Aboveground biomass (less 5 cm of stubble) was sampled. Grain was then separated using a thresher. Grain and straw were air dried before measuring gravimetric water content. All plant samples were dried at 75°C and ground to pass a 2-mm mesh screen for plant N analysis.

The model needs initial conditions for soil water, soil temperature, soil chemistry, soil organic matter, and microorganism pools. Model default values of soil chemistry were used. Unit gradient flow was assumed as the soil bottom boundary condition at 220 cm; however, comparisons between simulated and measured variables were made only to 180 cm.

Model Description

Detailed descriptions of the different components of the RZWQM are available elsewhere (Ahuja et al., 2000; Hanson et al., 1998). In the model, water infiltration is calculated with the Green–Ampt equation (Green and Ampt, 1911) and vertical water redistribution is calculated by solving the Richards equation. Soil hydraulic properties are estimated using the Brooks–Corey equation (Brooks and Corey, 1964) with modifications (Ahuja et al., 2000). The generic crop model included in RZWQM can be parameterized to simulate specific crops (Hanson, 2000). The plant model simulates both plant population development and plant growth. Crop phenology, while not explicitly simulated, is handled through seven growth stages: (i) dormant seeds, (ii) germinating seeds, (iii) emerged plants, (iv) established plants, (v) plants in vegetative growth, (vi) reproductive plants, and (vii) senescent plants. Simulated management practices include crop plantings at different dates, fertilizer (inorganic and organic) and irrigation applications, and tillage operations. Organic manure and crop residue (C and N) dynamics on the soil surface and subsoil are also simulated.

Organic Matter–Nitrogen Cycling

The OMNI submodel simulates Organic Matter–NItrogen cycling in RZWQM (Shaffer et al., 2000). Residues (crop stover, manure, and other organics) are partitioned between fast and slow pools based on their C/N ratios. There are three soil organic matter (OM) pools with C/N ratios of 8 (fast pools), 10 (medium pool), and 12 (slow pool). All of the above pools are dynamically linked. In addition, there are three living microorganism pools for aerobic heterotrophs, autotrophs, and facultative heterotrophs. Residue and OM pools are subject to first-order decay with respect to each C concentration, as affected by the soil water O_2 concentration, soil pH, ion strength, heterotrophic microbial population, soil temperature, and the degree of soil water saturation (Shaffer et al., 1992).

A fraction of the decayed residue and OM is transferred to other pools and the rest of the C is converted to CO_2. The model also uses CO_2 as a C source. Nitrogen is released as NH_4 from the residue and OM pools during the decaying process. Ammonium is nitrified to NO_3 following a zero-order equation as a function of the soil temperature, soil O_2 concentration, soil pH, ion strength, autotrophic microbial population, and the degree of water saturation (Shaffer et al., 1992). Nitrate from nitrification and applied commercial fertilizers is subject to denitrification under anaerobic conditions as a first-order equation. Ammonia volatilization is estimated from the partial pressure gradient of NH_3 in the soil and air, with due consideration for wind speed and soil depth. The denitrification rate coefficient is a function of the soil temperature, soil pH, ion strength, total soil C, anaerobic microbial population, and the degree of soil water saturation. The RZWQM model default values of OM decay, nitrification, denitrification, and volatilization rates were used (Ahuja et al., 2000).

Model Parameterization and Calibration

Field-measured values of soil profile water content, profile soil temperature, crop residue mass, soil profile NO_3, bulk density, and soil OM content of different N experiments at planting in the year 2001 were used as initial conditions for model simulations (Table 2). Crop and soil data of the experiment with N dosage at 200 kg N ha^{-1} yr^{-1} (WC200N) from 2001 to 2003 were used for model calibration, and data from 400 kg N ha^{-1} yr^{-1} (WC400N), 600 kg N ha^{-1} yr^{-1} (WC600N), and 800 kg N ha^{-1} yr^{-1} (WC800N) dosages were used in the model testing. The RZWQM model needs to be calibrated for soil hydraulic properties, nutrient properties, and plant growth parameters (Hanson et al., 1999).

The detailed procedures for calibrating the hydraulic parameters of RZWQM have been laid out by Hanson et al. (1999) and Ahuja and Ma (2002). Because measured data were not available, the model default values of hydraulic parameters for a silt loam soil were used as initial guesses for these parameters in the simulations (Table 3). After following the above

Table 2. Measured soil initial conditions used for the RZWQM simulations.

				Soil water content				Residual nitrate			
Soil depth	**Soil temperature**	**Bulk density**	**Organic matter**	**(1)†**	**(2)**	**(3)**	**(4)**	**(1)**	**(2)**	**(3)**	**(4)**
cm	°C	g cm^{-3}	mg kg^{-1}	cm^3 cm^{-3}				μg N g^{-1}			
0–15	26.6	1.22	13.5	0.21	0.24	0.23	0.21	5.1	5.3	5.6	9.9
15–30	25.8	1.43	13.0	0.26	0.25	0.25	0.25	1.0	4.5	11.7	58.9
30–105	19.6	1.46	8.5	0.29	0.27	0.29	0.29	0.3	6.2	8.5	51.8
105–170	14.9	1.56	8.5	0.30	0.31	0.30	0.30	1.9	14.6	19.4	52.0
170–200	14.9	1.49	6.5	0.33	0.31	0.33	0.33	4.6	17.3	17.8	39.8
200–212	14.9	1.49	6.5	0.36	0.33	0.32	0.32	4.5	17.8	18.5	40.0

† (1) WC200N, (2) WC400N, (3) WC600N, (4) WC800N.

Table 3. Soil properties used in the RZWQM simulations.

Depth	K_{sat}†	Sand	Silt	Clay	33 kPa water content‡
cm	cm h^{-1}		kg kg^{-1}		cm^3 cm^{-3}
0–105	0.88	0.20	0.65	0.15	0.306
105–212	0.12	0.50	0.05	0.45	0.322

† K_{sat} is saturated hydraulic conductivity. Ksat and Sand, Silt, and Clay values given in the table are model default values for silt loam soil, as there were no measurements of these parameters in the experiment.

‡ The 33 kPa water content values were calibrated.

calibration procedure, we further calibrated the 33 kPa soil water content to improve the match between the measured and simulated soil moisture. The calibrated values of 33 kPa water content for silt loam soil along with measured sand, silt, and clay fractions are given in Table 3.

Calibration of the soil nutrient component of the model involves establishment of the initial values for fast and slow soil residue pools; slow, medium, and fast soil humus pools; and the three microbial pools: (i) aerobic heterotrophs, (ii) autotrophs, and (iii) anaerobic heterotrophs. In our experiment, we had measured values of soil OM content (Table 2), which were used as a reference set for calculation of the different residue, soil humus, and microbial pools (Ahuja et al., 2000).

The crop parameters were calibrated after a sensitivity analysis to identify input parameters that needed calibration. Sensitivity analyses of RZWQM to changes in input parameters have been reported (Ma et al., 2000, Walker et al., 2000). The biomass-to-leaf-area conversion coefficient (SLW) in the regional crop parameter set has the strongest influence on crop yield (Walker et al., 2000; Ma et al., 2000; Table 4); however, changes in SLW alone to achieve correct yield results can lead to unrealistically high leaf area index (LAI) in simulations (Ma et al., 2000). In this study, we optimized all nine regional crop parameters recommended for calibration (Table 4; Hanson et al., 1999). Twelve species-specific parameters also were calibrated to correctly simulate the crop cultivars used in the experiment (Table 5). Procedures and methods for calibrating the crop parameters are described elsewhere (Hanson et al., 1999; Ahuja and Ma, 2002). Farahani et al. (1999) developed plant-growth parameters for corn to test the model in Colorado, USA. These parameters were modified by Ma et al. (2003). Saseendran et al. (2004) parameterized the generic crop model of RZWQM for simulation of winter wheat in eastern Colorado. Calibration of parameters for the corn cultivar Yedan24 and for winter wheat cultivar Gaoyou 503 used in the study for the NCP climate are based on Ma et al. (2003) and Saseendran et al. (2004), respectively. These parameters were calibrated further for the location through optimization using an objective function based on field-measured values of grain yield, biomass, soil water content at different layers, N uptake by grain, N uptake by aboveground biomass, and residual NO_3–N in the soil profile (180 cm) at harvest.

Table 4. Calibrated regional parameters for simulation of corn and winter wheat in the double cropping system in North China Plains using RZWQM.

Parameter	Value	
	Corn	Wheat
Maximum active N uptake rate, g plant^{-1} d^{-1}	1.3	2.5
Daily respiration as a function of photosynthate (fraction)	0.2	0.02
Biomass to leaf area conversion coefficient (SLW), g m^{-2}	13.6	1.1
Age effect on photosynthesis in the propagule development stage (fraction)	0.85	0.9
Age effect on photosynthesis in the seed development stage (fraction)	0.7	0.45
Maximum rooting depth, m	2.0	3.0
Minimum leaf stomatal resistance, s m^{-1}	200	100
Nitrogen sufficiency index (fraction)	0.9	NA†
Luxurious nitrogen uptake factor (fraction)	1.0	NA

† NA, not applicable for wheat crop.

Table 5. Calibrated species-specific parameters for simulation of winter wheat and corn using RZWQM in the North China Plains.

Parameter	Value	
	Corn	Wheat
Min. time for seeds to germinate, d	4	3
Min. time for seedling to emerge, d	7	12
Min. time for plants to grow to 4-leaf stage, d	19	20
Min. time for plants to complete vegetative stage, d	31	148
Min. time for plants to complete reproductive stage, d	37	20
Min. N content for leaves (proportion)	0.02	0.005
Max. N content for leaves (proportion)	0.03	0.02
Min. N content for stems (proportion)	0.02	0.005
Max. N content for stems (proportion)	0.03	0.02
Min. N content for roots (proportion)	0.01	0.02
Min. N content for propagules (proportion)	0.008	0.005
Max. N content for seeds (proportion)	0.018	0.06

Four statistics were used to evaluate simulation results: (i) root mean squared error (RMSE), Eq. [1], between predicted and observed values; (ii) relative error (RE), Eq. [2]; (iii) bias or mean relative error (MRE), Eq. [3]; and (iv) model efficiency (E), Eq. [4].

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \qquad [1]$$

$$\mathrm{RE}_i = \frac{(P_i - O_i)}{O_i}100\% \qquad [2]$$

$$\mathrm{MRE} = \frac{1}{n}\sum_{i=1}^{n}\mathrm{RE}_i \qquad [3]$$

$$E = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - O_{\mathrm{avg}})^2} \qquad [4]$$

where P_i is the ith predicted value, O_i is the ith observed value, O_{avg} is the average of observed values, and n is the number of data pairs. Values of E are equivalent to the coefficient of determination (R^2) if the values fall around a 1:1 line of predicted vs. observed data, but E is generally lower than R^2 when the predictions are biased, and E can be negative.

The objective function is calculated as the average of the normalized prediction mean errors of the above variables. For normalization of the prediction mean errors, their respective average measured values were used. We used a direct search for optimization of the crop parameters, constraining their values to increments of 5% at a time (the number of model runs at this increment level exceeded 100000) between an upper limit of +50% and lower limit of −50% from Saseendran et al. (2004) for the winter wheat crop. A similar procedure was conducted for optimization of the crop parameters for corn from the reported parameters of Ma et al. (2003). The calibrated crop parameters are listed in Tables 4 and 5.

Measured as well as simulated data of soil water, plant N uptake, residual soil N, and grain and biomass yield were analyzed for treatment differences ($P < 0.05$) by one-way analysis of variance (Dowdy and Wearden, 1991).

Model Applications for Nitrogen and Water Management

Once an agricultural system model is adequately calibrated and tested, it has the potential for use in evaluation of alternative crop–soil management practices for the location in terms of their production potential and impact on the environment. Conventional methods for evaluation of the alternative management practices are based on site- and season-specific experiments that need to be repeated when soils and climates are changed, at immense costs of revenue and time. The model-based method is less expensive and can be used for evaluating alternative crop production scenarios. To demonstrate the potential use of the RZWQM model for testing various management alternatives in corn–winter wheat double-cropping systems, we ran the model with different irrigation and N application rates for the location during the experimental period from 2001 to 2003. We did not have long-term data available for running the model for longer periods in order to analyze the risks related to climate variability of the location on different N and water management practices. Therefore, the results from these investigations should be considered preliminary.

First, irrigation rates of 0 (rainfed), 25, 50, and 100% of the current irrigation rates used in the field experiments (Table 1) were evaluated under a single N rate of 200 kg N ha^{-1} yr^{-1}. This rate was chosen for the analysis based on the fact that, in this study, in both measured and model predicted data, there is no statistically significant difference (as discussed below) in grain yield, biomass yield, N uptake of aboveground biomass, or N uptake of grain between field-based N treatments at 200, 400, 600, and 800 kg N ha^{-1} yr^{-1}. Hence the lowest N rate of 200 kg N ha^{-1} yr^{-1} was selected for further evaluating the different irrigation rates. In a second step, the optimum irrigation rate was further evaluated for different N rates at 0, 50, 100, 200, 400, 600, and 800 kg N ha^{-1} yr^{-1}. In this way, the model was used to extend field experimental results to more optimal application rates, and to evaluate N leaching in conjunction with grain production at these new rates.

Table 6. Comparison of observed and model simulated results during the calibration period (Exp. WC200N).†

Crop Year/Date	Observed	Simulated	RE	RMSE	*E*
	kg ha^{-1}		%	kg ha^{-1}	
	Grain yield				
Corn (2001)	6241	6644	6.5	334	0.91
Wheat (2001–2002)	4901	4467	−8.9		
Corn (2002)	6150	5736	−6.7		
Wheat (2002–2003)	3267	3394	3.9		
Corn (2003)	5623	5767	2.6		
	Biomass				
Corn (2001)	12237	11825	−3.4	1406	0.18
Wheat (2001–2002)	12553	9169	−25.2		
Corn (2002)	12060	12072	0.1		
Wheat (2002–2003)	8167	8617	5.5		
Corn (2003)	11026	11146	1.1		
	Grain N uptake				
Corn (2001)	93	112	20.4	19	0.12
Wheat (2001–2002)	119	84	−29.4		
Corn (2002)	91	96	5.4		
Wheat (2002–2003)	74	75	1.1		
Corn (2003)	91	76	16.0		
	Biomass N uptake				
Corn (2001)	159	168	5.3	12	0.77
Wheat (2001–2002)	150	140	−7.3		
Corn (2002)	157	160	1.8		
Wheat (2002–2003)	95	117	22.6		
Corn (2003)	151	151	−0.4		
	Residual soil NO_3–N (0–180 cm)				
28 Sept. 2001 (at corn harvest)	65	91	37.5	38	−0.54
13 June 2002 (at wheat harvest)	68	84	22.8		
28 Sept. 2002 (at corn harvest)	62	85	36.8		
13 June 2003 (at wheat harvest)	126	106	−16.3		
13 Oct. 2003 (at corn harvest)	81	131	60.9		

† RE is Relative Error (Eq. 2); RMSE is Root Mean Squared Error (Eq. 1); *E* is Efficientcy (Eq. 4).

RESULTS AND DISCUSSION

Soil Water Content Simulations

Grain yield, biomass, grain N uptake, biomass N uptake, and residual NO_3–N in the soil at harvest for the WC200N experiment during all five cropping seasons of the experimental period, 2001 to 2003, were used to calculate the objective function (calibration targets) for model calibration. Evaluation of the calibration data set shows that the model can be calibrated to achieve a satisfactory match between simulated and field-measured crop growth (Table 6), soil water contents (Fig. 1 and 2a), and crop and soil N parameters (Table 6). Simulated water contents in different soil layers showed reasonably good agreement with field-measured values, with an RMSE of 0.053 m^3 m^{-3} (Fig. 1). In contrast to deeper soil

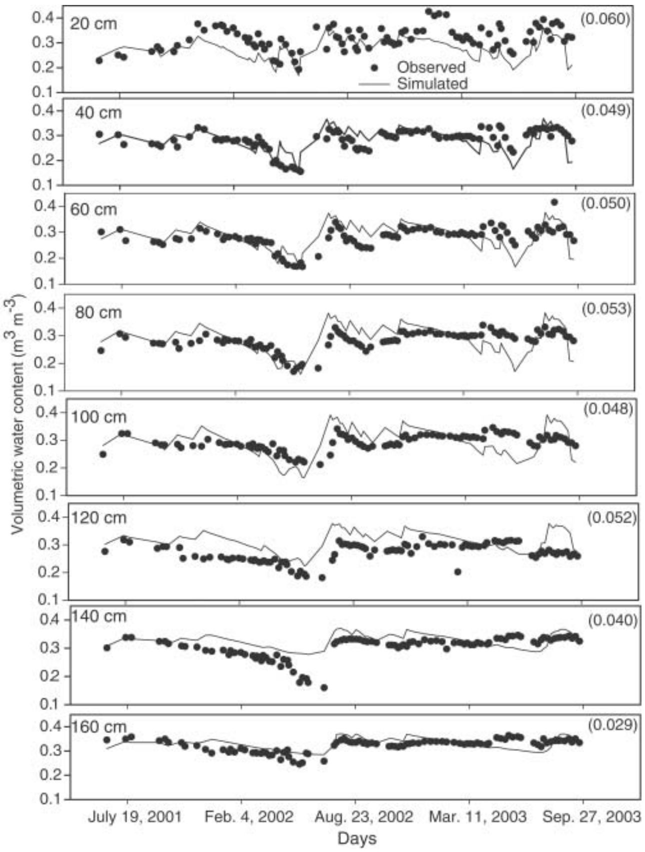

Fig. 1. Comparison between model-predicted and field-measured soil water contents at various soil depths for the 200 kg N ha^{-1} yr^{-1} treatment (model calibration). Values in parentheses are root mean squared errors of soil water predictions (m^3 m^{-3}).

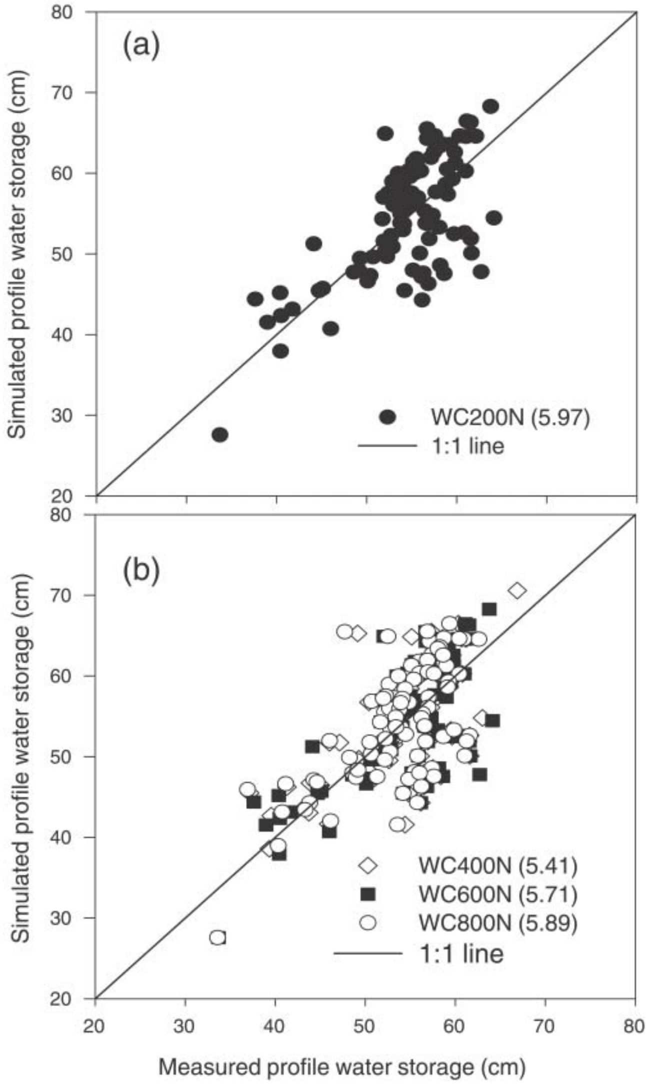

Fig. 2. Comparison between the model-predicted and field-measured soil profile (180-cm) water storage: (a) calibration results for the 200 kg N ha^{-1} yr^{-1} treatment (WC200N) during 2001 to 2003; (b) validation results for 400, 600, and 800 kg N ha^{-1} yr^{-1} (WC400N, WC600N, and WC800N, respectively) during 2001 to 2003. Numbers in parentheses are corresponding root mean squared errors.

layers with RMSE values of 0.049, 0.050, 0.053, 0.048, 0.052, 0.040, 0.029, and 0.062 m^3 m^{-3}, respectively, for the 40-, 60-, 80-, 100-, 120-, 140-, 160-, and 180-cm depths, simulated water contents in the top 20-cm soil layer (RMSE of 0.060 m^3 m^{-3}) showed less correspondence with the field-measured values. Soil water dynamics in the surface soil layers are more complex than deeper layers due to high spatial and temporal variations in OM contents, macropores, and other properties. In addition, a neutron probe was used for measurement of soil water for all soil layers in this experiment. At the 20-cm depth, it is possible that the neutron probe measurements were not very reliable (Wu et al., 1999; Jaynes and Miller, 1999). Although macropores can be simulated in the model (Ahuja et al., 2000), we did not have field measurements and quantifications for simulating macropores in this study. Nonetheless, simulated soil profile water storage (0–180 cm) showed reasonable agreement with the measured values (Fig. 2a), with an RMSE of 5.9 cm (0.04 m^3 m^{-3} for depth-averaged volumetric water content).

During model validation, predictions of total soil profile (0–180 cm) water storage for all three N treatments (400, 600, and 800 kg N ha^{-1} yr^{-1}) under both wheat and corn crops (five crop seasons during 2001 to 2003) have relatively good agreement with the measured values (Fig. 2b). The RMSE values of the total soil profile (0–180-cm) water storage were between 5.4 and 5.9 cm, and MRE values fell between −1.4 and 1.7%. In general, the model simulated the correct timing of most of the observed drying and wetting events with time for all treatments (Fig. 3 and 4). Year 2001 was a relatively dry year with annual precipitation of 290 mm, whereas Year 2003 was a wet year (annual precipitation of 458 mm), and Year 2002 was an average year (annual precipitation of 397 mm) but with more irrigation (Table 1). Thus, measured total soil profile (0–180-cm) water storage in 2002 and 2003 was higher than in 2001 (Fig. 3), and the total soil profile (0–180-cm) water storage simulations for all the N experiments showed similar trends. In Fig. 3, we present results of only one of the experiments (WC400N). Although model predictions also showed higher soil water contents in 2002 and 2003, the extremely low water content predicted by the model around 9 June 2003 at the end of the 2002–2003 wheat harvest (Fig. 3) was not consistent with the observations, but the model correctly predicted a dip in soil water content at the 2001–2002 wheat crop harvest (1 June 2002 in Fig. 3). The aberration in model prediction can be due to factors that are not represented correctly in the present model. Furthermore, comparison of model predictions of soil water in different soil layers with field-measured values reveals better agreement at the 40-, 60-, 80-, 100-, 120-, 140-, and 160-cm depths, with respective RMSE values of 0.039, 0.040, 0.041, 0.048, 0.047, 0.038, and 0.027 m^3 m^{-3}, than at the 20-cm depth, with an RMSE value of 0.066 m^3 m^{-3} (Fig. 4). Analysis of variance between different N treatments did not show

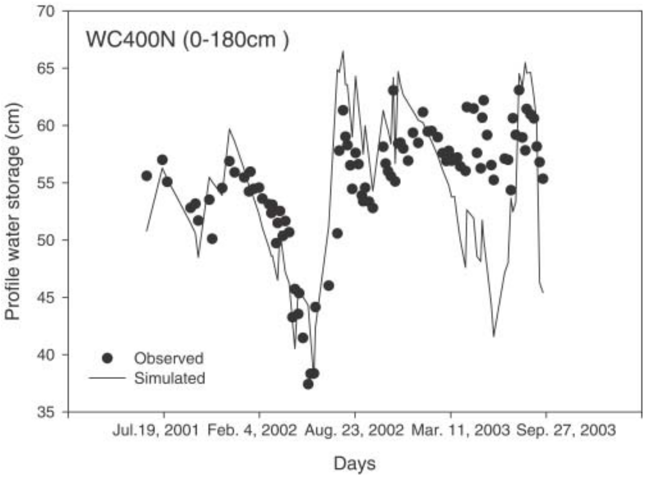

Fig. 3. Comparison between model-predicted and field-measured soil profile (180-cm) water contents for the 400 kg N ha^{-1} yr^{-1} treatment (other N rates have similar trends, not shown).

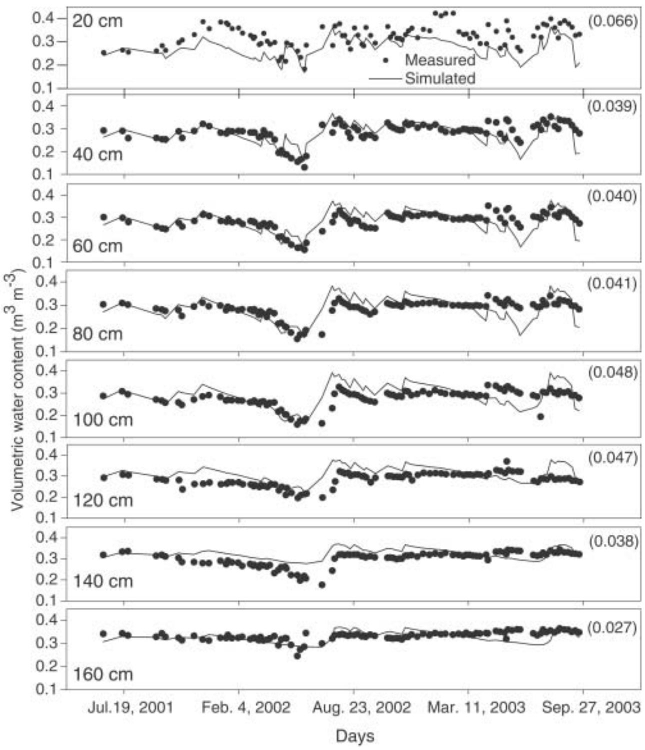

Fig. 4. Comparison between model-predicted and field-measured soil water contents at various soil depths for the 400 kg N ha^{-1} yr^{-1} treatment (other N rates have similar trends, not shown). Values in parentheses are root mean squared errors.

any significant differences for both measured ($p = 0.47$) and model predicted ($p = 0.91$) soil water contents. The accuracy of soil water predictions during model validation was comparable to calibration accuracies. Differences between calibration and validation RMSEs of soil water were −0.006, 0.010, 0.010, 0.012, 0.00, 0.005, 0.002, and 0.002 m^3 m^{-3}, respectively, for the 20-, 40-, 60-, 80-, 100-, 120-, 140-, and 160-cm depths. This indicates an appropriate level of calibration for predictive purposes, as well as parameter stability.

Grain Yield and Biomass

Analysis of variance between different N treatments (200, 400, 600, and 800 kg N yr^{-1}) did not show any significant differences in measured ($p = 0.97$) or predicted ($p = 0.49$) grain yields. During calibration, grain yield simulations for the five cropping seasons had an RMSE of 334 kg ha^{-1} per season (Table 6). The REs (Eq. [2]) of grain yield predictions for the five cropping seasons were between −8.9 and 6.5%. Measured aboveground biomass for the WC200N treatment varied between 8167 and 12 553 kg ha^{-1}, whereas the model-simulated amounts ranged from 8617 to 12 072 kg ha^{-1} and REs ranged from −25.2 to 5.5% (Table 6). The statistics are affected by a poor match in biomass for one season (wheat, 2001–2002) out of five.

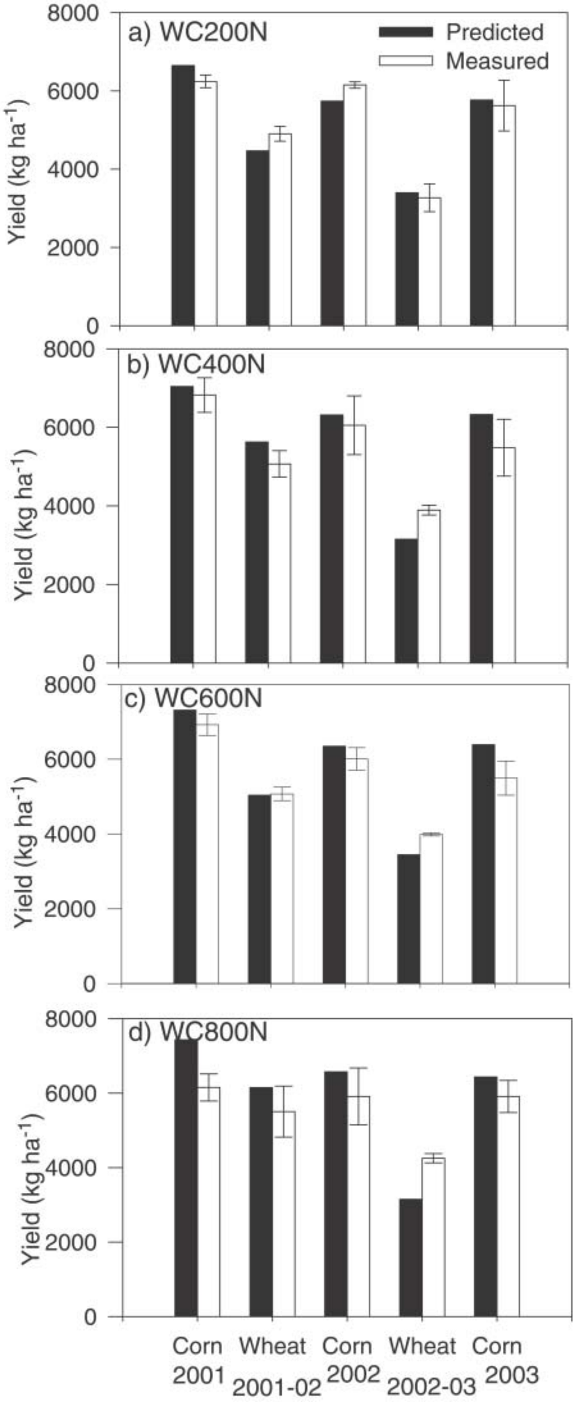

Fig. 5. Comparison between model-predicted and measured grain yields for the 200, 400, 600, and 800 kg N ha^{-1} yr^{-1} (WC200N, WC400N, WC600N, and WC800N, respectively) treatments during 2001 to 2003. Error bars represent ± one standard deviation of the measured grain yield from the mean of replications.

During model validation runs, predictions of grain yield of both corn and wheat for the five cropping seasons were in good overall agreement with the field-measured values (Fig. 5), and accuracies were comparable to those during calibration. Measured grain yields for all the seasons and N treatments ranged from 3267 to 5502 kg ha^{-1} for wheat, and from 5481 to 6919 kg ha^{-1} for corn. Corresponding ranges of simulated grain yields were from 3394 to 6145 kg ha^{-1} for wheat, and from 5736 to 7317 kg ha^{-1} for corn. Relative errors of model predictions of grain yields during individual crop seasons across different N treatments were between −14 and 12% for wheat and 3 and 19% for corn (data not shown). The MRE and RMSE values of grain yield predictions (corn and wheat predictions combined) ranged from 3 to 8% and 524 to 891 kg ha^{-1} (compared with a calibration RMSE of 334 kg ha^{-1}), respectively. Out of 20 grain yield predictions (this includes the calibration treatment), eight were within ±1 standard deviation (SD) of the measured values from the mean (Fig. 5). Of the remaining 12 predictions, nine were within ±2 SD, and the rest within ±3 SD.

During model validation, the biomass prediction accuracies were comparable to grain yield predictions. Out of the 20 biomass simulations (including the calibration treatment), five were within 1 SD of the measured values from the mean (Fig. 6). The RE values for the biomass predictions were between −18 and 6% for corn and −22 and −13% for wheat. For biomass predictions (corn and winter wheat predictions combined), the MRE ranged from −3 to −1%, and the RMSE ranged from 1517 to 1830 kg ha^{-1}(compared with a calibration RMSE of 1406 kg ha^{-1}).

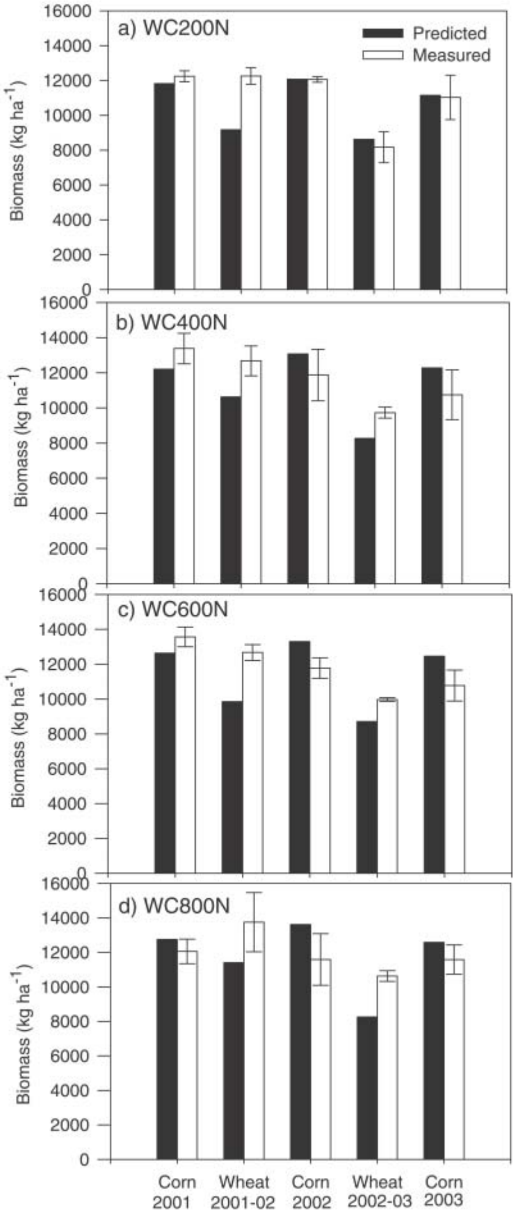

Fig. 6. Comparison between model-predicted and measured aboveground biomass for the 200, 400, 600, and 800 kg N ha^{-1} yr^{-1} (WC200N, WC400N, WC600N, and WC800N, respectively) treatments during 2001 to 2003. Error bars represent ± one standard deviation of the measured aboveground biomass from the mean of replications.

Nitrogen Uptake

Analysis of variance conducted for plant N uptake differences due to different N rates showed no significant effect in both measured ($p = 0.43$) and model-predicted ($p = 0.35$) values. During model calibration, the RMSE of simulated grain N uptake was 19 kg ha^{-1}, with the RE of individual predictions ranging from −29 to 20% (Table 6), and simulated biomass N uptake was predicted with a RMSE of 12 kg ha^{-1} and a RE between −7 and 23% ($E = 0.77$).

Field-measured total N uptake by biomass varied from 95 to 201 kg N ha^{-1} across application rates and crop seasons, whereas the model predictions during the validation runs produced a comparable range in prediction values from 112 to 220 kg N ha^{-1} (Fig. 7). In general, both biomass and grain N uptake predictions during validation runs were less accurate than calibration. During validation, the REs of biomass N uptake predictions across crop seasons and N rates ranged from −20 to 35%, and the RMSE values ranged from 29 to 37 kg N ha^{-1}.

Grain N uptake predictions during calibration and validation were less accurate than biomass predictions, showing overestimations in 12 out of 20 cases, and only four out of 20 predictions fell within 1 SD of the measured grain N uptake from the mean value (Fig. 8). The RE values of grain N uptake ranged from −31 to 44%, and the RMSE values ranged from 23 to 33 kg N ha^{-1}. The relatively low accuracies in grain N uptake predictions were not consistent with the higher accuracy in grain yield prediction by the model discussed above. Simulations of root growth and distribution in different soil layers and the nutrient uptake computations of the model need further improvement to correct this inconsistency; however, investigations on how this improvement can be made and what increase in accuracy can be obtained are beyond the scope of this study.

Total Soil Profile Residual Nitrate Nitrogen

A number of plant–soil–environment factors characterized by large temporal and spatial variability interact and influence N cycling in the soil. This is reflected in the high variability observed in the residual N measurements. The negative model efficiency (E) for soil residual N simulations is caused by these high variabilities among only five sample points (Table 6). Measured soil profile residual N contents showed high standard deviations (Fig. 9). Nevertheless, analysis of variance brought out significant differences between different N treatments in residual soil N levels in both measured ($P < 0.001$) and model-predicted ($P < 0.001$) data.

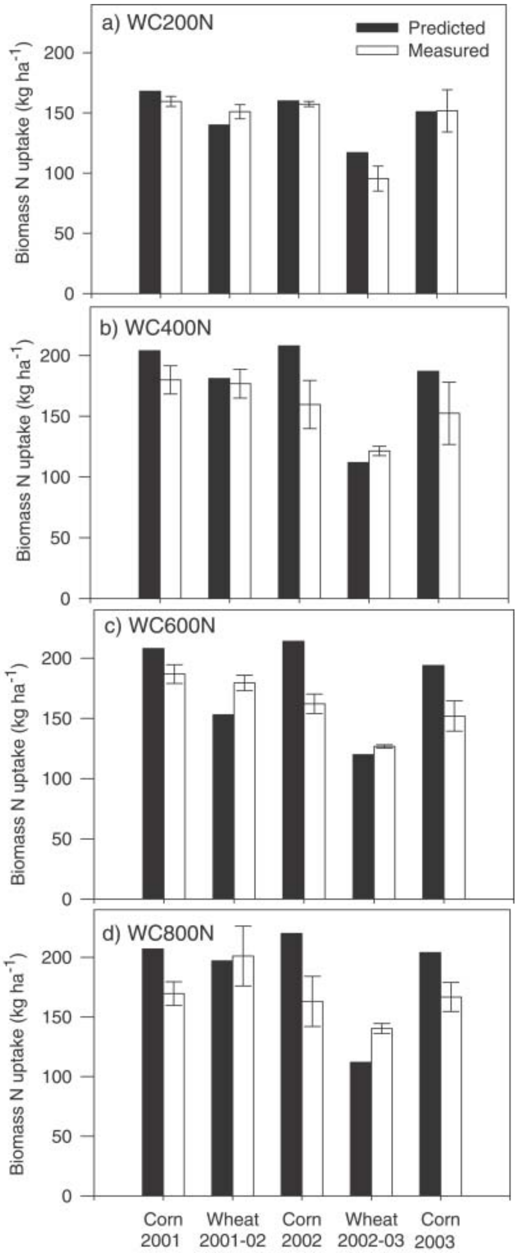

Fig. 7. Comparison between the model-predicted and measured aboveground biomass N uptake for the 200, 400, 600, and 800 kg N ha^{-1} yr^{-1} (WC200N, WC400N, WC600N, and WC800N, respectively) treatments during 2001 to 2003. Error bars represent ± one standard deviation of the measured aboveground biomass N uptake from the mean of replications.

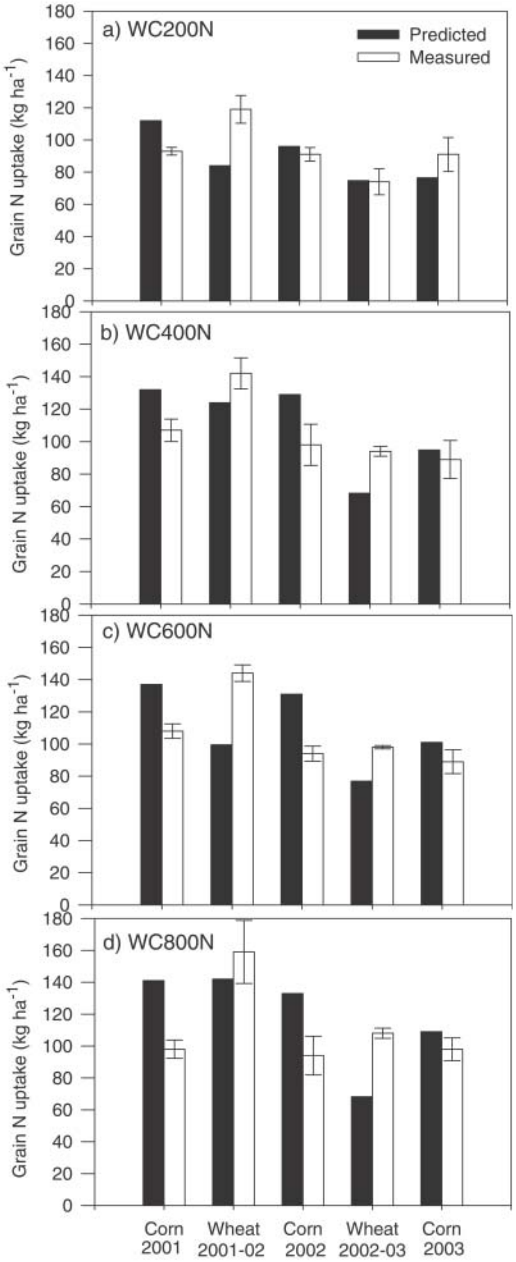

Fig. 8. Comparison between the model-predicted and measured grain N uptake for the 200, 400, 600, and 800 kg N ha^{-1} yr^{-1} (WC200N, WC400N, WC600N, and WC800N, respectively) treatments during 2001 to 2003. Error bars represent ± one standard deviation of the measured grain N uptake from the mean of replications.

During calibration, the REs of residual NO_3–N in the soil at harvest simulations ranged from −16 to 61% for the five cropping seasons, with an RMSE of 39 kg ha^{-1}.

Sixteen out of 20 (including the calibration treatment) residual soil N predictions were within 1 SD of the mean of the measured values (Fig. 9). During validation, the highest prediction errors were for the WC200N and WC600N experiments, with their predicted five-crop-season mean residual N amount deviating from the measured by −14% for WC600N and 14% for WC600N. Errors of this magnitude may not be very serious, taking into account the uncertainty involved in the field quantification of this parameter, and the bias (MRE) is relatively low.

Simulated Nitrogen Losses

No field-measured values of volatilization, seepage, and denitrification losses of N from the crop–soil environments are available for this study. We compared the model predictions of these variables with those reported in the literature. Li et al. (2001), Wang et al. (2002), and Cai et al. (2002) reported volatilization losses of 10 to 37, 18, and 1 to 18% of applied N in the field, respectively. The predicted N volatilization losses increased with N application rate

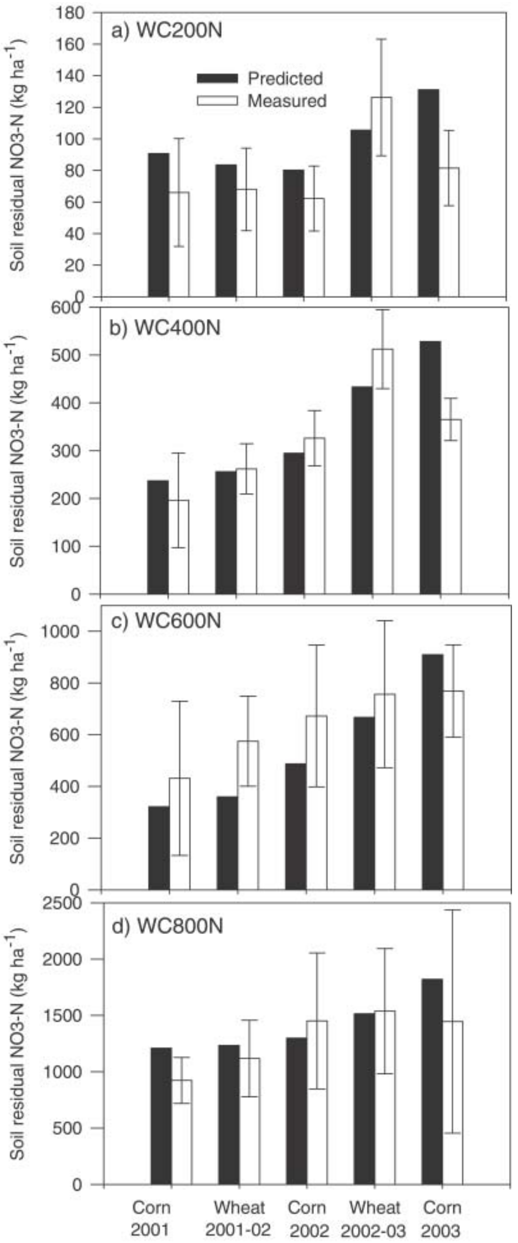

Fig. 9. Comparison between the model-predicted and measured soil residual NO_3–N (0–180 cm) at harvest of the crops for the 200, 400, 600, and 800 kg N ha^{-1} yr^{-1} (WC200N, WC400N, WC600N, and WC800N, respectively) treatments during 2001 to 2003. Error bars represent ± one standard deviation of the measured soil residual NO_3–N from the mean of replications.

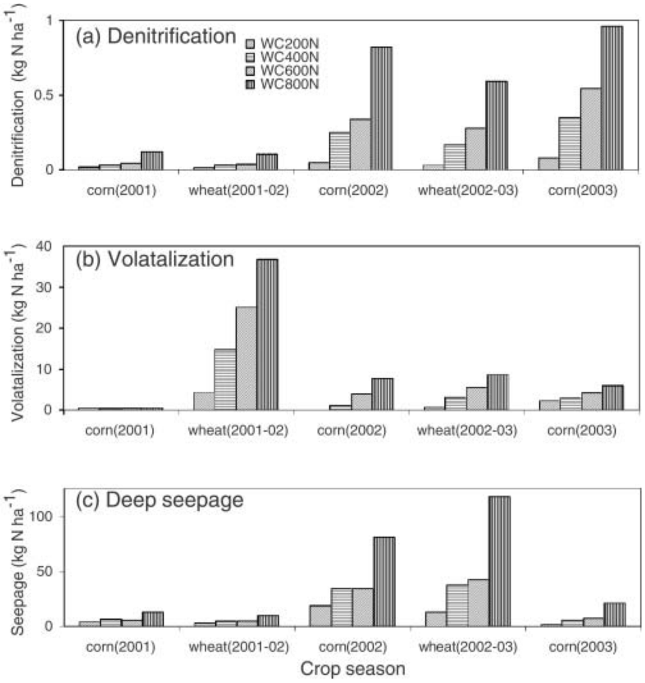

Fig. 10. The RZWQM-predicted N losses due to denitrification, volatilization, and deep seepage per crop season in the wheat–corn double cropping system under 200, 400, 600, and 800 kg N ha^{-1} yr^{-1} (WC200N, WC400N, WC600N, and WC800N, respectively) treatments.

from 2 to 13% (Table 7). Cai et al. (2002) reported a 1.8% denitrification loss of applied N in the field, whereas the simulated denitrification losses ranged from 0.2 to 0.4% for various N application rates. In general, model predictions were reasonably close to the values reported for the region. Numerical simulations showed consistent increases in N losses due to volatilization, seepage, and denitrification with increased N application rates (Table 7, Fig. 10). Simulation results also show that NH_3 volatilization and N seepage are the main sources of loss of fertilizer-applied N. Nitrogen lost through deep seepage is a potential source for contamination of groundwater in these areas with increased application rates in agriculture (Zhang et al., 1995, 2003), requiring more attention for its control through proper N fertilizer and water management.

The simulation results of N losses across crop seasons from 2001 to 2003 show that the volatilization loss is higher than average for the wheat crop season 2001–2002. The relatively dry 2001 and early half of 2002, with only about 134 mm of rainfall recorded during the wheat season (data not shown), resulted in low soil profile

Table 7. Model predicted total initial, applied, and mineralized N; volatilization, seepage, and denitrification losses of N; and N uptake, residual N at harvest and N efficiency (NUE) for the five crop seasons under various N treatment rates. All N values refer to inorganic N.

Trial	Initial soil N (measured)	N applied	N Mineralized	Volatilization	Seepage	Immobilization	Denitrification	Plant N uptake	Residual N†	NUE‡ (Measured values in parentheses)
	kg ha^{-1} (0–220 cm simulated depth)									
WC200N	187	500	411	8	41	59	0.3	850	140	0.84 (0.85)
WC400N	386	1000	402	22	88	58	0.8	1008	611	0.64 (0.50)
WC600N	450	1500	401	40	95	60	1.2	1006	1145	0.41 (0.34)
WC800N	1500	2000	400	60	242	61	2.6	1059	2471	0.27 (0.31)

† Residual N on the harvest date of the 5th crop in the simulation study. As the field experiment started in the year 1998, amount of residual N presented here represents the cumulative effect from 1998 to 2003.

‡ NUE = (plant N uptake under a particular) N treatment−plant N uptake at of the 0 kg N ha^{-1} treatment)/amount of N applied.

water storage (Fig. 3). Higher recorded air temperatures (data not shown) resulted in increased NH_3 volatilization losses during this period. The simulations also showed that N seepage losses were higher than average for the corn crop season of 2002 and for the wheat crop season of 2002–2003. The relatively wet latter half of 2002 and 2003 (262 mm of rainfall received during the corn season and 172 mm of rainfall during the wheat season), combined with irrigation (Table 1), resulted in greater seepage losses of water and N from the root zone.

Accumulation of inorganic N in the soil profile accompanies increased N leaching (seepage) as fertilizer amounts are increased under full irrigation rates (Table 7). This indicates excess amounts of both N and water in the soil profile, which are not taken up by the crop. Table 7 also shows increased accumulation of N during the simulation period with increasing application rate, but the N dynamics are not shown here. Due to the relatively short experimental period (1998–2003), full dynamic equilibrium in soil profile N has not been obtained, particularly at the highest application rate. Because crops are planted soon after the harvest of the previous crop in the double-cropping system, the soil residual N generally will be available for use by the subsequent crop. As the rate of N application increases, the inorganic N left in the soil at harvest may not be taken up fully by the subsequent crop. This residual N will be subject to leaching to groundwater when rainfall occurs between crop seasons, potentially causing serious environmental degradation in the region.

Nitrogen Use Efficiency

Nitrogen use efficiency is defined as

$$\text{NUE} = \frac{\text{Plant N uptake under a particular N treatment} - \text{Plant N uptake of the 0 kg N ha}^{-1}\text{ treatment}}{\text{amount of N applied}}$$

The NUE of different N treatments were computed for both measured and model-predicted scenarios (Table 7). To make comparisons of NUE for the different N rates without a control experiment with a zero-N treatment, the calibrated model was run with a zero-N rate and the results were used in the NUE computations of both measured and model-predicted cases. Predicted NUE was in close agreement with the measured values (Table 7). The highest NUE was observed for the 200 kg N ha^{-1} yr^{-1} treatment in both model-predicted and measured cases.

Nitrogen and Water Management

Differences in predicted grain yield, biomass, and plant N uptake between irrigation treatments at the full rate (Table 1) and 50% of the full rate were not found to be statistically significant in a paired *t*-test ($p = 0.17$); however, predicted values of these variables at 0 and 25% of the full rate were significantly different ($p = 0.02$) from those at the full rate.

Model simulations showed that about 10% of the water applied at the full rate was lost to deep seepage out of the root zone of the crop vs. 1% in the 50% irrigation. In Table 8, predicted deep seepage loss of N to groundwater in the full irrigation treatment (41 kg ha^{-1}) was about 10 times more than that predicted for the 50% irrigation experiment (4 kg ha^{-1}). This low seepage rate explains the insensitivity of N seepage to further reductions in irrigation or increased N application rates.

Plant N uptake for the full and 50% irrigation rate treatments were similar (Table 8). The NUE of the 50% irrigation rate treatment was higher (0.98) than the full irrigation rate treatment (0.83). Volatilization loss at the 50% irrigation rate increased by 50% compared with the full irrigation rate, but this loss was more than compensated by the reduction in seepage loss. Residual N in the soil at harvest in the full irrigation rate and 50% rate treatments were about the same, but increased considerably with a further decrease in irrigation amount due to the combination of limited plant uptake and seepage (Table 8). Considering all of the above aspects of N dynamics in the soil–crop systems, the irrigation at 50% of the full rate can be considered the optimum needed for both crop yield and environmental quality. Reducing water use this much has additional environmental and societal benefits in terms of improved groundwater quality and quantity.

Table 8. Summary of crop yield, N inputs plant N uptake, NUE, and N losses due to volatilization, seepage, and denitrification predicted by RZWQM for the five crop seasons of 2001 through 2003 for 0 to 100% irrigation levels with 200 kg N ha^{-1} yr^{-1} N rates, and 0 to 800 kg N ha^{-1} yr^{-1} N rates with 50% irrigation in the corn–wheat double cropping system.

	Avg. crop yield		Total N input†			Total N losses†				
Management	Corn	Wheat	Initial	applied	Mineralized	Plant uptake‡	N-seepage	Soil Residual	Volatilization	NUE§
	kg ha^{-1} (0–220 cm simulated depth)									
Irrigation rates under N at 200 kg ha^{-1}										
Full rate (as applied now)	6049	3931	187	500	411	850	41	140	8	0.83
50% of full rate	6276	3613	187	500	383	850	4	142	12	0.98
25% of full rate	4997	2600	187	500	354	755	2	203	18	0.81
0% of full rate	4190	1871	187	500	361	598	2	340	48	0.53
N rates under 50% Irrigation¶										
0 kg N ha^{-1} yr^{-1}	3927	2823	187	0	311	360	3	29	3	–
50 kg N ha^{-1} yr^{-1}	4739	3304	187	125	348	531	3	34	4	1.37
100 kg N ha^{-1} yr^{-1}	5210	4120	187	250	354	661	4	49	6	1.20
200 kg N ha^{-1} yr^{-1}	6276	3613	187	500	383	850	4	142	12	0.98
400 kg N ha^{-1} yr^{-1}	6880	3845	187	1000	383	1106	4	362	32	0.75
600 kg N ha^{-1} yr^{-1}	6715	3525	187	1500	386	1013	4	910	73	0.44
800 kg N ha^{-1} yr^{-1}	6829	3632	187	2000	385	1058	4	1310	265	0.35

† Total over five crop seasons (i.e., 2.5 yrs.).

‡ Includes both above and below ground biomass.

§ NUE may exceed unity for: NUE = (plant N uptake under a particular) N treatment − plant N uptake at of the 0 kg N ha^{-1} treatment)/amount of N applied.

¶ Total N applied in two crop seasons (i.e., 1 yr of double cropping).

The 50% irrigation rate was further evaluated for optimizing the N application rate. The RZWQM model was run for the five cropping seasons, with N rates of 0, 50, 100, 200, 400, 600, and 800 kg N ha^{-1} yr^{-1} under irrigation at 50%. For N rates of 200 kg ha^{-1} yr^{-1}, average predicted grain yields were 6276 and 3613 kg ha^{-1} for corn and wheat, respectively, and the predicted total plant N uptake was 850 kg N ha^{-1} (Table 8). Nitrogen use efficiencies were >0.98 for N rates of 200 kg ha^{-1} yr^{-1} and below. Deep N seepage losses remained more or less constant, with an average value of 4 kg ha^{-1} yr^{-1} for N rates of 50, 100, and 200 kg ha^{-1} yr^{-1}. Nitrogen seepage losses did not increase with increased fertilizer rates at the 50% irrigation rate. Predicted N volatilization losses were 8, 6, 6, 8, 12, and 33% of the total applied N for N rates of 50, 100, 200, 400, 600, and 800 kg ha^{-1} yr^{-1}, respectively. Residual soil N at harvest at the end of five cropping seasons for the 400, 600, and 800 kg N ha^{-1} yr^{-1} treatments were higher by 220, 768, and 1168 kg ha^{-1} compared with the 200 kg N ha^{-1} yr^{-1} treatment (142 kg N ha^{-1}). Again, N accumulated in the soil profile due to limitations in plant uptake and seepage under reduced irrigation. During longer periods, some of the accumulated N would be leached from the soil profile in very wet years. Extrapolation to longer time periods is possible with the model, but was not pursued in this study. Taking into account the plant N uptake, NUE, residual N accumulation in the soil, and volatilization, the 200 kg N ha^{-1} yr^{-1} N treatment with 50% of the existing irrigation level is recommended for water and N management in the corn–winter wheat double-cropping system in the NCP. These values could be further refined with higher resolution optimization, but the main effects of water and N have been identified here.

CONCLUSIONS

The RZWQM model was evaluated for modeling a double-cropping system comprised of winter wheat and corn (two crops per year) in the NCP. This is the first evaluation of RZWQM for modeling a double-cropping system. Grain yield, biomass, N uptake, soil water content (total profile and at soil depths), and residual NO_3–N were selected as indicators of model performance, because both production and environmental quality should be considered. Testing of the model against observed data for five cropping seasons during the 3-yr period under four different N treatments indicated that the model is able to simulate many variables of the winter wheat–corn double-cropping system reasonably well. As such, the model has potential for developing sustainable N and water management practices. The best predictions were obtained for grain yield, biomass, and soil water content. The model was able to simulate the wet and dry periods of water in the soil profile. Plant N uptake and residual soil NO_3–N at harvest were predicted with a lesser degree of accuracy in comparison to biomass, grain yield, and soil water. Attempts to rectify this problem through better calibration of the model did not lead to improved results. The generic plant model needs to be improved further to get better predictions of crop N uptake.

Taking into account the variability in the measured values of soil residual NO_3–N, the model predictions were accurate enough to provide guidance for decision making. The simulated N losses indicated that increased N application rates will result in increased N losses by volatilization, seepage, and denitrification. Although we do not have field data for verification of these results in this case, the results fall within the range of values reported in the literature. The simulation results showed that as much as half of the applied N at 800 kg N ha^{-1} yr^{-1} can be lost through the combined effects of volatilization, seepage, and denitrification. At the present irrigation rate, seepage losses (N leaching) increased by more than 200 kg ha^{-1} across the range of application rates. In an initial attempt to optimize the N and water application rates at the location using the validated model, we found that an N rate of 200 kg N ha^{-1} yr^{-1} with irrigation at 50% of the current application rate will give near-optimum grain yields with reduced contamination of the environment.

High levels of agricultural production in the NCP depend largely on irrigation. Like many other locations worldwide, irrigation is causing rapid declines in the groundwater table, at local rates of 0.8 to 1.0 m yr^{-1} (Hu and Yin, 1999). This is a serious concern for agricultural sustainability. Water-saving agricultural practices for reducing irrigation and a net reduction in the crop evapotranspiration losses are necessary to slow down the groundwater table decline. Reducing irrigation by 50% in this region could stabilize the groundwater table (Hu and Yin, 1999), because most of the excess irrigation water is evaporated. Thus, the findings of this study have important implications for groundwater management in the NCP. These conclusions are preliminary, but the resource, environmental, and socioeconomic implications of reducing water and N inputs by approximately 50% are dramatic. To make more concrete and precise recommendations, the model needs to be run with many years of weather data to incorporate the climate variability impacts on crop productivity in this area.

Finally, N application in excess of crop requirements is a potential source for contamination of groundwater, and the N volatilization flux from the applied fertilizer on agricultural lands is a potential source of greenhouse gases in the atmosphere that can contribute to global warming. The calibrated and tested RZWQM model can be a useful tool for developing management practices to alleviate these problems.

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