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Agricultural Systems 89 (2006) 457–477
AGRICULTURAL SYSTEMS
www.elsevier.com/locate/agsy

Modeling a wheat–maize double cropping system in China using two plant growth modules in RZWQM

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Received 21 January 2005; received in revised form 28 September 2005; accepted 27 October 2005

Abstract

Agricultural system models are potential tools for evaluating soil-water–nutrient management in intensive cropping systems. In this study, we calibrated and validated the Root Zone Water Quality Model (RZWQM) with both a generic plant growth module (RZWQM-G) and the CERES plant growth module (RZWQM-C) for simulating winter wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) double cropping systems in the Northern China Plain (NCP), China. Data were obtained from an experiment conducted at Yucheng Integrated Agricultural Experimental Station (36°57′N, 116°36′E, 28 m asl) in the North China Plain (NCP) from 1997 to 2001 (eight crop seasons) with field measurements of evapotranspiration, soil water, soil temperature, leaf area index (LAI), biomass and grain yield. Using the same soil water and nutrient modules, both plant modules were calibrated using the data from one crop sequence during 1998–1999 when detailed measurements of LAI and biomass growth were available. The calibrated models were then used to simulate maize and wheat production in other years. Overall simulation runs from 1997 to 2001 showed that the RZWQM-C model

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doi:10.1016/j.agsy.2005.10.009

simulated grain yields with a RMSE of 0.94 Mg ha^{-1} in contrast to a RMSE of 1.23 Mg ha^{-1} with RZWQM-G. The RMSE for biomass simulation was 2.07 Mg ha^{-1} with RZWQM-G and 2.26 Mg ha^{-1} with RZWQM-C model. The RMSE values of simulated evapotranspiration, soil water, soil temperature and LAI were 1.4 mm, 0.046 m^3 m^{-3}, 1.75 °C and 1.0 for RZWQM-G and 1.4 mm, 0.047 m^3 m^{-3}, 1.84 °C and 1.1 for RZWQM-C, respectively. The study revealed that both plant models were able to simulate the intensive cropping systems once they were calibrated for the local weather and soil conditions. Sensitivity analysis also showed that a reduction of 25% of current water and N applications reduced N leaching by 24–77% with crop yield reduction of 1–9% only.

Keywords: Agricultural system; Crop growth model; Evapotranspiration; Soil water; Soil temperature; Wheat; Maize; North China Plain

1. Introduction

The North China Plain (NCP) is the largest region of agricultural importance in China. It lies in Northeastern China between 32–40°N and 114–121°E, covering about 18 million hectares of farm lands (18.3% of the national total) and producing about 21.6% of the total grain yield of edible crops and more than 36.2% of the total cotton yield of the country. In the NCP, wheat grain yield increased from 2.27 Mg ha^{-1} in 1980 to 4.69 Mg ha^{-1} in 2000, and maize grain yield from 3.18 to 5.27 Mg ha^{-1}, while fertilizer application increased from 102 kg ha^{-1} yr^{-1} in 1980 to 612 kg ha^{-1} in 2000 (China Statistics Bureau, 2001). Climatically, there are marked interannual and seasonal variations in precipitation and temperature in this area. While 80% of the annual precipitation is concentrated in the summer months (from June to September), spring is typically dry. Precipitation decreases from 900 mm yr^{-1} near the Huaihe river in the south to 480 mm yr^{-1} in the northern part of the NCP. Winter wheat–maize double crop rotations (two crops harvested in a year) dominate cropping systems in the region. Due to sparse rainfall and associated soil water deficit, winter wheat crops are usually irrigated. Since the 1970s, the NCP has been confronted with serious challenges associated with increased water deficit and water quality degradation. More than 50% of the irrigated land uses groundwater, causing groundwater levels to decline at an average rate of about 1 m yr^{-1} in the past two decades in the NCP (Hu et al., 2005). In order to meet the increasing need for grain and fiber, intensive agricultural management prevails in the region with over-application of fertilizer and increased crop water needs. Nitrogen fertilizer plays a critical role in producing high yields; however, its over-use results in decreased economic returns and declines in surface and groundwater quality. Continuation of the current agromanagement practices can pose a big challenge to sustainable agricultural production in the NCP (Hu et al., 2005).

Agricultural scientists and planners in the area are being confronted with the task of developing timely and viable alternative soil-water–crop management systems to counteract the current downward trends in environmental degradation and agricultural productivity. To address these emerging challenges in agriculture, there is an urgent need to synthesize experimental research results from various disciplines at the agricultural system level that will lead to improved management practices (Peterson et al., 1993). Agricultural system models that integrate information from processes and field experiments are being recognized as viable solutions in this direction (Elliott and Cole, 1989; Mathews et al., 2002). For adaptation and application of state-of-the-art agricultural system models for such purposes, they need to be well-calibrated and thoroughly validated for their performance in the agroclimate of the region.

Use of crop simulation models to evaluate crop production systems in the NCP has been rare. Recently, Hu et al. (2006) used the generic crop module in RZWQM (Root Zone Water Quality Model; Ahuja et al., 2000b), referred to herein as RZWQM-G, to evaluate and develop nitrogen and water management strategies in a winter wheat–maize double cropping system at Luancheng experimental station in the NCP. They found that RZWQM-G was useful for simulating grain yield, biomass, N uptake and soil water content. Recently, Ma et al. (2006) linked the CERES crop growth module with RZWQM (RZWQM-C). However, no evaluation of RZWQM-C was done for winter wheat. The main objective of this study was to evaluate how well RZWQM can simulate the winter wheat–maize double cropping systems using the generic plant growth module (Hanson, 2000) and the CERES crop growth modules (Ma et al., 2006) based on experiments conducted at the Yucheng Experimental Station in NCP. Building on the previous study by Hu et al. (2006), this study compares the RZWQM-G and RZWQM-C models for simulating yield, biomass, leaf area index, soil water, evapotranspiration, and soil temperature. Comparing the two plant growth modules using the same soil water and nutrient modules may be insightful for further model development. The validated models were further utilized to evaluate the current water and N management in terms of crop production and N leaching.

2. Materials and methods

Winter wheat–maize double cropping experiments were conducted at Yucheng Integrated Agricultural Experimental Station (36°57′N, 116°36′E, 28 m above sea level), NCP, China from 1997 to 2001. The NCP of China is an alluvial plain of the Yellow River with predominantly silty loam soil (Argic Rusty Ustic Cambisols) (Zitong, 1999). The climate of the NCP is temperate monsoonal with rainfall concentrated in the summer months. An automatic weather station AMRS-I (Changchun Meteorological Equipment Company, China) was used to measure daily solar radiation, air temperature, relative humidity, rainfall and wind speed. Soil temperature was measured hourly at depths of 0, 5, 10, 15, 20, 40, 60, and 100 cm beneath the ground. Significant inter-annual variability was observed in the annual rainfall received (from 400 to 842 mm) at the location during the experimental period (Table 1).

Winter wheat (variety Zhixuan 1) and maize (variety Yedan 22) were used. Crop varieties, and fertilizer and irrigation amounts were kept constant throughout the experiment (1997–2001). Chicken manure was applied at a rate of 1000 kg ha^{-1}

Table 1
Precipitation (mm) recorded at the experimental site from October 1997 to December 2001

Month	1997	1998	1999	2000	2001
January		1	0	12	40
February		25	0	11	25
March		24	19	1	4
April		19	21	24	16
May		132	55	23	3
June		33	99	55	164
July		119	77	182	182
August		209	24	198	195
September		15	33	107	109
October	0	9	61	103	104
November	0	0	11	0	0
December	0	0	0	0	0
Yearly	–	586	400	717	842

before sowing winter wheat each year. Urea was surface broadcast at 100 kg N ha^{-1} on 6 March, 15 April, 12 May, 5 July, 5 August, 5 September, and 5 October every year. Primary tillage to a depth of 15 cm using a moldboard plow for winter-wheat and secondary tillage to a depth of 5 cm using cultivators for maize were conducted. Irrigation amount and timing are listed in Table 2. Soil water content was measured

Table 2
Irrigation amounts and dates from 1997 to 2001

Crop	Date	Irrigation amount (mm)
Wheat	05-Oct-1997	38
Wheat	06-Mar-1998	38
Wheat	15-Apr-1998	38
Wheat	12-May-1998	38
Maize	10-Jun-1998	67
Maize	02-Aug-1998	67
Maize	05-Sep-1998	20
Wheat	30-Nov-1998	100
Wheat	22-Mar-1999	100
Wheat	24-Apr-1999	100
Wheat	12-May-1999	100
Maize	15-Jun-1999	50
Maize	10-Aug-1999	100
Wheat	08-Apr-2000	50
Wheat	28-Apr-2000	80
Wheat	28-May-2000	100
Maize	08-Jul-2000	50
Maize	08-Aug-2000	100
Wheat	15-Oct-2000	20
Wheat	23-Mar-2001	30
Wheat	02-Apr-2001	30
Wheat	07-May-2001	30
Maize	20-Jun-2001	30

with a neutron probe down to 220 cm depth at 10-cm intervals. Actual evapotranspiration (AET) was measured daily with a weighing lysimeter (diameter: 2 m, depth: 5 m, and weight with soil: approximately 34 Mg) with a precision of 0.04 mm day^{-1} (Yang et al., 2000). Above-ground biomass (5-day intervals), leaf area index (LAI) (5-day intervals), and grain yield of both winter wheat and maize were measured. Above-ground biomass was measured by harvesting a 1-m^2 area. LAI was measured in situ at 5-day intervals with a CID-201™ instrument (CID Inc, USA). Grain yields were recorded by harvesting a subplot of 200 m^2.

Three statistics were used to evaluate simulation results: (i) Root Mean Square Error (RMSE), Eq. (1), between simulated and observed values; (ii) Mean Relative Error (MRE), Eq. (2), which gives the bias of the simulated versus observed values; and (iii) Model Efficiency (E, between measured and simulated variables), Eq. (3).

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

$$\mathrm{MRE} = \frac{1}{n}\sum_{i=1}^{n}\frac{(P_i - O_i)}{O_i}100\% \tag{2}$$

$$E = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - O_{\mathrm{avg}})^2} \tag{3}$$

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

2.1. Model description

2.1.1. RZWQM

RZWQM is an agricultural system model that integrates biological, physical and chemical processes and simulates the impact of soil-water–crop management practices on agricultural production and soil-water quality (Ahuja et al., 2000b). RZWQM has a detailed soil-water balance module that uses the Green-Ampt equation for water infiltration and the Richards' equation for redistribution of water among different soil layers (Ahuja et al., 2000a). Potential evapotranspiration is calculated using the extended Shuttleworth–Wallace equation modified to include the surface crop residue dynamics on aerodynamics and energy fluxes (Farahani and DeCoursey, 2000). The soil carbon/nitrogen dynamic module contains two surface residue pools, three soil humus pools and three soil microbial pools. N mineralization, nitrification, denitrification, ammonia volatilization, urea hydrolysis, methane production, and mircrobial population processes are simulated in reasonable detail (Shaffer et al., 2000). Management practices simulated in the model include: tillage; applications of manure and fertilizers; planting and harvesting operations; irrigation; and surface crop residue dynamics (Rojas and Ahuja, 2000).

In the RZWQM, soil temperature is calculated by assuming that the water moving through the soil carries heat energy proportional to the specific heat of water to deeper layers similar to piston displacement during rainfall and irrigation events (Ahuja et al., 2000a). During non-rainy periods, conduction of heat between soil layers also takes place by solving the heat equation. Surface soil (1 cm) temperature is assumed equal to the average air temperature of the day. The model does not take into account soil freezing and thawing effects. When snow covers the soil surface, the surface soil temperature is assumed to be 0 °C.

2.1.2. Generic plant growth model in RZWQM

RZWQM has a generic plant growth model that can be parameterized for simulating specific crops. Phenological development is not explicitly simulated; however, it is handled through seven growth stages: (1) dormant seeds, (2) germinating seeds, (3) emerged plants, (4) established plants, (5) plants in vegetative growth, (6) reproductive plants, and (7) senescent plants. Plants advance from one growth stage to another after meeting a predefined minimum days modified by an environmental fitness function representing water, nitrogen, and temperature stresses. The generic plant growth model of RZWQM has been parameterized for simulation of maize, soybean and winter wheat crops (Ma et al., 2000, 2001; Saseendran et al., 2004, 2005). RZWQM using the generic plant growth module is denoted as RZWQM-G.

2.1.3. CERES-wheat and CERES-maize in RZWQM

The CERES-wheat and CERES-maize plant growth models were from DSSAT 3.5 (Decision Support System for Agrotechnology Transfer) package (Tsuji et al., 1994; Hoogenboom et al., 1999; Jones et al., 2003). Recently, the CERES plant growth modules of DSSAT were coupled with the soil water and nitrogen simulation routines of RZWQM and developed the RZWQM-CERES Hybrid (Ma et al., 2006) model. The CERES plant growth module simulates detailed yield components, leaf numbers, and phenological and morphological developments of the crop. The hybrid model provided users not only with detailed simulations of soil surface residue dynamics, tillage and other soil management practices, and detailed soil water and soil carbon/nitrogen process but also with detailed plant growth. The hybrid model has been tested for maize production only (Ma et al., 2006) and not tested for wheat production. RZWQM using the CERES plant growth module is denoted as RZWQM-C.

2.2. Model parameterization and calibration

The minimum driving variables for RZWQM are daily solar radiation, maximum and minimum temperature, and rainfall. Soil parameters are essential in simulation, where soil water supply is a critical constraint for crop production. Soil hydraulic conductivity, maximum crop rooting depth, and upper and lower limits of water content are required. Typical crop management factors include planting dates, planting depth, row spacing, and plant population. Also, the amount and method of irrigation and fertilization are required.

For accurate simulations, the models need to be calibrated for soil hydraulic properties, nutrient properties and plant growth parameters for the site and crops simulated (Hanson et al., 1999). Both RZWQM-G and RZWQM-C models have common soil water, soil nutrient/carbon, and crop–soil-water management modules but different crop modules. Hence, separate calibrations are needed only for the crop specific parameters of these models. Calibrations of the models were conducted following the procedures laid out by Hanson et al. (1999) and Ahuja and Ma (2002). We calibrated both models for simulation of winter wheat and maize using the same winter wheat–maize double crop sequence experiment during 1998–1999. Also, both models were run with the same initial conditions and crop, soil, and water management inputs. Furthermore, the same calibration procedures and objective functions, i.e. RMSEs of biomass growth pattern (5 day intervals), LAI development (5 day intervals), soil water in different soil layers, actual evapotranspiration (Lysimetric - daily), and soil temperature in different soil layers (daily) were used.

For simulation of soil-water balance, each soil horizon needs to be defined in terms of its physical (bulk density, particle density, porosity, and texture) and hydraulic properties. Hydraulic properties are defined in RZWQM using the Brooks and Corey (1964) functions with slight modifications (Ahuja et al., 2000a). The Brooks–Corey parameters compiled by Rawls et al. (1982) for the 11 soil textural classes are available in the soil database for use if measured values are not available. In this study, we did not have field measurements of soil hydraulic properties. Hence, the default soil hydraulic properties for a silty loam soil were used (Rawls et al., 1982).

Calibration of the soil nutrient component of the model involves establishment of initial C/N (Soil Carbon–Nitrogen) pool sizes for the fast and slow residue pools; slow, medium, and fast humus pools; and the three microbial pools (aerobic heterotrophs, autotrophs, and anaerobic heterotrophs) (Hanson et al., 1999). In this experiment, we had measured values of soil organic matter contents, which were used to initialize the different residue, soil humus, and microbial pools (Ahuja et al., 2000b; Ma et al., 1998). Crop growth modules of RZWQM-G and RZWQM-C models were calibrated last.

2.2.1. *Calibration of the generic plant growth module in RZWQM*

Procedures and methods for calibrating the generic plant growth parameters for RZWQM-G were described in Hanson et al. (1999) and Ahuja and Ma (2002). Calibration of model parameters for the maize cultivar "Yedan22" and for winter wheat cultivar "Zhixuan 1" used in the study for NCP climate were based on Ma et al. (2003) and Saseendran et al. (2004), respectively, and the calibrated parameters are listed in Table 3. These parameters were calibrated based on field-measured grain yield, biomass, and LAI of one winter wheat–maize double crop sequence during 1998–1999 when detailed measurements of LAI and biomass were available. We used a direct (grid) search for optimization of the crop parameters by increments of 5% at a time between specified lower and upper bounds, based on literature and default values available. The combination of these parameters with the lowest RMSE in

Table 3
Calibrated generic plant growth parameters in RZWQM-G for simulation of wheat (cv. Zhixuan 1) and maize (cv. Yedan 22) in the North China Plain

Parameter	Value	
	Maize	Wheat
Maximum active N uptake rate (g plant^{-1} day^{-1})	2.5	0.5
Daily respiration as a function of photosynthate (fraction)	0.01	0.005
Biomass to leaf area conversion coefficient (g LA^{-1})	7.4	1.2
Age effect on photosynthesis in the propagule development stage (fraction)	1	0.9
Age effect on photosynthesis in the seed development stage (fraction)	1	0.3
Maximum rooting depth (m)	2.5	2.0
Minimum leaf stomatal resistance (s m^{-1})	200	200
Nitrogen sufficiency index (fraction)	1.0	NA
Luxurious nitrogen uptake factor (fraction)	1.0	NA
Minimum time for seeds to germinate (days)	2	2
Minimum time for seedling to emerge (days)	6	8
Minimum time for plants to establish (days)	5	11
Minimum time for plants to complete vegetative stage (days)	37	148
Minimum time for plants to complete reproductive stage (days)	28	35

NA – not applicable for wheat crop.

the simulations of grain yield, biomass, and soil-water content was selected as the final estimates of these parameters.

2.2.2. Calibration of the CERES (wheat and maize) plant growth module in RZWQM

We also used final grain yield, biomass growth, and LAI of both winter wheat and maize crops in the double cropping sequence during 1998–1999 to compute the genetic coefficients for CERES-wheat and CERES-maize modules in RZWQM-C

Table 4
Genetic coefficients developed for simulation of winter wheat (cv. Zhixuan 1) using the RZWQM-C model

No.	Parameter	Value	Range
1	Relative amount that development is slowed for each day of unfulfilled vernalization, assuming that 50 days of vernalization is sufficient for all cultivars	6	(0.5–8.0)
2	Relative amount that development is slowed when plants are grown in a photoperiod 1 hour shorter than the optimum (which is considered to be 20 h)	3.5	(2.0–4.0)
3	Relative grain filling duration based on thermal time (degree-days above a base temperature of 1 °C), where each unit increases above zero adds 20 degree-days to an initial value of 430 degree-days	0.0	(0.0–9.0)
4	Kernel number per unit weight of stem (less leaf blades and sheaths) plus spike at anthesis (1/g)	9.0	(2.0–10.0)
5	Kernel filling rate under optimum conditions (mg/day)	1.4	(1.0–5.0)
6	Non-stressed dry weight of a single stem (excluding leaf blades and sheaths) and spike when elongation ceases (g)	1.4	(1.0–2.0)
7	Phyllochron interval (°C)	85	(60–90)

Values given in brackets are the range used in calibration of the parameter.

Table 5
Genetic coefficients developed for simulation of maize (cv. Yedan 22) using the RZWQM-C model

No.	Parameter	Value	Range
1	Thermal time from seedling emergence to the end of Juvenile phase during which the plants are not responsive to changes in photoperiod (degree-days)	140	(100–500)
2	Extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development is at maximum rate, which is considered to be 12.5 h (days)	0.9	(0.0–1.0)
3	Thermal time from silking to physiological maturity (degree-days)	735	(500–900)
4	Maximum possible number of kernels per plant	837	(500–900)
5	Kernal filling rate during the linear grain filling stage and under optimum conditions (mg/day)	11.0	(4.0–12.0)
6	Phyllochron interval (degree-days)	38	(35–55)

Values given in brackets are the range used in calibration of the parameter.

model. Godwin et al. (1989) suggested an iterative approach to reach reasonable estimates of the genetic coefficients of DSSAT crop models through trial-and-error adjustments to match the observed phenology and yield with simulated values, if the data for calibration of the genetic coefficients are limited. Following this approach, we used a direct (grid) search for optimization of the crop parameters by increments of 5% at a time between specified lower and upper bounds (Table 4 for wheat and Table 5 for maize). The combination of cultivar parameters that gave the minimum RMSE were selected (Tables 4 and 5) and used in further validation of the model.

3. Results and discussion

3.1. Model calibration

Both models were calibrated to similar levels of accuracy for grain yield, LAI development, soil water content, evapotranspiration (ET), and soil temperature for the 1998–1999 crop seasons (Table 6), but accuracy in the case of above-ground biomass differed greatly between the models. Harvested biomass was under-simulated by 13% for wheat and 28% for maize using RZWQM-G, and by 13% for wheat and 24% for maize using RZWQM-C. Simulated wheat yield was 5.02 Mg ha^{-1} by RZWQM-G and 4.92 Mg ha^{-1} by RZWQM-C, which was close to the measured value of 5.38 Mg ha^{-1}. Simulated maize yield was 10.70 Mg ha^{-1} by RZWQM-G and 10.20 Mg ha^{-1} by RZWQM-C with measured yield of 11.88 Mg ha^{-1}. After calibration, the models were then run for all the eight cropping seasons from 1997 to 2001.

3.2. Model validation

3.2.1. Soil temperature

In general, soil temperature simulations in the 5, 10, 15, 20, and 60 cm soil layers from 1997 to 2001 by both RZWQM-G and RZWQM-C models correctly

Table 6
Root Mean Square Errors (RMSE) for model calibrations using data from 1998 to 1999 crop growing seasons

Variables	Winter wheat		Maize	
	RZWQM-G	RZWQM-C	RZWQM-G	RZWQM-C
Soil water ($m^3 m^{-3}$)	0.045	0.046	0.041	0.037
Soil water storage (cm)	3.83	4.08	4.87	4.38
ET (mm day^{-1})	1.47	1.43	2.02	2.21
LAI	1.66	1.30	0.54	1.23
Soil temperature (°C)	1.61	1.68	1.87	1.93
Biomass (Mg ha^{-1})	0.94	1.98	2.58	2.36

Note. As grain yield was measured only at harvest, no RMSE was calculated.

followed the measured seasonal patterns (Fig. 1), but day to day fluctuations in temperature in these soil layers were not captured well (with RMSE values across soil layers of 1.75 °C for RZWQM-G and 1.84 °C for RZWQM-C). Overall, both models under-estimated soil temperature slightly (Table 7). RMSEs of soil temperature simulations in different soil layers ranged from 1.81 to 1.98 °C with RZWQM-G and 1.67 to 1.93 °C with RZWQM-C. The difference in soil temperature simulations between the models reflects the difference in the amount of soil water (and the heat energy it carries) removed from different soil layers to meet crop ET requirements as simulated by the different crop modules of RZWQM-G and RZWQM-C models.

Departure of daily soil temperature simulations from measured values in different soil layers ranged from −8 to +8 °C. One reason for high simulation errors in soil temperature simulations is the assumption of an average atmospheric temperature as the upper boundary condition for soil heat flux in the soil temperature module in RZWQM (Flerchinger et al., 2000b). Effects of standing and flat crop residue on surface soil water and heat flux were also not considered in the current version of RZWQM (Flerchinger et al., 2000a). Soil freezing processes also were not simulated (Flerchinger et al., 2000b). Incorporation of these processes and factors can lead to improvement of soil temperature simulations by the models (Flerchinger et al., 2000a). Better temporal soil temperature predictions would improve simulations of seed germination, N mineralization and cycling, root growth and water and nutrient uptake in the crop models.

3.2.2. Soil water content

Soil water content simulations by both models at various soil depths corresponded well with measured values (Fig. 2). The RMSEs for water-content simulations in all soil layers during the experimental period were 0.046 $m^3 m^{-3}$ by RZWQM-G and 0.047 $m^3 m^{-3}$ by RZWQM-C, and corresponding RMSEs of total profile soil water storage were 4.36 and 4.60 cm. In general, the models slightly overestimated total soil water storage (Table 7). Errors in soil water simulations by both models were highest in the first 10 cm soil layers with RMSEs of 0.11 $m^3 m^{-3}$ for RZWQM-G and 0.12 $m^3 m^{-3}$ for RZWQM-C. Simulations for layers below 10 cm

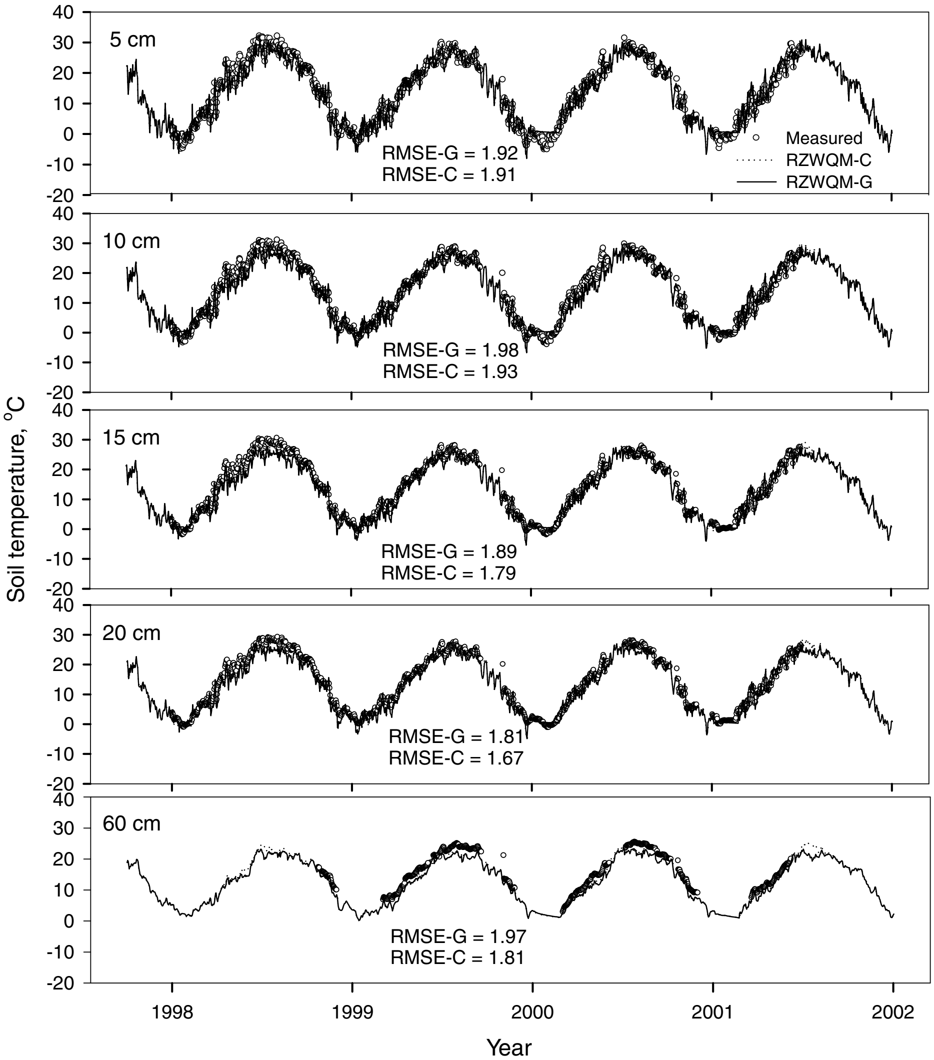

Fig. 1. Temporal variation of measured, and RZWQM-G and RZWQM-C model simulated soil temperatures from 1997 to 2001. RMSE-G and RMSE-C are the Root Mean Square Errors from RZWQM-G and RZWQM-C simulations.

improved drastically with soil depth down to 30 cm, and then remained more or less constant with depth to 220 cm with average RMSE of 0.034 $m^3\ m^{-3}$ for both models. One factor contributing to the apparent higher degree of error in the top soil layer is the usage of neutron probe that is inadequate for correct measurement of soil water in the top soil layers (Wu et al., 1999; Jaynes and Miller, 1999). Thus, we recommend ignoring the measured values at 10 cm, but they are reported here to highlight this difficulty.

Table 7
Root Mean Square Error (RMSE), Mean Relative Error (MRE) and Model Efficiency (E) of RZWQM-C and RZWQM-G simulated ET, profile soil water content, and soil temperature for each crop season

Crop (yr)	RZWQM-C			RZWQM-G		
	RMSE	MRE (%)	E	RMSE	MRE (%)	E
ET						
Wheat (1997–1998)	–	–	–	–	–	–
Maize (1998)	–	–	–	–	–	–
Wheat (1998–1999)	1.21 mm	59.4	0.58	1.25 mm	84.5	0.55
Maize (1999)	1.67 mm	10.9	0.06	1.53 mm	−8.9	0.39
Wheat (1999–2000)	1.18 mm	6.0	0.53	1.26 mm	0.8	0.41
Maize (2000)	1.78 mm	9.5	0.58	1.69 mm	−9.4	0.62
Wheat (2000–2001)	1.14 mm	27.4	0.64	1.35 mm	−8.9	0.43
Maize (2001)	1.91 mm	−10.4	−0.11	1.83 mm	−4.5	0.00
Profile soil water storage						
Wheat (1997–1998)	–	–	–	–	–	–
Maize (1998)	–	–	–	–	–	–
Wheat (1998–1999)	3.89 cm	6.1	−0.06	3.70 cm	6.0	0.00
Maize (1999)	6.19 cm	14.6	0.88	6.32 cm	15.8	0.87
Wheat (1999–2000)	2.51 cm	4.8	−0.27	3.16 cm	6.0	−1.00
Maize (2000)	3.96 cm	8.4	−3.71	4.35 cm	9.6	−4.26
Wheat (2000–2001)	1.35 cm	2.6	0.96	1.70 cm	3.4	0.94
Maize (2001)	3.48 cm	4.2	0.26	3.11 cm	3.9	0.41
Soil temperature						
Wheat (1997–1998)	2.25 °C	−13.8	0.97	2.11 °C	−12.8	0.98
Maize (1998)	2.41 °C	−8.0	0.99	2.17 °C	−7.0	0.99
Wheat (1998–1999)	1.75 °C	−11.1	0.98	1.76 °C	−1.9	0.98
Maize (1999)	2.00 °C	−1.2	0.99	1.90 °C	−21.3	0.99
Wheat (1999–2000)	2.01 °C	−27.9	0.97	1.88 °C	−27.3	0.97
Maize (2000)	1.58 °C	−4.3	1.00	1.34 °C	−2.6	1.00
Wheat (2000–2001)	1.75 °C	−13.9	0.98	1.77 °C	−10.5	0.98
Maize (2001)	1.21 °C	−1.1	1.00	1.23 °C	−0.0	1.00

– data not available.

3.2.3. Evapotranspiration (ET)

Lysimetric measurements of ET from 1998 to 2001 were available for comparison with model simulations (Fig. 3). The seasonal patterns of measured ET during the period were reflected in both model simulations. Measured daily ET amounts ranged from 0.01 to 8.34 mm whereas, the RZWQM-G and RZWQM-C model simulated amounts ranged from 0.01 to 7.27 mm, and 0.04 to 6.4 mm, respectively. Corresponding statistics are shown in Table 7. ET values simulated by the models were generally lower than measured values due to simulated lower LAI compared to measured values (Fig. 4). Cumulative ET patterns during the crop growing seasons of winter wheat and maize from 1998 to 2001 showed some correspondence with the measured values (Fig. 3). The cumulative ET pattern for maize showed better correspondence with measured values compared to winter wheat. The cumulative ET simulated by RZWQM-G was lower than measured by 11%, 26%, and 30% for winter

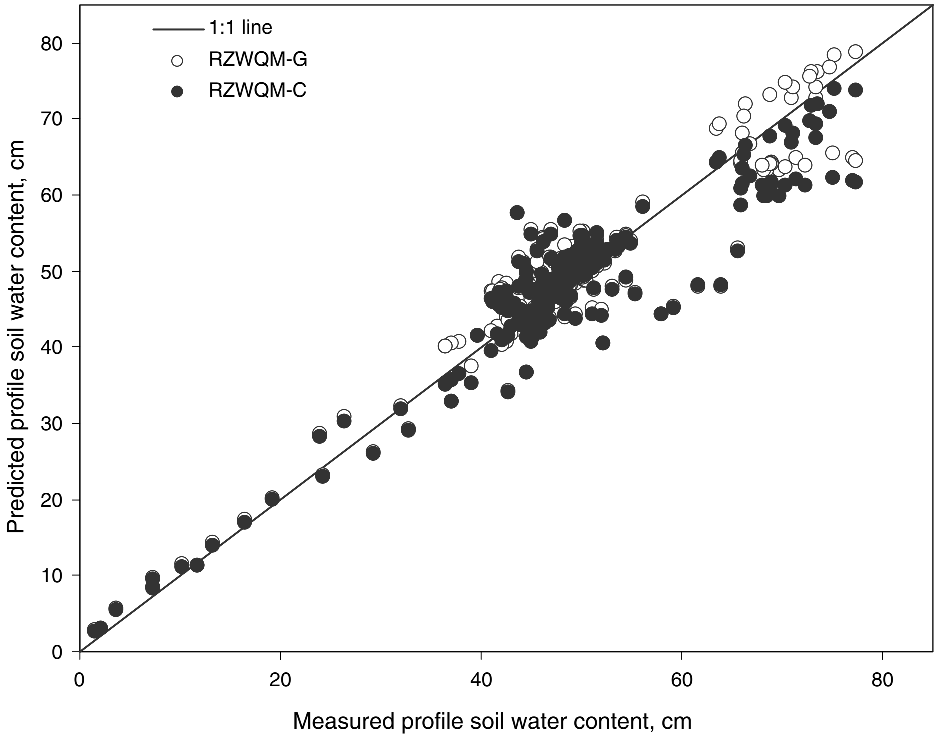

Fig. 2. Comparison of measured and RZWQM-G and RZWQM-C model simulated total profile soil water from 1997 to 2001. Measurement soil profile depths varied between 10 and 220 cm.

wheat and 19%, 26%, and 23% for maize during the crop seasons from 1998 to 2001. RZWQM-C simulated cumulative ET for the respective crop seasons were lower than measured by 19%, 31%, and 37% for winter wheat and 22%, 28%, and 22% for maize. LAI simulations for both models need improvement for better ET simulations. Simulated ET depends on accurate LAI simulation, which influences canopy resistance. Because ET is calculated using the Shuttleworth–Wallace equations in RZWQM (Farahani and Ahuja, 1996), simulations may correspond with measurement only if canopy resistance is well-defined.

3.2.4. Leaf area index (LAI)

RMSEs of simulated LAI by RZWQM-G and RZWQM-C models were 1.0 and 1.1, respectively. LAI measurements from only 1998 to 2001 were available for comparison with the model simulations (Fig. 4). In general, RZWQM-G simulated better LAI for maize than RZWQM-C as reflected in their RMSEs (Table 8). However, winter wheat LAI simulation of both models were comparable (Table 8). Higher deviations of LAI simulations of both models occurred from 5th November to 30th November 1998 during the early growth periods of 1998–1999 winter wheat growing season, and from 17th April to 27th April 2001 during

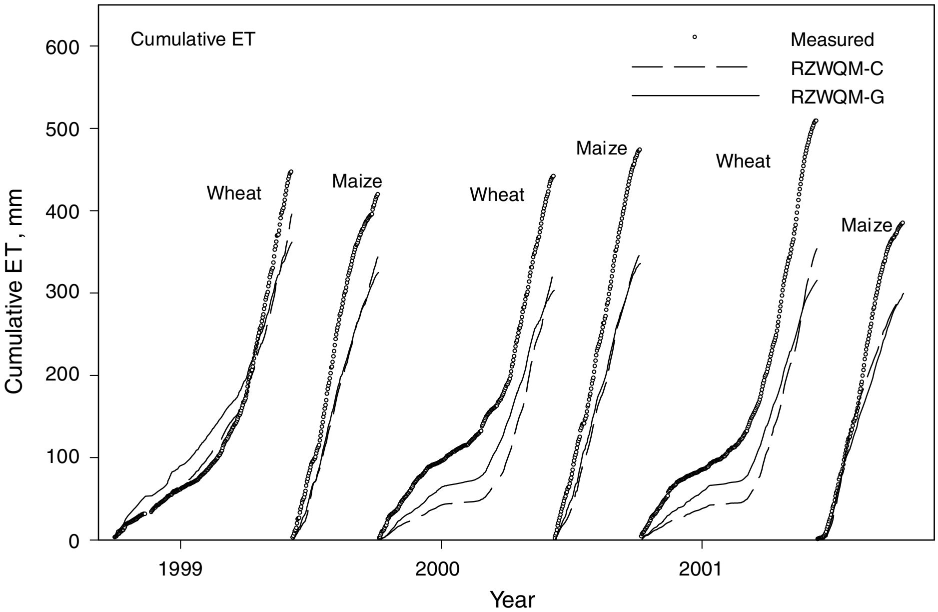

Fig. 3. Comparison of measured (lysimetric), and RZWQM-G and RZWQM-C model simulated cumulative ET for each growing season from 1998 to 2001.

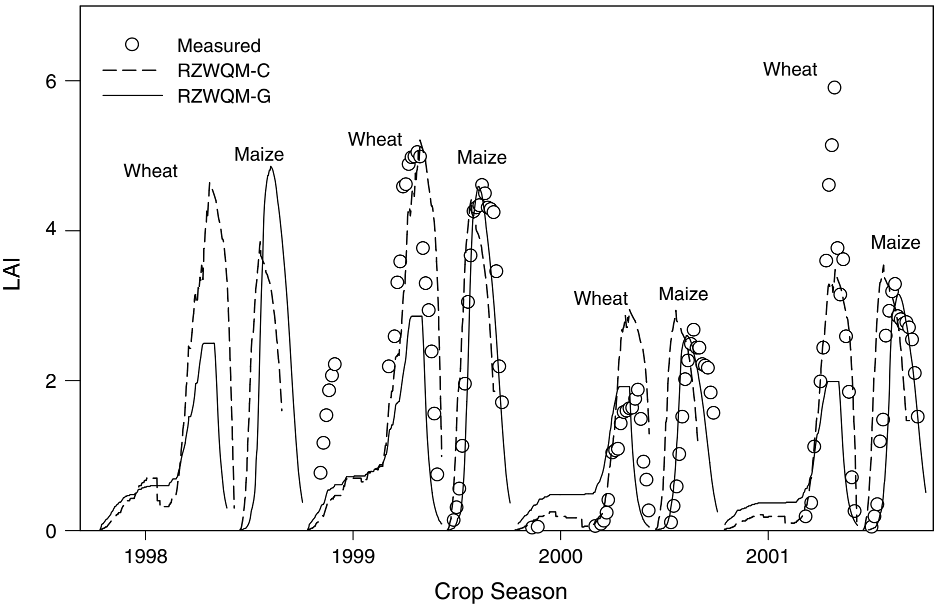

Fig. 4. Comparison between measured, and RZWQM-G and RZWQM-C model simulated LAI of winter wheat and maize from 1997 to 2001. No measurements were taken in 1997–1998.

Table 8
Root Mean Square Error (RMSE), Mean Relative Error (MRE) and Model Efficiency (*E*) of RZWQM-C and RZWQM-G simulated LAI, grain yield, and biomass for each crop season

Crop (yr)	RZWQM-C			RZWQM-G		
	RMSE	MRE (%)	*E*	RMSE	MRE (%)	*E*
LAI						
Wheat (1997–1998)	–	–	–	–	–	–
Maize (1998)	–	–	–	–	–	–
Wheat (1998–1999)	1.11	−4.0	0.40	1.66	−56.1	−0.34
Maize (1999)	1.30	38.3	0.45	0.56	−23.4	0.88
Wheat (1999–2000)	0.88	117.1	−0.60	0.74	22.7	−0.27
Maize (2000)	1.34	223.9	−1.89	0.78	25.6	0.20
Wheat (2000–2001)	0.97	19.7	0.71	0.59	−26.4	−0.15
Maize (2001)	1.28	20.9	0.84	0.59	−25.5	0.70
Grain yield						
Wheat (1997–1998)	–	6.8	–	–	7.7	–
Maize (1998)	–	14.2	–	–	35.1	–
Wheat (1998–1999)	–	−8.6	–	–	−6.7	–
Maize (1999)	–	−14.1	–	–	−9.9	–
Wheat (1999–2000)	–	12.3	–	–	35.3	–
Maize (2000)	–	14.9	–	–	24.8	–
Wheat (2000–2001)	–	−28.4	–	–	−4.5	–
Maize (2001)	–	−5.2	–	–	12.4	–
All seasons	0.94 Mg ha^{-1}	−1.0	0.87	1.23 Mg ha^{-1}	11.8	0.78
Above-ground biomass						
Wheat (1997–1998)	–	–	–	–	–	–
Maize (1998)	–	–	–	–	–	–
Wheat (1998–1999)	1.98 Mg ha^{-1}	−42.2	0.85	0.94 Mg ha^{-1}	−16.9	0.97
Maize (1999)	2.36 Mg ha^{-1}	92.2	0.92	2.58 Mg ha^{-1}	−18.7	0.58
Wheat (1999–2000)	0.40 Mg ha^{-1}	43.5	0.98	2.16 Mg ha^{-1}	77.4	0.71
Maize (2000)	1.54 Mg ha^{-1}	3.9	0.97	1.79 Mg ha^{-1}	13.0	0.94
Wheat (2000–2001)	3.82 Mg ha^{-1}	10.9	0.63	2.50 Mg ha^{-1}	50.0	0.84
Maize (2001)	1.66 Mg ha^{-1}	12.0	0.59	2.60 Mg ha^{-1}	−17.2	0.89

– Data not available.

the middle growth periods of 2000–2001 season (Fig. 4). It was observed that during the 1998–1999 winter wheat crop season, from the planting date on 5th October 1998 to 30th November 1998, only 7.4 mm of rainfall was recorded at the station. The crop was irrigated on 30th November 1998. From the day of planting (5th October, 1998) until the first irrigation on 30th November 1998, RZWQM-G calculated water stress ranged from 0.08 to 0.37 (on a 0–1 scale, with 0 indicating no stress and 1 maximum stress) leading to a serious decline in actual leaf area expansion. During the same period the RZWQM-C model also calculated water stress between 0.06 and 0.58 for 10 consecutive days. It appears that the water stress was not severe enough to cause a decline in actual leaf area growth as much as simulated by the models. Large errors in winter wheat LAI simulations were observed from 17th April to 27th April in 2001 (Fig. 4).

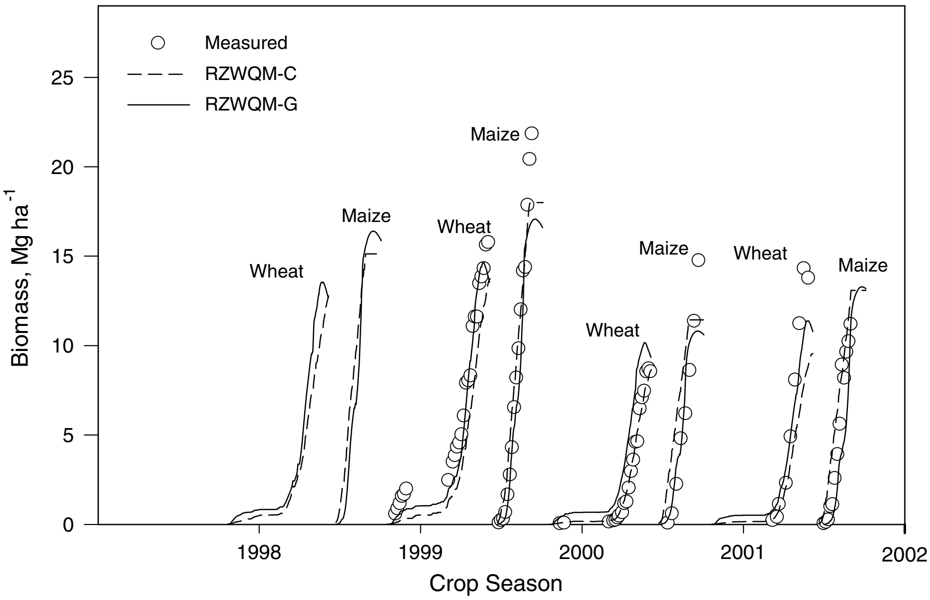

Fig. 5. Comparison of measured (5 day intervals), and RZWQM-G and RZWQM-C model simulated crop biomass growth of winter wheat and maize from 1997 to 2001. No measurements were taken in 1997–1998.

3.2.5. Above-ground biomass

Above-ground biomass simulations with both RZWQM-G and RZWQM-C models for winter wheat and maize from 1998 to 2001 followed the measured pattern with some exceptions towards maturity (Fig. 5). RMSEs of biomass simulations were 2.06 and 2.20 Mg ha^{-1} by RZWQM-G and RZWQM-C models, respectively (Table 8). In the 1998–1999 winter wheat, 1999 maize, 2000 maize, and 2000–2001 winter wheat seasons, both models simulated biomass accumulation at much slower rates (growth ceased between 5 and 13 days earlier) than measurements indicated. This resulted in significant differences between the end of the season biomass amount simulated by the models and the measured biomass at maturity.

3.2.6. Grain yield

RMSEs for grain yield simulations by RZWQM-G and RZWQM-C were 1.23 and 0.95 Mg ha^{-1}, respectively, for the 8 crop seasons from 1997 to 2001 (Fig. 6). Both models responded well to yearly differences in yield (Table 8). Small errors in grain yield simulations by both models were caused by biomass simulation during water-stress periods and the associated under-simulation of LAI. Temperature and N stresses simulated by RZWQM-G were not severe enough to cause significant yield reductions. RZWQM-G over-estimated grain yield by 8% for the winter wheat (1997–1998), 35% for maize (1998), 35% for winter wheat (1999–2000), 25% for maize (2000), and 12% for maize (2001); and under simulated grain yield by 7% for winter wheat (1998–1999), 10% for maize (1999), and 4% for winter wheat

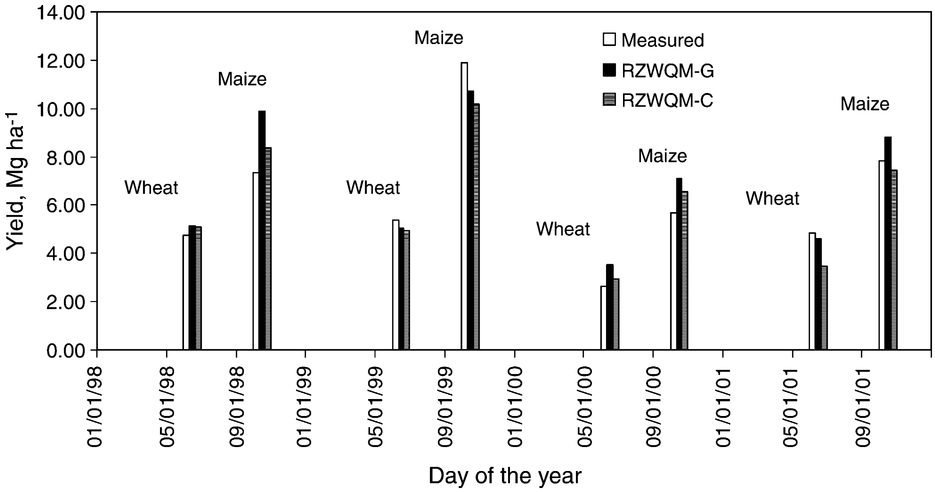

Fig. 6. Comparison of measured, and RZWQM-G and RZWQM-C model simulated grain yields from 1997 to 2001.

(2000–2001) (Fig. 6). RZWQM-C over simulated grain yield by 7% for the winter wheat (1997–1998), 14% for maize (1998), 12% for winter wheat (1999–2000), and 15% for maize (2000); and under simulated grain yield by 9% for winter wheat (1998–1999), 14% for maize (1999), and 28% for winter wheat (2000–2001), and 5% for maize (2001) (Fig. 6). Although the RZWQM-C model simulated grain yields were superior to the RZWQM-G simulations (Fig. 6), RZWQM-G was slightly better at simulating biomass.

3.2.7. Evaluation of the current water and N applications

Well-calibrated and validated agricultural system models are valuable tools for assessing the impacts of management practices on crop production variability and associated environmental impacts (Ahuja et al., 2000b; Saseendran et al., 2004, 2005; Mathews et al., 2002; Thornton and Wilken, 1998). In a preliminary attempt to show the potentials of the validated models in farm management decision support, we used both models to simulate the impacts of managing irrigation water and N fertilizer at 75%, 50%, 25%, and 0% of the current application rates (as used in the experiment) in the winter wheat–maize double cropping system on grain yield and deep N seepage loss in the NCP over the duration of the experiment (eight crop seasons from 1997 to 2001).

The sensitivity analyses showed that relative reductions in the amount of maize and wheat grain yields, and deep N seepage loss as simulated by both models in response to different irrigation and N rates were comparable (Table 9). It can be inferred from the simulations that a 25% reduction in water and N application rate reduced yield by only 1–9% whereas N leaching was reduced by 24–77%. Reduction in maize yield was much less than for winter wheat due to low rainfall during the wheat growing season. The results are in agreement with the current belief in

Table 9
Simulated effects of different levels of irrigation and N management on grain yield and N leaching from 1997 to 2001

Model	Effect on	Crop	Level of irrigation (% of current rate)			
			75	50	25	0
			% change from full rate			
RZWQM-C	Grain yield	Maize	−1	−5	−12	−28
		Wheat	−1	−11	−21	−33
	N Leaching	Total	−48	−77	−88	−100
RZWQM-G	Grain yield	Maize	−4	−9	−17	−25
		Wheat	−6	−22	−23	−25
	N Leaching	Total	−77	−91	−94	−97
			Level of N (% of current rate)			
			75	50	25	0
			% change from full rate			
RZWQM-C	Grain yield	Maize	−1	−1	−1	−18
		Wheat	−9	−9	−9	−11
	N Leaching	Total	−24	−48	−72	−88
RZWQM-G	Grain yield	Maize	0	−2	−6	−19
		Wheat	−5	−20	−35	−42
	N Leaching	Total	−32	−51	−83	−83

NCP that irrigation for winter wheat is more important than for maize and winter wheat is the major crop consuming ground water (Hu et al., 2005).

4. Summary and conclusions

Sustainable agricultural production in pace with its demand for providing food and fodder for the increasing human and animal population is a formidable challenge facing agricultural scientists of the NCP, China. Intensive cropping systems with high inputs of fertilizer and water have been practiced for decades in China to increase crop production, resulting in fast degradation of the soil and water environment in these areas. However, field experiments involving various soil-water–crop–nutrient alternatives to develop best management practices for optimum crop production and environmental sustainability are formidable due to the time and money involved. A viable alternative to this problem is to make use of comprehensive agricultural system models to analyse outcomes of various management alternatives, after thorough calibration and validation with experimental data of the region.

This study is the first to evaluate the generic plant growth module and CERES crop growth modules in RZWQM for wheat and maize production in a winter wheat–maize double cropping system. Results of the study have shown comparable simulations for soil water and temperature, LAI, and ET by both models. Although soil temperature and ET simulations of both models matched the seasonal and inter-annual trends very well, daily values deviated from field-measured data. It is important to improve the soil temperature simulation ability of the models for better simulations of soil carbon/nitrogen processes, seed germination and crop growth. The RZWQM-C model gave better simulations for grain yield compared to RZWQM-G, but RZWQM-G simulated above-ground biomass slightly better than the RZWQM-C model. In general, both models were found to have equal potential for simulation of the winter wheat-maize double cropping system in the NCP, China. We also showed how both models could be further utilized to evaluate current water and N management practices and to propose alternatives in the NCP. As a preliminary attempt to use the validated models for decision support for managing irrigation water and N use in the double cropping system, we found that a 25% reduction in irrigation or N from the current rate can reduce N leached to the ground water by 24–77%, while reducing crop production by only 1 to 9%. These findings show prospects for reducing the current rates of depletion and salinization of ground water resources in the area through judicious optimization of resource inputs in agriculture. In this context, the validated models hold potential promise for further developing best water and N management practices for sustainable agriculture in the region. In addition, although there were slight differences in simulation results using a generic and a CERES-wheat (-maize) plant growth module in RZWQM the responses to management practices were comparable.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (Grant No. 40328001).

References

Ahuja, L.R., Johnsen, K.E., Rojas, K.W., 2000a. Water and chemical transport in soil matrix and macropores. In: Ahuja, L.R., Rojas, K.W., Hanson, J.D., Shafer, M.J., Ma, L. (Eds.), Root Zone Water Quality Model. Modeling Management Effects on Water Quality and Crop Production. Water Resources Publications, LLC, Highlands Ranch, CO, pp. 13–50.

Ahuja, L.R., Rojas, K.W., Hanson, J.D., Shafer, M.J., Ma, L. (Eds.), 2000b. Root Zone Water Quality Model. Modeling Management Effects on Water Quality and Crop Production. Water resources publications, LLC, CO, USA, p. 372.

Ahuja, L.R., Ma, L., 2002. Parameterization of agricultural system models: current approaches and future needs. In: Ahuja, L.R., Ma, L., Howell, T.A. (Eds.), Agricultural System Models in Field Research and Technology Transfer. Lewis Publishers, London, pp. 273–316.

Brooks, R.H., Corey, A.T., 1964. Hydraulic properties of porous media. Hydrology paper 3. Colorado State Univ., Fort Collins, CO, USA, pp. 1–15.

China Statistics Bureau, 2001. Annual Agricultural Statistics of Henan Province. China Statistics Press, Beijing, pp. 112–115.

Elliott, E.T., Cole, C.V., 1989. A perspective on agroecosystem science. Ecology 70, 1597–1602.

Farahani, H.J., Ahuja, L.R., 1996. Evapotranspiration modeling of partial canopy/residue covered fields. Transactions of the American Society of Agricultural Engineers 39, 2051–2064.

Farahani, H.J., DeCoursey, D.G., 2000. Potential evapotranspiration processes in the soil–crop-residue system. In: Ahuja, L.R., Rojas, K.W., Hanson, J.D., Shafer, M.J., Ma, L. (Eds.), Root Zone Water Quality Model. Modeling Management Effects on Water Quality and Crop Production. Water Resources Publications, LLC, Highlands Ranch, CO, pp. 51–80.

Flerchinger, G.N., Aiken, R.M., Rojas, K.W., Ahuja, L.R., 2000a. Development of the Root Zone Water Quality Model (RZWQM) for over-winter conditions. Transactions of the American Society of Agricultural Engineers 43, 59–68.

Flerchinger, G.N., Aiken, R.M., Rojas, K.W., Ahuja, L.R., Johnsen, K.E., 2000b. Soil heat transport, soil freezing and snowpack conditions. In: Ahuja, L.R., Rojas, K.W., Hanson, J.D., Shafer, M.J., Ma, L. (Eds.), Root Zone Water Quality Model, Modeling Management Effects on Water Quality and Crop Production. Water Resources Publications, LLC, Highlands Ranch, CO, pp. 281–314.

Godwin, D.C., Ritchie, J.T., Singh, U., Hunt, L.A., 1989. A User's Guide to CERES-wheat – v2.10. International Fertilizer Development Center, Muscle Shoals, p. 89.

Hanson, J.D., 2000. Generic crop production model for the root zone water quality model. In: Ahuja, L.R., Rojas, K.W., Hanson, J.D., Shafer, M.J., Ma, L. (Eds.), Root Zone Water Quality Model. Modeling Management Effects on Water Quality and Crop Production. Water Resources Publications, LLC, Highlands Ranch, CO, pp. 81–118.

Hanson, J.D., Rojas, K.W., Shaffer, M.J., 1999. Calibrating the Root Zone Water Quality Model. Agronomy Journal 91, 171–177.

Hoogenboom, G., Wilkens, P.W., Tsuji, G.Y., 1999. Decision Support System for Agrotechnology Transfer (DSSAT) v.3. vol. 4, University of Hawaii, Honolulu.

Hu, C., Delgado, J.A., Zhang, X., Ma, L., 2005. Assessment of groundwater use by wheat (*Triticum aestivum* L.) in the Luancheng Xian region and potential implications for water conservation in the Northwestern North China plain. Journal of Soil and Water Conservation 60 (2), 80–88.

Hu, C., Saseendran, S.A., Green, T.R., Ma, L., Li, X., Ahuja, L.R., 2006. Evaluating nitrogen and water management for intensive cropping systems in China. Vadoze Zone Journal, vol. 5, in press.

Jaynes, D.B., Miller, J.G., 1999. Evaluation of the Root Zone Water Quality Model using data from Iowa MESA. Agronomy Journal 91, 192–200.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. DSSAT Cropping system model. European Journal of Agronomy 18, 235–265.

Ma, L., Hoogenboom, G., Ahuja, L.R., Ascough II, J.C., Saseendran, S.A., 2006. Evaluation of the RZWQM-CERES-Maize hybrid model for maize production. Agricultural Systems 87, 274–295.

Ma, L., Ahuja, L.R., Ascough II, J.C., Shaffer, M.J., Rojas, K.W., Malone, R.W., Cameira, M.R., 2000. Integrating system modeling with field research in agriculture: applications of the Root Zone Water Quality Model (RZWQM). Advances in Agronomy 71, 233–292.

Ma, L., Nielsen, D.C., Ahuja, L.R., Malone, R.W., Saseendran, S.A., Rojas, K.W., Hanson, J.D., Benjamin, J.G., 2003. Evaluation of RZWQM under varying irrigation levels in eastern Colorado. Transactions of American Society of Agricultural Engineers 46 (1), 39–49.

Ma, L., Shaffer, M.J., Ahuja, L.R., 2001. Application of RZWQM for soil nitrogen management. In: Ahuja, L.R., Ma, L., Howell, T.A. (Eds.), Agricultural System Models in Field Research and Technology Transfer. Lewis Publishers, CRC Press, Boca Raton, FL, pp. 265–301.

Ma, L., Shaffer, M.J., Boyd, J.K., Waskom, R., Ahuja, L.R., Rojas, K.W., Xu, C., 1998. Manure management in an irrigated silage corn field: experiment and modeling. Soil Science Society of American Journal 62, 1006–1017.

Mathews, R., Stephens, W., Hess, T., Middleton, T., Graves, A., 2002. Applications of crop/soil simulation models in tropical agricultural systems. Advances in Agronomy 76, 31–124.

Peterson, G.A., Westfall, D.G., Cole, C.V., 1993. Agroecosystem approach to soil and crop management research. Soil Science Society of American Journal 57, 1354–1360.

Rawls, W.J., Brakensiek, D.L., Saxton, K.E., 1982. Estimation of soil water properties. Transactions American Society of Agricultural Engineers 25, 1316–1320, p. 1328.

Rojas, K.W., Ahuja, L.R., 2000. Management practices. In: Ahuja, L.R., Rojas, K.W., Hanson, J.D., Shafer, M.J., Ma, L. (Eds.), Root Zone Water Quality Model. Modeling Management Effects on Water Quality and Crop Production. Water Resources Publications, LLC, Highlands Ranch, CO, pp. 245–280.

Saseendran, S.A., Nielsen, D.C., Ma, L., Ahuja, L.R., Halvorson, A.D., 2004. Modeling nitrogen management effects on winter wheat production using RZWQM and CERES-Wheat. Agronomy Journal 96, 615–630.

Saseendran, S.A., Ma, L., Nielsen, D.C., Ahuja, L.R., 2005. Simulation of planting date effects on maize performance in Eastern Colorado using CERES and RZWQM. Agronomy Journal 97, 58–71.

Shaffer, M.J., Rojas, K.W., DeCoursey, D.G., Hebson, C.S., 2000. Nutrient chemistry process-OMNI. In: Ahuja, L.R., Rojas, K.W., Hanson, J.D., Shafer, M.J., Ma, L. (Eds.), Root Zone Water Quality Model. Modeling Management Effects on Water Quality and Crop Production. Water Resources Publications, LLC, Highlands Ranch, CO, USA, pp. 119–144.

Thornton, P.K., Wilken, P.W., 1998. Risk assessment and food security. In: Tsuji, Y.G., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, pp. 329–345.

Tsuji, G.Y., Uehara, G., Balas, S. (Eds.), 1994. DSSAT Version 3. International benchmarks sites network for agrotechnology transfer. Univ. of Hawaii, Honolulu.

Wu, L.S., Chen, W., Baker, J.M., Lamb, J.A., 1999. Evaluation of the Root Zone Water Quality Model using field-measured data from a sandy soil. Agronomy Journal 91, 177–182.

Yang, J.F., Li, B.Q., Liu, S.P., 2000. A large weighing lysimeter for evapotranspiration and soil-water–groundwater exchange studies. Hydrological Processes 14, 1887–1897.

Zitong, G. (Ed.), 1999. Chinese Soil Taxonomy. Sciences Press, Beijing, p. 864.