Simulating management effects on crop production, tile drainage, and water quality using RZWQM–DSSAT

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Abstract

The objective of this study was to explore if more crop-specific plant growth modules can improve simulations of crop yields, and N in tile flow under different management practices compared with a generic plant growth module. We calibrated and evaluated the Root Zone Water Quality Model (RZWQM) with the Decision Support for Agrotechnology Transfer (DSSAT v3.5) plant growth modules (RZWQM–DSSAT) for simulating tillage (NT — no till, RT — ridge till, CP — chisel plow, and MP — moldboard plow), crop rotation {CC — continuous corn, and CS — corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.]}, and nitrogen (N) (SA — single application at preplant, and LSNT — late spring soil N test based application) and manure (SM — fall injected swine manure) management effects on crop production and water quality. Data from 1978 to 2003 from a water quality experiment near Nashua (Nashua experiments), Iowa, USA, were used. The model was calibrated using data from one treatment plot and validated for the rest of the plots. Simulated management effects on annual N loading in tile flow were agreeable with measured effects in 85%, 99%, 88%, and 78% of the cases for tillage, crop rotation (CS vs. CC), N application timing (SA vs. LSNT), and swine manure applications (SM vs. SA), respectively. On average, the LSNT plots were simulated to have 359 kg ha^{-1} higher corn yield compared to SA, when the observed increase was 812 kg ha^{-1}. Grain yield simulations were not sensitive to differences between RT and NT, between SM and SA treatments, and between CS and CC. We conclude that considering the uncertainties of basic input data, processes in the field, and lack of site specific weather data, the results obtained with this RZWQM–DSSAT hybrid model were not much better than the results obtained earlier with the generic crop growth module.

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1. Introduction

Information to help farmers select economically and environmentally sustainable crop management practices involving various combinations of tillage, crop rotation, fertilizer and manure management practices is needed to prevent contamination and/or degradation of soil and water resources. Several years of field testing to account for soil and climate variability are required to provide such information for locations with different soils, water resources and weather regimes (Verma et al., 1995). To improve information transfer, agricultural sys-

tem simulation models can be valuable tools for synthesis of the long-term research results and subsequent extrapolation to other climates and soils (Peterson et al., 1993; Mathews et al., 2002; Saseendran et al., 2004; Saseendran et al., 2005).

The Root Zone Water Quality Model (RZWQM) is a process-oriented agricultural system model that integrates biological, physical, and chemical processes to simulate the impact of agricultural management practices on crop production and water quality (Ahuja et al., 2000). The generic crop model included in RZWQM can be parameterized to simulate specific crops (Hanson, 2000). However, the DSSAT (Decision Support System for Agrotechnology Transfer) suite of crop models (Tsuji et al., 1994; Hoogenboom et al., 1999; Jones et al., 2003) can simulate detailed yield components, leaf numbers, and

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phenological development for specific crops. Recently the CROPGRO-soybean, CERES-maize (*Zea mays* L.), and CERES-wheat (*Triticum aestivum* L.) plant growth modules of DSSAT were coupled with the soil water and nitrogen simulation routines of RZWQM to develop the RZWQM–CROPGRO (Ma et al., 2005) and RZWQM–CERES-maize hybrid (Ma et al., 2006) models (hereafter referred to as RZWQM–DSSAT).

Advantages of using RZWQM–DSSAT come from combining the detailed simulations of soil surface residue dynamics, tillage and other soil management practices, and detailed soil water and soil carbon/nitrogen processes of RZWQM with the detailed crop specific plant growth models of the DSSAT. Ma et al. (2005, 2006) reported that RZWQM–DSSAT simulation results for soybean and maize production were comparable to those using the original CROPGRO and CERES models. However, RZWQM–DSSAT has not been tested for its suitability to simulate long-term impacts of different tillage, crop rotation, N fertilizer, and manure management practices on water quality and crop production.

Previous simulations using RZWQM with a generic plant growth module using data from the Nashua experiments were reported (Singh and Kanwar, 1995; Singh et al., 1996; Kumar et al., 1998a,b, 1999). However, those studies used data only for 3 to 4 years for model calibration and validated the results for only one or two of the selected plots. The response variables were also selective and limited to one or two depending on the problem studied. There were no attempts to evaluate the model for simulating the relative advantageous of the different management practices on crop performance and water quality, which is essential for assessing the potential of the model as a decision support tool in agricultural management. In this context, there is also a need to model the Nashua experiment for its whole duration (26 years), all plots (36 plots), and at the whole system level responses for synthesis of information and transfer of technology across differing climates and soils. In a companion study, Ma et al. (2007a-this issue) used RZWQM with generic crop growth module for this purpose. The objective of this study was to calibrate and evaluate the RZWQM–DSSAT hybrid with crop specific plant growth modules, for simulating the relative effects of tillages, crop rotations, and N and manure management on crop production, tile drainage, and water quality in the Nashua experiments.

2. Materials and methods

2.1. Experiments

Data for our study were obtained from the 'Nashua experiments' that have been conducted to quantify the impact of management practices on crop production and water quality (Karlen et al., 1991; Bakhsh et al., 2000). The soils are predominantly Floyd loam (fine-loamy, mixed, mesic *Aquic Hapludolls*), Kenyon silty-clay loam (fine-loamy, mixed, mesic *Typic Hapludolls*) and Readlyn loam (fine-loamy, mixed, mesic *Aquic Hapludolls*) with 30 to 40 g kg^{-1} (3 to 4%) organic matter (Voy, 1995). Soil slopes varied from 1 to 3% among the various plots. The field experiments were established on a 15 ha research site in 1978 using a randomized complete block design with three replications. From 1978 to 1992, there were four tillage treatments [chisel plow (CP), ridge tillage (RT), moldboard plow (MP), and no-till (NT)] and two crop sequences [continuous corn (CC) and both phases of a corn and soybean rotation (CS and SC)]. From 1993 to 1998 there were two tillage (CP and NT), eight N management treatments (different rates, times of application, fertilizer and/or manure) for CP and four N treatments for NT with no change in the number of crop sequences (i.e. CC, and CS and SC) (total 36 plots). The CC was replaced with CS or SC in 1999 and the experiments were continued along with ten N fertilizers and swine manure (SM) treatments in the CP and two SM treatments in the NT. Data from experiments of plot 25 were used for model calibration because it had both rotations and water table records. Data from 1990 to 2003 (plot 25) were used for calibration, but all simulations were run for 1 January 1978 through 31 December 2003. Data from experiments in the remaining plots were used in the model evaluation (Ma et al., 2007a-this issue). A list of the major management practices for each of the 36 plots from 1978 to 2003 is presented in Table 1. Plots #8, #17, #20, #27, #30, and #31 had hydraulic

Table 1
Major management practices applied to each plot from 1978 to 2003

Plot #	Dominant soil type	Crop rotation			Fertilization for corn only			Tillage		
		78–92	93–98	99–03	78–92	93–98	99–03	78–92	93–98	99–03
1, 7, 30	Readlyn/Kenyon	CS	CS	CS	AA	SM	SM	CP	CP	CP
2, 16, 20	Readlyn/Kenyon	CS	CS	CS	AA	UAN	SM	MP	NT	NT
3, 24, 28	Readlyn/Kenyon	SC	SC	SC	AA	UAN (LSNT)	UAN	NT	NT	CP
4, 18, 33	Kenyon	SC	CS	CS	AA	UAN	SM+UAN	CP	CP	CP
5 [a], 21 [a], 26 [a]	Readlyn/Kenyon	CC	CC	SC	AA	UAN	SM	CP [a]	CP	CP
6 [a], 32 [a], 36 [a]	Readlyn/Kenyon	CC	SC	SC	AA	UAN	SM+UAN	RT	CP	CP
8, 9, 19	Readlyn/Floyd	CS	CS	CS	AA	UAN (LSNT)	UAN (LSNT)	RT	CP	CP
10, 15, 29	Kenyon	CS	CS	CS	AA	UAN (LSNT)	UAN	NT	NT	CP
11, 23, 27	Kenyon	SC	SC	SC	AA	SM	SM	RT	CP	CP
12, 17, 34	Kenyon/Floyd	SC	SC	SC	AA	UAN (LSNT)	UAN (LSNT)	MP	CP	CP
13 [a], 22 [a], 35 [a]	Readlyn/Floyd	CC	CC	CS	AA	SM	SM	MP	CP	CP
14 [a], 25 [a], 31 [a]	Readlyn/Kenyon	CC	SC	SC	AA	UAN	SM	NT	NT	NT

CS: corn–soybean rotation with corn during even years; SC: soybean–corn rotation with corn during odd years; CC: continuous corn; CP: chisel plow; RT: ridge till; MP: moldboard plow; NT: no till; AA: anhydrous ammonia; UAN: urea–ammonia–nitrate; LSNT: late spring N test; SM: swine manure.
[a] Plots with water table measurements. Plots #8, #17, # 20, #27, #30 and #31 were excluded from this study.

Table 2
Selected soil properties used in the model calibrations (Ma et al., 2007b-this issue)

Soil depth (cm)	Bulk density (g/cm^3)	θ_s (cm^3/cm^3)	λ	K_{sat} (cm/h)	1/3 bar SW (cm^3/cm^3)	15 bar SW (cm^3/cm^3)	LK_{sat} (cm/h)	SRGF
0–20	1.45	0.442	0.086	3.60	0.300	0.1451	3.60	1.0
20–41	1.51	0.430	0.070	6.05	0.270	0.1321	6.05	1.0
41–50	1.51	0.430	0.070	8.50	0.260	0.1278	8.50	0.8
50–69	1.60	0.405	0.092	11.50	0.234	0.1164	11.50	0.5
69–89	1.60	0.405	0.092	14.50	0.234	0.1164	14.50	0.4
89–101	1.69	0.372	0.060	1.80	0.260	0.1278	9.4	0.0
101–130	1.80	0.333	0.060	1.80	0.280	0.1365	17.2	0.0
130–150	1.80	0.333	0.060	0.01	0.280	0.1365	0.01	0.0
150–200	1.80	0.333	0.060	0.01	0.280	0.1365	0.01	0.0
200–252	1.80	0.333	0.060	0.01	0.280	0.1365	0.01	0.0

SW = soil water content; θ_s = saturated SW; λ = particle size distribution index; K_{sat} = saturated hydraulic conductivity; LK_{sat} = lateral K_{sat}; SRGF = soil root growth factor.

properties different from other plots and hence were not used in the analysis (Ma et al., 2007a-this issue).

Soils within the experimental area are characterized by seasonally high water tables and therefore, row crops respond favorably to subsurface drainage. Tile drains were installed in 1979 at 1.2 m depth and 28.5 m spacing. The center tile for each plot has a sump for measuring drainage volume and collecting water samples for chemical analysis. Measurements of tile flow and N concentration (yearly N loading/yearly tile flow) in the tile water were available from 1990 to 2003. Water table depth was measured weekly during the crop growth period (June to October) using an observation well in 12 plots from 1992 to 2003 (Table 1). Soil water contents were measured by gravimetric method about 3 to 5 times during the crop growth period (June to October) from 1990 to 1999. NO_3–N concentrations in the soil profile were also measured simultaneously. Grain yield for all crops harvested from 1978 to 2003 was measured. Above ground crop biomass, and grain and biomass N content data were collected for some years during 1990 through 2000.

2.2. Other input data for the simulations

The minimum driving variables for the model are daily total solar radiation, maximum and minimum temperature, wind speed, relative humidity (RH), and precipitation (as break point rainfall data). These data were collected at the experiment site from 1998 to 2003. Temperature and precipitation data for 1978–1997 were collected from an NCDC (National Climate Data Center) weather station at Charles City, Iowa (43°05′ N, 92°40′ W; elev. 309.1 m) located at about 15 km from the site. Solar radiation (1978–1991), wind speed (1978–1997), RH (1978–1997) were collected from an NCDC weather station at Mason City, Iowa (43°09′ N, 93°20′ W; elev. 373.4 m) located approximately 54 km from the experimental site. Solar radiation for the years 1992–1997 was from a weather station at the National Soil Tilth Laboratory, Ames, Iowa (41°57′ N, 93°32′ W; elev. 304.4 m), approximately 136 km southwest of the site. Whenever break point rainfall data were not available and hourly data were available in the above data, the break point data were obtained using the procedure developed by Singh et al. (1996). When only daily rainfall values were available,

they were converted into breakpoint data assuming a uniform rainfall distribution over a 4 h period.

A 250 cm deep soil profile divided into 10 layers was used for the model simulations (Kumar et al., 1999) (Table 2). The experimental site consists of predominantly Floyd, Kenyon, and Readlyn soil associations (Karlen et al., 1991). Soil physical and hydraulic properties for each layer were based on Ma et al. (2007a-this issue) and are listed in Table 2. The soils of the experiment site were assumed to contain macropores, and macropore number, sizes, and continuity were adopted from Kumar et al. (1998b). Four statistics were used in the study to evaluate model performance: (i) Root Mean Square Error (RMSE), which shows the average deviation between simulated and observed values; and (ii) Relative Error (RE) and (iii) Mean Relative Error (MRE), which gives the bias of the simulated value relative to the observed value were used in the simulation evaluations (Hu et al., 2006).

Table 3
Cultivar coefficients calibrated for simulations of GH 2343, NK 4640Bt, and NK45-T5 corn hybrids using the RZWQM–DSSAT hybrid model. Values given in parenthesis are the ranges used in calibration of the parameter

No.	Parameter	NK45-T5	NK 4640Bt	GH 2343 [a]
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) [200–500].	200	220	250
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) [0–1].	0.4	0.4	0.25
3	Thermal time from silking to physiological maturity [500–900].	760	700	710
4	Maximum possible number of kernels per plant [500–900].	900	670	700
5	Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day) [4–12].	6.0	9.5	9.0
6	Phylochron interval (degree days) [35–55].	38.9	49.9	38.9

[a] One of the varieties was used as surrogate for other short-term varieties in the study.

Table 4
Cultivar coefficients calibrated for simulations of SOI 237, Kruger 2343 and Sans. S2062 soybean cultivars using the RZWQM–DSSAT model

Model parameters [a]	SOI 237	Kruger 2343	Sans. S2062
CSDL	14.35	13.45	14.30
PPSEN	0.245	0.245	0.245
EM–FL	19.0	25.0	22.0
FL–SH	7.9	7.9	7.9
FL–SD	14.8	14.8	14.8
SD–PM	36.0	32.0	32.0
FL–LF	24.0	26.0	26.0
LFMAX	1.90	1.8	1.50
SLAVR	410.0	400.0	400.0
SIZLF	180.0	180.0	180.0
XFRT	1.0	1.0	0.6
WTPSD	0.295	0.165	0.165
SFDUR	22.0	22.0	22.0
SDPDV	1.75	1.55	1.55
PODUR	12.0	11.0	11.0

[a] CSDL Critical Short Day Length below which reproductive development progresses with no day length effect (for short day plants) (hour); PPSEN Slope of the relative response of development to photoperiod with time (positive for short day plants) (1/h); EM–FL Time between plant emergence and flower appearance (R1)(photothermal days); FL–SH Time between first flower and first pod (R3) (photothermal days); FL–SD Time between first flower and first seed (R5) (photothermal days); SD–PM Time between first seed (R5) and physiological maturity (R7)(photothermal days); FL–LF Time between first flower (R1) and end of leaf expansion (photothermal days); LFMAX Maximum leaf photosynthesis rate at 30 C, 350 vpm CO_2, and high light(mg CO_2/m^2 s); SLAVR Specific leaf area of cultivar under standard growth conditions (cm^2/g); SIZLF Maximum size of full leaf (three leaflets) (cm^2); XFRT Maximum fraction of daily growth that is partitioned to seed+shell; WTPSD Maximum weight per seed (g); SFDUR Seed filling duration for pod cohort at standard growth conditions (photothermal days); SDPDV Average seed per pod under standard growing conditions (#/pod); PODUR Time required for cultivar to reach final pod load under optimal conditions (photothermal days).

2.3. Model calibration

Soil hydraulic properties and soil carbon and nitrogen parameters for plot 25 were calibrated and discussed in detail by Ma et al. (2007a-this issue, b-this issue). Based on these soil parameters, parameters for RZWQM–DSSAT crop growth model were calibrated to derive cultivar specific parameters for the seven corn hybrids and three soybean cultivars used in the field experiments. Plot 25 had measured grain yield for 1978–2003 and above ground biomass measurements for 1990 to 2000. After initializing the model for conditions on 1 January 1978, a continuous simulation was run for 1978 through 2003. Most of the data at the Nashua site was collected between 1990 and 2003, so yield data only from that period was used with the other parameters for calibration. We conducted a 'direct search' optimization of cultivar specific parameters that were constrained between upper and lower limits over the range of values as available in the DSSAT v3.5 database (Tsuji et al., 1994). This enabled us to minimize an objective function calculated as the MRE of the simulated grain yield, biomass, grain and biomass N uptakes, and soil water contents in different layers. Cultivar specific coefficients for three representative corn hybrids (GH 2343, NK 4640 Bt and NK45-T5) and three representative soybean cultivars (SOI 237, Kruger 2343 and Sans. S2062) were obtained (Tables 3 and 4),

although other varieties were also used for a year or two (Karlen et al., 1991).

3. Results and discussion

3.1. Calibration

Data from 1990 to 2003 from plot No. 25 were used for model calibration, but a continuous simulation was run for 1978 through 2003 after initializing the model for conditions on 1 January 1978. This plot was under no-till management with continuous corn from 1978 to 1992 and a soybean–corn rotation from 1993 to 2003. Fertilizer applications were at a constant rate of 202 kg N ha^{-1} as anhydrous ammonia (AA) from 1978 to 1992. From 1993 to 1998, N was applied in spring at 110 kg ha^{-1} as urea ammonium nitrate (UAN) for corn. In 1999, two N (UAN) applications were made for corn, one at pre-plant (30 kg ha^{-1}) and another in the late spring (139 kg ha^{-1}). Swine manure for an N equivalent of 106 kg N ha^{-1} in 2001 and 132 kg N ha^{-1} in 2003 corn crops also were applied.

The simulated volumetric soil water from 1990 to 1999 (only data available for comparisons) had an RMSE of 0.04 m^3 m^{-3} and MRE of 6.2% (Table 5), while simulations of total soil profile water storage (120 cm) had an RMSE of 4.15 cm (MRE=9.2%). Water table depth simulations showed reasonable correspondence with observed fluctuations with MRE of 13.2%, and RMSE of 16.0 cm (Table 5). RMSEs of daily and yearly tile drainage simulations were 0.12 cm day^{-1} and 9.41 cm yr^{-1} (Table 5). Drainage data for 1999 was removed from the tile drainage and N in tile drainage analysis as flooding and equipment damage were reported (Ma et al., 2007a-this issue). In addition to the errors introduced by the modeling uncertainties, errors in computations of soil water, water table and tile flow were mainly introduced by lack of site specific rainfall data and the specification of a single set (for different soil layers) of average K_{sat} values to represent all experimental plots in the model, when there was considerable amount of spatial heterogeneity in observed soil properties across various types of soils in the field (Ma et al., 2007b-this issue). However,

Table 5
Root Mean Squared Error (RMSE), Mean Relative Error (MRE) of model simulations of different soil, water and crop variables during model calibration. Data used was for plot 25 from 1978 to 2003

Simulated variables	RMSE	MRE (%)
Soil water (m^3 m^{-3})	0.04	6.2
Soil profile water (cm)	4.15	9.2
Water table (cm)	16.0	13.2
Tile drainage (cm day^{-1})	0.12	[a]
Tile drainage yearly (cm)	9.41	24.1
NO$_3$–N in tile flow (mg N L^{-1}),	16.1	[a]
Yearly NO$_3$–N in tile flow (kg N ha^{-1} yr^{-1})	14.16	21.4
Grain yield (kg ha^{-1}),	1244	−5.8
Biomass (kg ha^{-1}),	1939	8.8
Biomass N uptake (kg N ha^{-1}),	55.2	32.5
Grain N uptake (kg N ha^{-1}),	66.5	43.6
Soil NO$_3$–N concentration (mg N L^{-1})	5.8	[a]
Residual soil profile NO$_3$–N (kg N ha^{-1})	61.4	65.4

[a] Not computed as there were many days with zero observed or simulated values.

at the end of the 26-yr simulation, the difference between cumulative observed and simulated daily tile drainage was only 4.9 cm, and difference in annual N loading in the drainage water was only 5.4 kg N ha^{-1}. RMSE of daily N concentration in tile drainage simulation was 16.1 mg N L^{-1} (Table 5). Simulation error for daily N concentration in tile flow was caused primarily by uncertainties in the calibration for different soil organic and microbial pools and the extent to which these errors propagated into the daily mineralization of organic matter in the model (mainly microbial processes). Total annual N loading on tile flow from the plot was simulated better than daily N concentrations. Simulations of yearly tile N loading resulted in an RMSE of 14.16 kg N ha^{-1} and MRE of −21.4% (Table 5). Simulations of residual N in the soil profile (120 cm) and soil N concentrations had RMSEs of 61.4 kg N ha^{-1} and 5.8 mg N L^{-1}, respectively (Table 5). Using RZWQM with the generic crop growth module, Ma et al. (2007a-this issue) obtained RMSEs for soil water, water table depth, annual tile drainage, flow weighted N concentration in tile drainage and yearly N load of 3.9 cm, 17.4 cm, 9.1 cm, 9.3 mg L^{-1} and 13.1 kg N ha^{-1} yr^{-1}, respectively.

Emergence dates of soybean, and emergence and silking dates of corn crops were collected in the experiments. Departures of simulated dates of emergence of the soybean cultivars were within ±1 day from the observed dates. Simulated dates of emergence and dates of silking of different corn cultivars departed from the observed dates between −5 and 3 days.

Grain yield and biomass data for 1993, 1994 and 1995 were not used for calibration because crop performance in those years was severely influenced by other factors (flood, hail and insects) that are not simulated in those models (Malone et al., 2007a-this issue). Only five biomass measurements were available for comparison with the model simulations (Fig. 1). RMSE of biomass simulations was 1939 kg ha^{-1} with an MRE of 8.8% (Table 5). REs of simulations during individual years were between 2.2 and 17.5%. Grain yield simulations (corn and soybean combined) had an RMSE of 1244 kg ha^{-1} (RMSE of corn grain yield was 1414 kg ha^{-1}, and soybean was 791 kg ha^{-1}) and MRE of −5.8% (Fig. 1, Table 5). Calibration of RZWQM with the generic crop growth module resulted in RMSE of corn grain yield 1776 kg ha^{-1} and soybean grain yield 295 kg ha^{-1}, and an MRE of 11% for the corn and soybean grain yield simulations put together (Ma et al., 2007a-this issue). Simulated soybean grain yield for 1996 had an RE of −43.3%. As stated above, weather data for the experimental site was available only from 1998, as such temperature and precipitation data used for simulations from 1978–1997 were collected from an NCDC weather station at Charles City, Iowa located at about 15 km from the site. There can be substantial differences in the intensity, duration, and amount of precipitation received at the experimental site and at Charles City from year to year depending on the weather systems affecting the area. The model simulated higher water stress leading to low LAI simulations and lower than observed yield in 1996. On average, model simulated LAI for the 1996 soybean crop was 50% less than the same crop in 1998. Unfortunately, there were no LAI measurements during the experimental period. RE of corn grain yield simulated in 2003 was −35.9%. The model
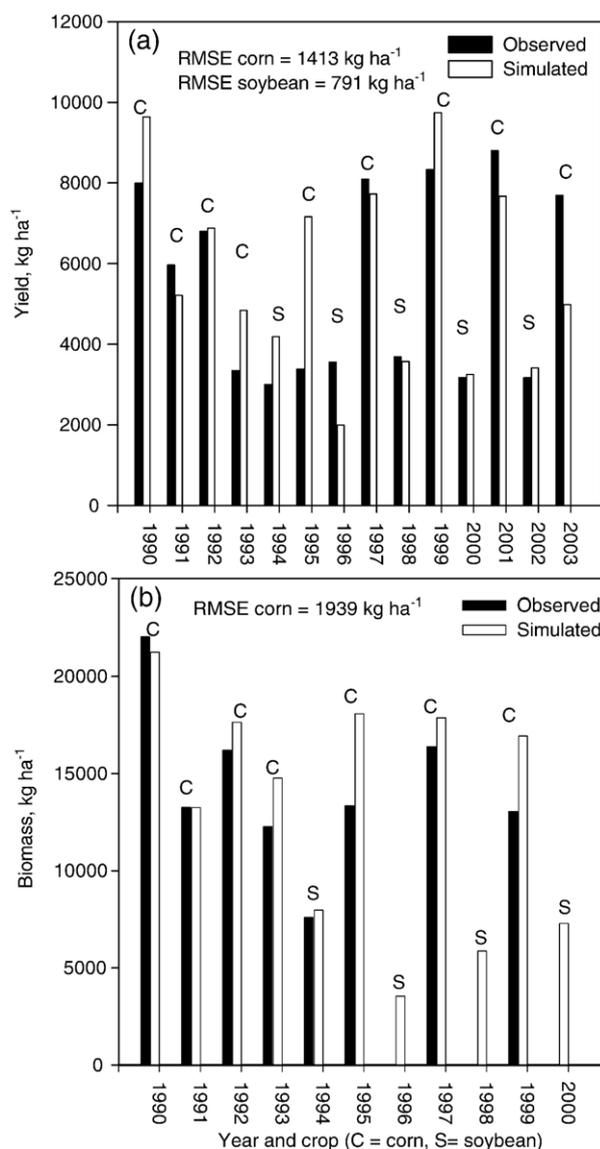

Fig. 1. Observed and simulated (a) grain yield, and (b) biomass of corn and soybean crops form 1990 to 2003. Observed data for 1993, 1994 and 1995 were not considered for calibration, but the model was run continuously from Jan 1, 1978 to 31 Dec., 2003. C = corn, S = Soybean. There was only one observation for soybean biomass, hence RMSE was not calculated. (RMSEs shown in the figures do not include data for 1993, 1994 and 1995).

simulated low grain yield in 2003 in response to the low rainfall received during July to August (8 cm) coinciding with flowering and early grain filling. During this crop season, the model simulated a water stress factor of 0.72 (in a scale from 0 to 1; 0=no water stress, and 1=maximum water stress) for photosynthesis during the grain-filling phase of the crop. On average, the grain yield simulations (both corn and soybean) had an MRE of −7.2%. This under-simulation was mainly caused by over-simulation of plant water stress in the model that reduced the biomass growth and leaf area expansion. It is possible that the uncertainty in the precipitation input in the model simulations, as discussed above, is playing a role here.

Biomass and grain N uptake simulations had RMSEs of 55.2 and 66.5 kg N ha^{-1}, respectively with corresponding MREs of
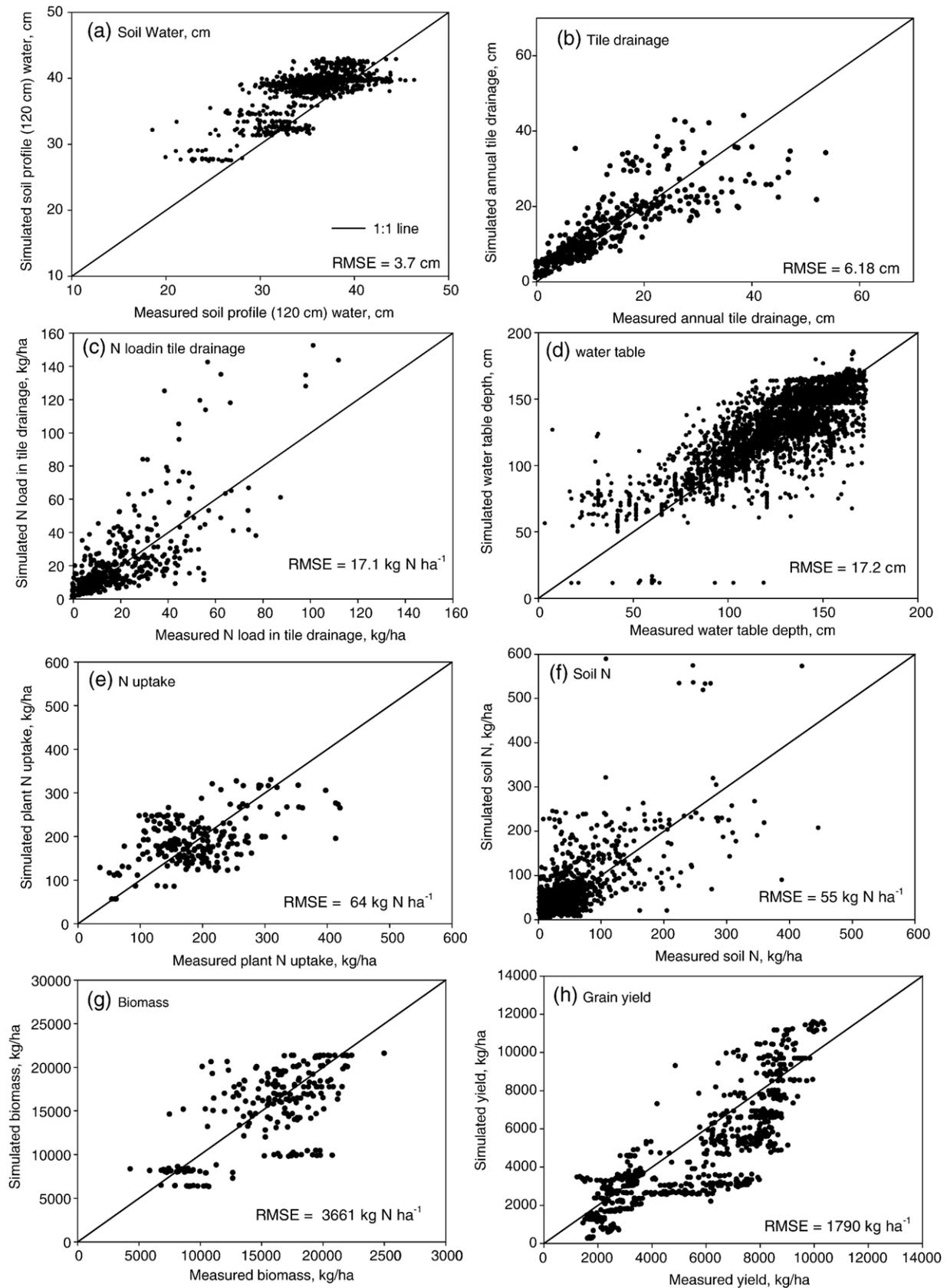
Fig. 2. Measured and simulated soil profile water, annual tile drainage, annual N load in tile drainage, water table depth, residual soil N, biomass N uptake, and grain and biomass yield for all the 30 plots (every plot and year are treated as a unique value) in the Nashua experiments.

32.5 and 43.6% (Table 5). REs of individual year crop grain and biomass N uptake simulations ranged between −16.8 and 115.5%, and −16.9 and 73.8% respectively. Ma et al. (2007a-this issue) also found high simulated RMSE (48 to 67 kg N ha^{-1}) for plant N uptake when they used the generic plant growth module in RZWQM and they contributed the high RMSE to errors in simulated N loading and residual soil N.

3.2. Model evaluation for simulations of management effects

Simulations for all the other plots were made by initializing the model for conditions on 1 January 1978 and then allowing the model to run through 31 December 2003. Six plots (#8, #17, #20, #27, #30, and #31) were excluded in this study because of their distinctly different hydrology from the rest of plots (Ma et al., 2007a-this issue). However, there were still at least two replicates for each treatment for the remaining 29 plots. Comparisons of measured and simulated management effects are presented as differences between two specified treatments (Figs. 3–7). The simulated responses coincide with observed effects if all the data points fall on the 1:1 line (x=y). In agricultural experiments, error associated with measurements of many of the variables is expected. Therefore, for an acceptable match between the simulated and observed effect of any particular treatment, the data points in the figure should fall either in the first or third quadrant made by the x–y axes. When the data points fall in the 2nd or 4th quadrants, the simulated

response was opposite of the observed. All our results represent average values for two to three replications in each treatment (Table 1).

Pooled data from the 30 plots for soil water storage, tile drainage, annual N loading in tile drainage, water table depth, residual soil N, biomass N uptake, grain yield, and biomass were with RMSEs of 3.7 cm, 6.18 cm, 17.1 kg N ha^{-1}, 17.2 cm, 55 kg N ha^{-1}, 64 kg N ha^{-1}, 1790 kg ha^{-1}, and 3661 kg ha^{-1}, respectively (Fig. 2). This level of accuracy was similar to what was reported by Ma et al. (2007a-this issue) using the generic plant growth model in RZWQM. Annual flow-weighted NO$_3$–N concentration in tile flow had an RMSE of 8.2 mg N L^{-1}. These results showed considerably scattering due to year-to-year climate variability and the uncertainties in input soil and weather data, and was very similar to what was observed by Ma et al. (2007a-this issue) when a generic plant growth model was used in RZWQM. In the following discussion, we only focused on simulated management effects by taking differences between two management practices rather than the absolute simulated values, so that simulation errors due to uncertainty in soil and weather inputs could be eliminated or minimized.

3.2.1. Tillage effects on tile drainage, N in tile drainage, and crop yield (experiments between 1978 and 1992)

Many productive soils of the Midwest need artificial drainage to remove excess water (Kanwar et al., 1983). Therefore, accurate model simulations of annual tile flow in response to
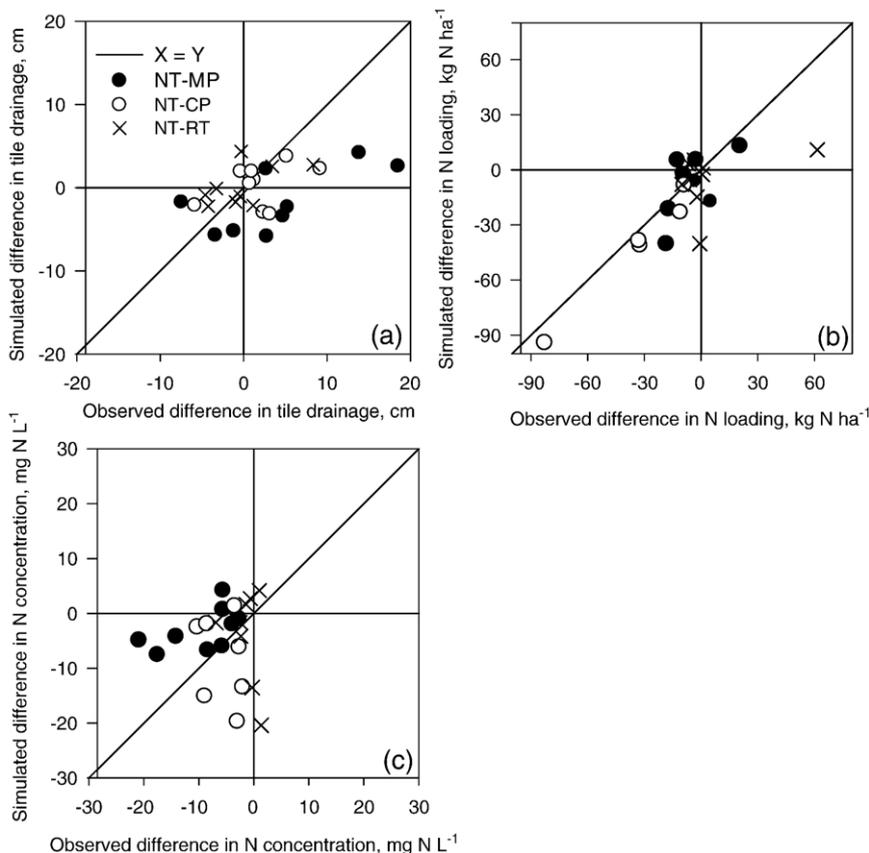

Fig. 3. Observed and simulated management effects of MP, CP, and RT relative to NT on (a) tile drainage, (b) N loading and (c) flow weighted N concentration in tile drainage. (MP = moldboard plow, CP = chisel plow, RT = ridge till, and NT = no till).
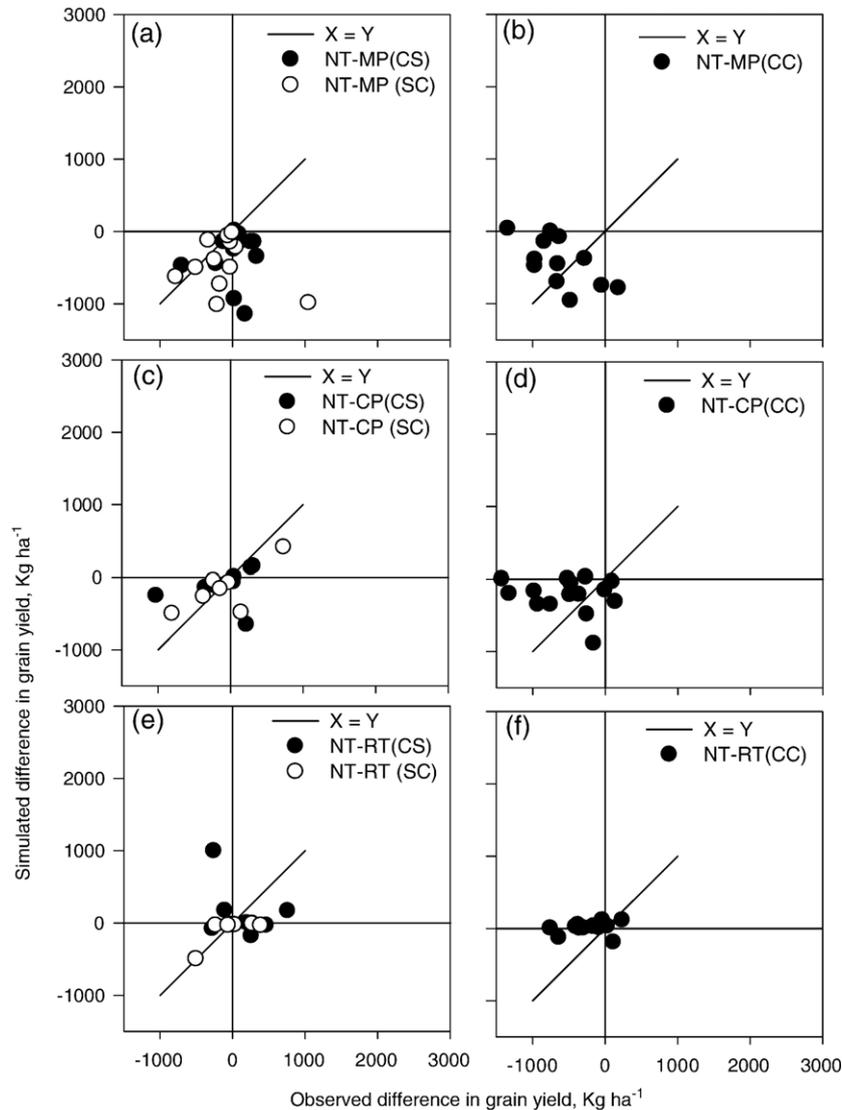
Fig. 4. Observed and simulated management effects of MP (a and b), CP (c and d), and RT (e and f) relative to NT on corn grain yield under CS, SC, and CC. (MP = moldboard plow, CP = chisel plow, RT = ridge till, NT = no till, CS: corn–soybean rotation with corn during even years, SC: soybean–corn rotation with corn during odd years, and CC = continuous corn).

different crop rotations and tillage practices conducted in the Nashua experiments are important in its evaluation as a management tool for agriculture in these areas. In general, the model simulated the observed differences in yearly tile flow in response to MP, CP and RT tillage treatments over NT fairly well (Fig. 3a). There were only 8 out of 27 (26%) observed tile drainage amounts that did not follow the observed trend and fell in the 2nd and 4th quadrants (Fig. 3a). Ma et al. (2007c-this issue) also obtained more than 70% agreement between measured and simulated tillage effects on tile flow using the RZWQM with the generic crop growth module.

Direct impacts of crop N management on NO_3–N in ground water have been identified (Hallberg, 1986). The amount of N in tile drainage from cropland gives a good indication of ground water N contamination potential for an N management system. In general, the observed and simulated effects of the MP, CP, and RT tillage effects on annual N loading and annual flow weighted N concentration in tile drainage relative to the NT

treatment compared well (Fig. 3b and c). For both N loading and flow weighted N concentration in tile drainage, 85% of the simulated values were plotted in the first and third quadrants in Fig. 3b and c, which was similar to what was obtained by Ma et al. (2007c-this issue) using the generic plant growth model in RZWQM (67–88%). Weed and Kanwar (1996) reported lower N concentration in tile drained water from plots under NT compared to tilled plots in the Nashua experiments. However, as reflected in Fig. 3b and c, the effect was not consistent in the long-term Nashua experiments, as the annual N loss in drain flow depended on tile flow amount and N in the soil.

The observed grain yield was generally enhanced by higher soil C and N concentrations under the MP, CP, and RT tillage treatments compared to NT (Karlen et al., 1991) (Fig. 4). In 83% of the crop seasons, the model accurately simulated the enhanced corn grain yield for MP and CP tillage treatments compared to NT (Fig. 4a, b, c, and d). In the CS and SC rotations the NT treatments were simulated to have 375 kg ha^{-1}

less corn yield on average compared to MP and CP, when the observed decrease was 74 kg ha^{-1}. In the CC rotation, simulated corn yield loss due to NT over MP and CP was 355 kg ha^{-1} compared to the observed value of 624 kg ha^{-1}. Higher simulated mineralization rates reduced N stress in these treatments (MP and CP) compared to NT. On average MP and CP treatments simulated 17 and 18% higher N mineralization compared to NT treatment, during corn years. Only 17% of the simulated grain yields deviated from the observed effect, and five of those eight occurred in the corn–soybean rotation (CS and SC). Simulations also failed in capturing correct yield trends (increase or decrease) for RT compared to NT for both CS and CC treatments (Fig. 4e and f). This means that RZWQM–DSSAT did not accurately simulate RT effects on various soil properties and processes because the model is one dimensional. As a consequence, the model simulated lower or equal N mineralization under RT compared to NT (data not presented). Since Ma et al. (2007c-this issue) also failed to simulate tillage effects on crop yield, tillage effects were due mainly to the soil water and nutrient status and less to plant growth modules used.

3.2.2. Crop rotation effects on tile drainage, N in tile drainage, and crop yield (experiments between 1978 and 1992)

In general, reductions in tile drainage due to CS and SC over CC were correctly simulated (Fig. 5a). Sixteen out of 18 simulations (88%) under the four tillage treatments followed the observed effects (see the data points in the first and third quadrants in Fig. 5a). Deviations of the remaining two simulations were not high. Similarly, RZWQM with generic crop growth module showed correct simulations of crop rotation effects for 67% of the observations (Ma et al., 2007c-this issue).

Kanwar et al. (1997) reported lower N losses to drainage water from CS and SC rotation compared to CC in the Nashua experiments. Comparisons between observed and simulated differences in annual N loading in tile drainage and annual flow weighted N concentration in tile drainage (yearly) in response to CS and SC compared to CC crop rotation for the four tillage systems are shown in Fig. 5b and c. In general, model simulations correctly followed observed reduction in annual N loading and N concentration in tile drainage from CS and SC compared to CC (all the data points were in the 3rd quadrant of the figure with a few points in the 1st quadrant). In the case of annual N loading in tile drainage and flow weighted N concentration, 99% (Fig. 5b and c) of the simulations followed the observed differences. Similar results were reported for simulations of the experiments with RZWQM (with the generic crop growth module), but with lesser degree of accuracy (54–88% depending on the year) (Ma et al., 2007c-this issue).

In the Nashua experiments, corn grain yields were significantly higher when grown in rotation with soybean than when grown continuously (Kanwar et al., 1997). RZWQM–DSSAT failed to simulate any of the observed crop rotation corn yield
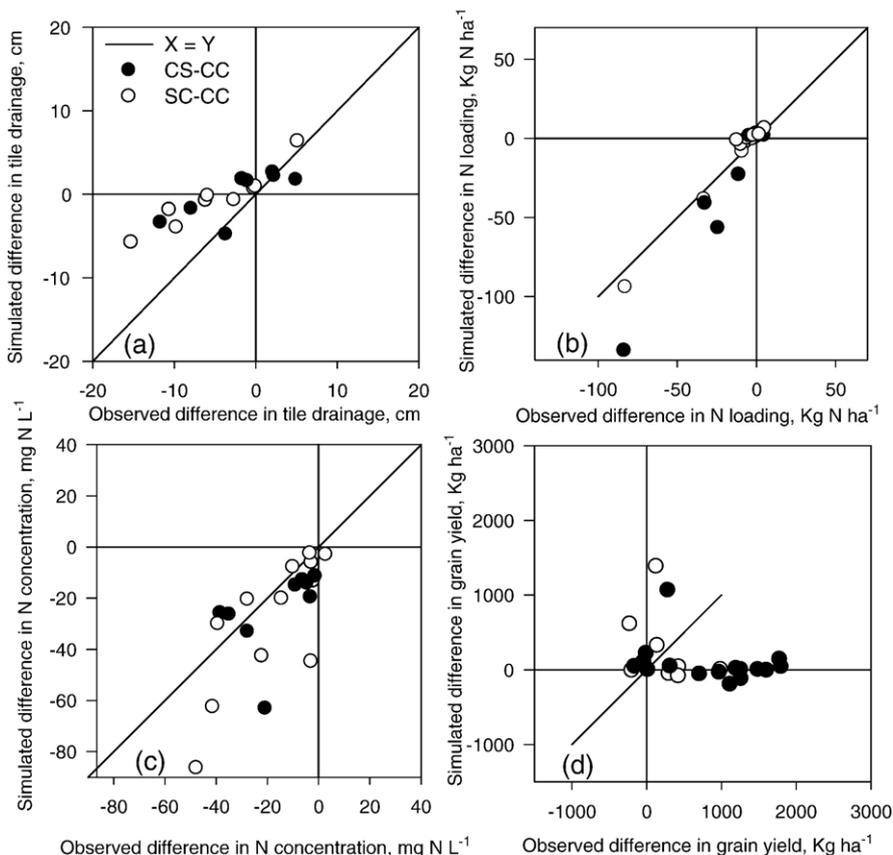

Fig. 5. Simulated and measured management effects of SC, CS and CC on annual tile drainage, annual N in tile drainage (N loading and flow weighted N concentration), and grain yield. (CS = corn–soybean rotation with corn during even years, SC = soybean–corn rotation with corn during odd years, and CC = continuous corn).

advantages in response to CS and SC compared to CC rotation (Fig. 5d). From the model point of view, higher yield from CS rotation than CC was due to possible N advantage from soybean. However, we found that simulated corn yield's response to N rate was only 5% on average when RZWQM–DSSAT was used to simulate a hypothetical CS rotation from 1978–2003 with UAN ranging from 100 to 200 kg N ha^{-1}. In contract, simulations using RZWQM with the generic crop growth module showed a 92% agreement between observed and simulated trend in corn yield in response to CS and CC rotation (Ma et al., 2007c-this issue), which might be due to a better N response of the generic crop growth model (Malone et al., 2007b-this issue).

3.2.3. N management effects on tile drainage, N in tile drainage, and crop yield. (experiments between 1993 and 1998)

Comparisons between observed and simulated differences in annual tile drainage in response to the SA and LSNT based N treatments for corn in the CS and SC rotation under NT and CP tillage treatments are shown in Fig. 6a. Increased tile drainage with SA over LSNT under NT was accurately (100% of the events) simulated by the model (all the plotted points fell in the first quadrant in Fig. 6a). With the exception of year 1993, all the observed decreases (99% of the events) in tile drainage with SA over LSNT under CP tillage treatment were also accurately

simulated. Excessive rainfall was reported in 1993, as such there were problems with accurate measurements of tile drainage that year due to instrument failures. It is important to mention here that as stated above, when the model calibrated for plot 25 was used for simulation of management effects for the remaining 29 plots, lateral hydraulic gradients were calibrated for each plot so that the simulated total tile drainage volume from 1990–2003 was reasonably matched to the measured amount (Ma et al., 2007a-this issue).

Based on LSNT, year-to-year N application rates in the LSNT treatments varied between 78 and 206 kg N ha^{-1}, and the N rates in SA treatments were between 110 and 112 kg N ha^{-1}. Fig. 6b and c give comparisons between observed and simulated differences in annual N loading in tile drainage in response to N management under NT and CP tillage treatments. In 21 of 24 comparisons (88%), observed annual N loading differences between SA and LSNT treatments were correctly simulated. The model also correctly simulated the increase in annual N loading in tile drainage under SA compared to LSNT under NT treatment, and the opposite effect of SA and LSNT on annual N loading under CP treatment. However, only 14 out of 24 (58%) of the observed differences in flow weighted N concentration in tile drainage between SA and LSNT were correctly simulated (Fig. 6c). Simulated increase in average N concentration in tile drainage due to LSNT compared to SA was only 0.1 mg N L^{-1} while the observed difference was 0.8 mg N L^{-1}.
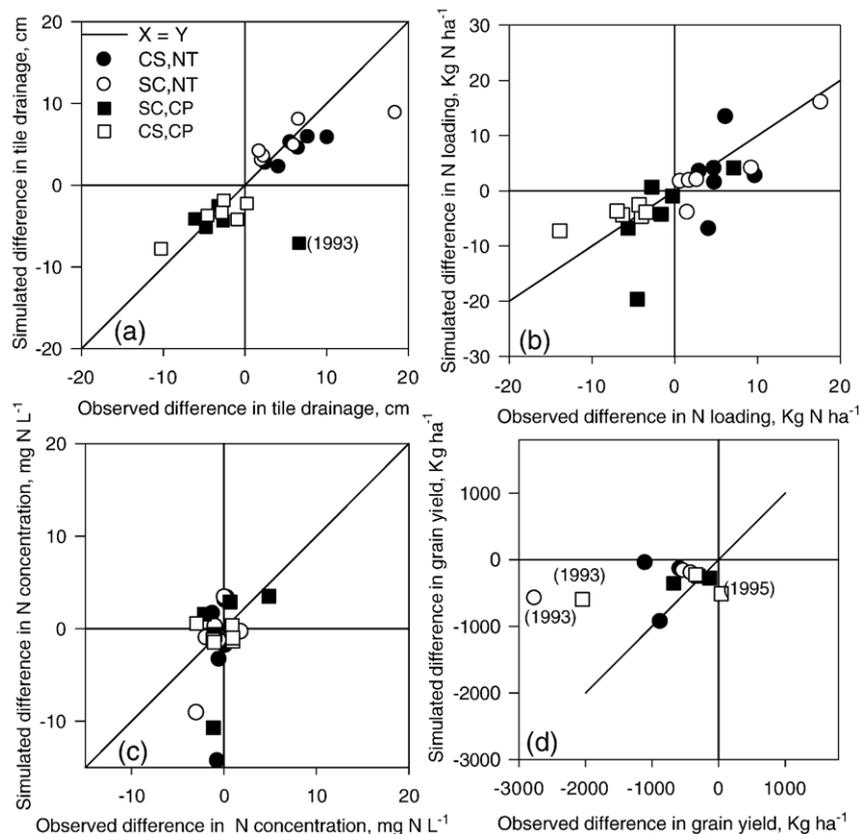

Fig. 6. Simulated and measured management effects between SA and LSNT (SA–LSNT) for CS and SC under CP and NT on tile drainage, N loading in tile drainage, flow weighted N concentration in tile drainage, and grain yield. (SA = single N application at pre-plant, LSNT = split dose N application at pre-plant and in late-spring based on late-spring soil N test, CP = chisel plow, NT = no till, CS = corn–soybean rotation with corn during even years, and SC = soybean–corn rotation with corn during odd years).

Fig. 6d compares observed and simulated differences in corn yield between SA and LSNT under the CS and SC rotations and CP and NT tillage treatments from 1993 to 1998. Bakhsh et al. (2000) reported significant increases in corn yield due to LSNT compared to SA for CP and NT treatments for corn in CS and SC rotation in the Nashua experiments, but their analysis could not ascertain if the yield response was caused by timing or rate of N fertilization. The model correctly (100% of the simulations) simulated the increased corn yield due to LSNT over SA (Fig. 6d), though the simulated increase was much less than the observed increase. Simulated yield responses were mostly due to the increased N rates under LSNT. On average the LSNT plots were simulated to have 359 kg ha^{-1} higher corn yield compared to SA, when the observed increase was 812 kg ha^{-1}. However, using RZWQM with the generic plant growth module, Malone et al. (2007b-this issue) simulated 10% higher in corn yield in the LSNT plots compared to a measured 14% increase; and 54% (measured was 10%) higher in flow weighted N concentration in the LSNT plots than in the SA plots (1993–1999), mostly because of higher N application rates.

Potential reasons for this aberration in model simulation were due to non-simulation of extreme events like flood, hail, high wind, and pest and diseases damage in the model. For example, 1993 was a transition year (Table 1), but excessive rains occurred throughout the Midwest that year (Bakhsh et al., 2000; Malone et al., 2007a-this issue). Malone et al. (2007a-this

issue) expressed concern that the low corn yield at Nashua compared to very high reports from other sites across Iowa in 1994 was also due to hail, wind, etc. that went unrecorded, since hail damage to the crops was also reported in 1995 (Andales et al., 2000). In 1993 and 1995, in the SC rotation under CP treatment, the simulated yield gain due to LSNT was 343 and 570 kg ha^{-1} against the observed yield gains of 2049 and −40 kg ha^{-1} (negative value indicates a yield loss this year), respectively (Fig. 6d). Also, in 1993, in the SC rotation under NT treatment, the simulated yield gain due to LSNT was 872 kg ha^{-1} against the observed yield gain of 2689 kg ha^{-1}. In 1994, simulated yield gain was 278 kg ha^{-1} against a measured value of 134 kg ha^{-1} in the CS rotation under CP treatment.

3.2.4. Swine manure management effects on tile drainage, N in tile drainage, and crop yield (experiments between 1993 and 2003)

Overall, our results indicate that the model was able to simulate effect of SM on tile drainage compared to SA reasonably well (Fig. 7). Effect of swine manure treatments on flow weighted N concentration and loading in tile drainage, and corn grain yields were the least accurately simulated by the model (Fig. 7). Comparison between observed and simulated trends in annual N loading and flow weighted N concentration in tile drainage between SA and SM treatments under corn–soybean rotation (both CS and SC) and CP tillage treatments are shown in Fig. 7b and c. Seventeen out of twenty two (78%)
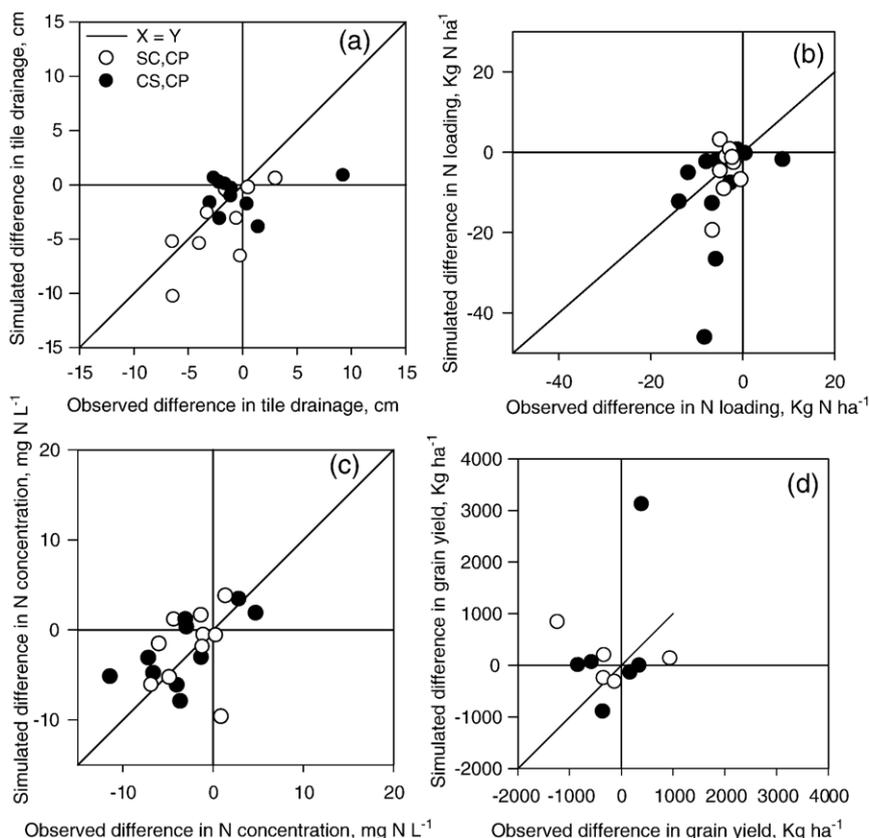

Fig. 7. Simulated and measured management effects between SA and SM (SA–SM) for CS and SC under CP on tile drainage, N loading in tile drainage, flow weighted N concentration in tile drainage, and grain yield. (SA = single N application at pre-plant, SM = fall injected swine manure, CP = chisel plow, CS = corn–soybean rotation with corn during even years, and SC = soybean–corn rotation with corn during odd years).

of the simulated differences in annual N loading and flow weighted N annual concentration between the treatments were simulated.

Both lower and higher grain yields for corn in the corn–soybean rotation due to SM compared to SA treatment were recorded (Fig. 7d). Four out of ten measured corn grain yields were higher under SA compared to SM treatment and six were lower. These inconsistent results indicate that the effect of SM treatment on corn growth depend not only on its nutrient (e.g., N and P) content but also on changes in soil hydraulic properties (porosity, water retention, and aeration) induced by the addition of the organic matter (manure) (Fleming et al., 1998). Singer et al. (2004) reported increased grain yields under swine manure treatments compared to organic N (SA) but suggested the effect was not necessarily due to soil N changes. Added organic matter can also alter the soil microbial and water dynamics in the soil interacting with the inter-annual climatic variability, affecting crop production differently in different years. These complex interactions are not modeled in RZWQM–DSSAT. As such, the model failed in simulating five out of eleven measured corn grain yield differences between the SA and SM treatments (Fig. 7d). Malone et al. (2007b-this issue) further discussed errors associated with fall and spring SM applications on N loading and crop production due to both errors in simulation of tile flow and N concentration in tile flow. In this study, we compared fall SM with spring SA. However, based on their discussion, it was not an easy task to directly compare SM and SA because of differences in timing of applications.

4. Summary and conclusions

We calibrated the RZWQM–DSSAT model for simulations of soil water, water table depth, tile drainage flow, annual N in tile flow, residual soil profile N, biomass and grain N uptake, and grain and biomass yield using 14 years data from a 26 year experiment conducted at Nashua, Iowa in the USA (Nashua experiments). The calibrated model was then applied for simulating the effects of tillage practices (RT, MP, CP, and NT), crop rotations (SC, CS and CC), and N (SA, and LSNT) and swine manure management practices on tile drainage volume, flow weighted N concentration in tile drainage, N loading in tile drainage, and corn grain yield. The model could be calibrated reasonably well for simulating grain and biomass yield, soil water, water table depth and tile drainage flow.

The calibrated model simulated 73% and 85% of the trends between CP, MP, RT and NT tillage practices on annual tile drainage and annual N in tile drainage, respectively. Trends in annual tile drainage, N loading in tile drainage, and flow weighted N concentration in tile drainage due to CS and SC rotation over CC were correctly simulated in 88, 99, and 99% of the years. Increased or decreasing trends in annual tile drainage with SA over LSNT were simulated in 100% of the years. Effect of SM treatments on N concentration and loading in tile drainage were the least accurately simulated. In addition to human errors in observations and instrument failures, deviations of the simulated tillage treatment effects from the observed effects can occur due to inadequate quantifications and representation of the different tillage effects on spatial soil physical and hydraulic properties in a one dimensional (vertical) model like RZWQM–DSSAT. Errors in simulations of tile drainage affect simulations of N in tile drainage as well, but errors in the latter can also be introduced by inadequate simulations of plant N uptake, and tillage effects on microbial population dynamics and N mineralization.

Under CS, SC and CC rotations, higher observed corn grain yield in the MP and CP treatments compared to NT were correctly (83% of the years) simulated. More studies on simulations of the effects of tillage practices on Rhizobia N fixation and dynamics in the soybean years may improve the subsequent corn yield simulation. Simulations totally failed in capturing the trends in RT effects on grain yields compared to NT under both CS and CC treatments, and in simulating the observed yield advantages due to CS and SC over CC under different tillage treatments. The model correctly (100% of the years) simulated the increased corn yield due to LSNT over SA, though the simulated increase was much less than the observed increase. The model failed in simulating the measured corn yield differences between SA and SM treatments in five out of eleven years.

Overall, the detailed crop-specific module in RZWQM (RZWQM–DSSAT) did not improve simulations of management effects over the generic plant growth module (Ma et al., 2007a-this issue). Very similar results were obtained in RZWQM with either plant growth modules, especially in terms of annual N loading. Yield responses to management were also very similar between the two plant growth modules, except that RZWQM with the generic plant growth module provided better corn yield responses to crop rotation (CS vs. CC). These results demonstrated that (1) once a plant growth module was calibrated for a site it could give reasonable results for that climate and soil conditions; (2) simulation errors for crop production (e.g., N uptake) were comparable using either plant growth modules for practical applications; and (3) simulation of soil water and nutrient status under various management practices was less affected by the type of plant growth modules used based on this long-term study under tile-drained soil conditions.

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