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RZWQM simulation of long-term crop production, water and nitrogen balances in Northeast Iowa

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Abstract

Agricultural system models are tools to represent and understand major processes and their interactions in agricultural systems. We used the Root Zone Water Quality Model (RZWQM) with 26 years of data from a study near Nashua, IA to evaluate year to year crop yield, water, and N balances. The model was calibrated using data from one 0.4 ha plot and evaluated by comparing simulated values with data from 29 of the 36 plots at the same research site (six were excluded). The dataset contains measured tile flow that varied considerably from plot to plot so we calibrated total tile flow amount by adjusting a lateral hydraulic gradient term for subsurface lateral flow below tiles for each plot. Keeping all other soil and plant parameters constant, RZWQM correctly simulated year to year variations in tile flow (r^2 = 0.74) and N loading in tile flow (r^2 = 0.71). Yearly crop yield variation was simulated with less satisfaction (r^2 = 0.52 for corn and r^2 = 0.37 for soybean) although the average yields were reasonably simulated. Root mean square errors (RMSE) for simulated soil water storage, water table, and annual tile flow were 3.0, 22.1, and 5.6 cm, respectively. These values were close to the average RMSE for the measured data between replicates (3.0, 22.4, and 5.7 cm, respectively). RMSE values for simulated annual N loading and residual soil N were 16.8 and 47.0 kg N ha^{-1}, respectively, which were much higher than the average RMSE for measurements among replicates (7.8 and 38.8 kg N ha^{-1}, respectively). The high RMSE for N simulation might be caused by high simulation errors in plant N uptake. Simulated corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] yields had high RMSE (1386 and 674 kg ha^{-1}) with coefficient of variations (CV) of 0.19 and 0.25, respectively. Further improvements were needed for better simulating plant N uptake and yield, but overall, results for annual tile flow and annual N loading in tile flow were acceptable.

Keywords: Subsurface drainage; N loading; Tile flow; Agricultural systems modeling; Agricultural management; Tillage; Crop rotation

1. Introduction

Agricultural system models have been improved tremendously in the last two decades because of advancements in computer technology, integration with field research, and real-time data collection. The Root Zone Water Quality Model (RZWQM) has evolved steadily since its debut in 1992 (Ahuja et al., 2000). By partnering with scientists at MSEA (Management Systems Evaluation Areas) sites, team members developing RZWQM have been able to integrate field research results (Watts et al., 1999) and test the model for: 1) water and pesticide movement in Minnesota (Wu et al. 1999); 2) surface runoff, nitrate and pesticide losses to seepage and runoff, and crop yield in Missouri (Ghidey et al., 1999); 3) crop yield, and water, nitrate and pesticide movement in Iowa (Jaynes and Miller, 1999); 4) crop yield, N uptake, plant biomass, leaf area index, soil water content, and soil N in Nebraska (Martin and Watts, 1999); and 5) leaf, stem, and seed biomass of corn in Ohio (Landa et al., 1999).

At another MSEA site near Nashua, IA the RZWQM has been evaluated extensively under tile-drained conditions to estimate pesticide leaching, N loss, and crop growth (Bakhsh et al., 2004a,b; Singh et al., 1996; Kumar et al., 1998a,b). This site is composed of 36 0.4-ha plots and has gone through three phases of study (1978–1992, 1993–1998, 1999–2003). In

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previous model applications, RZWQM was used only for selected plots (management systems) and years. Kumar et al. (1998a) tested RZWQM on three plots (Plot #13, #22, and #35) and for 1993 and 1995 growing seasons to study swine manure application on nitrate leaching in tile drains. In a subsequent study, they evaluated RZWQM on six plots (#14, #25, #31 for no till and #13, #22, and #35 for moldboard plow) from 1990 to 1992 to investigate macroporosity effects on pesticide transport to tile drains (Kumar et al., 1998b) and pesticide distributions in soils (Azevedo et al., 1997). Singh and Kanwar (1995a,b) and Singh et al. (1996) simulated tile drainage and nitrate-N losses to tile drains using RZWQM for 12 of the plots (continuous corn) from 1990 to 1992. The same set of data was later used by Kumar et al. (1999) to study tillage effects on water and nitrate movement with RZWQM. Bakhsh et al. (1999) applied RZWQM to three manure plots (#11, #23, and #27) for 1993–1996 data to study swine manure application on nitrate-N transport to tile drains. In order to fully integrate RZWQM with the long-term field study near Nashua, we need to simulate all the management practices (crop rotation, tillage, and N and

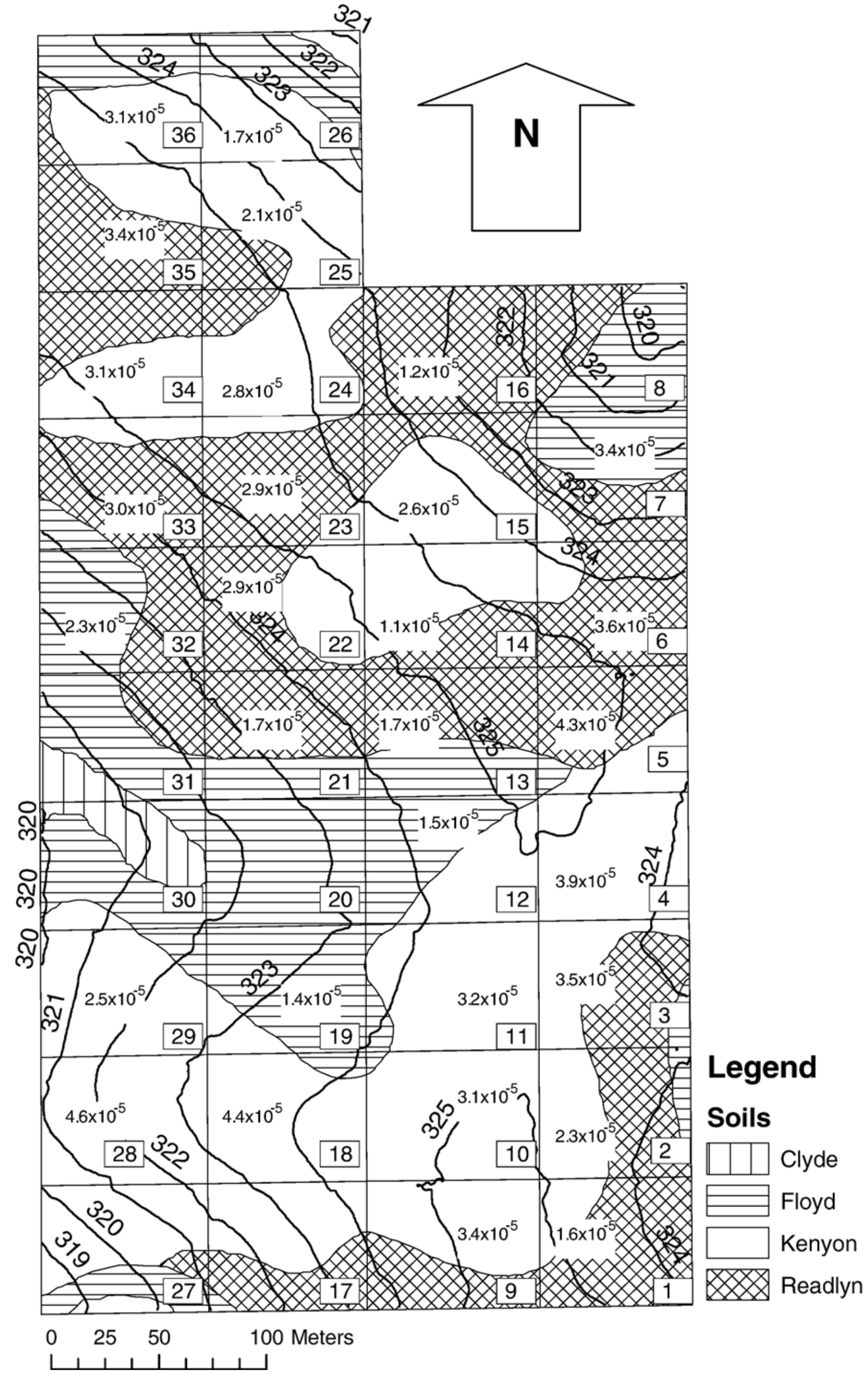

Fig. 1. Schematic of the 36 Nashua plots. Lines are digitized elevation and scientific numbers in each plot are calibrated lateral hydraulic gradients.

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 , 21, 26	Readlyn/Kenyon	CC	CC	SC	AA	UAN	SM	CP	CP	CP
6 , 32, 36	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/LCD)	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/LCD)	MP	CP	CP
13, 22, 35	Readlyn/Floyd	CC	CC	CS	AA	SM	SM	MP	CP	CP
14, 25, 31	Readlyn/Kenyon	CC	SC	SC	AA	UAN	SM	NT	NT	NT

CS: corn–soybean rotation; SC: soybean–corn rotation; 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; LCD: localized compaction and doming; SM: swine manure. Plots #8, #17, # 20, #27, #30 and #31 were excluded from this study.

manure management) for all the years on all the plots. Doing so will: 1) quantify weather variability; 2) identify possible experimental errors due to equipment failure or mismanagement; and 3) fill in data gaps that will allow analysis of water and N balances in the soil–plant–atmosphere continuum.

Since most RZWQM applications at other locations used only 2 to 4 years of field data as shown above (Ma et al., 2000, 2003; Bakhsh et al., 2004a,b; Jaynes and Miller, 1999; Kumar et al., 1998a,b), in this study, we recalibrated an improved version of RZWQM for one plot using the 26 years of data collected in Nashua, Iowa of the USA and then applied the calibrated soil and plant parameters to other plots with various management practices. Therefore, our objectives were to (1) demonstrate the calibration of RZWQM for plant and soil parameters using long-term field experiments and (2) analyze the overall goodness-of-simulation of RZWQM for crop yields as well as long-term water and N balances under different management practices. However, detailed analyses of simulation results for a specific management effect (rotation, tillage, and N management) were discussed by Ma et al. (2007a-this issue) and Malone et al. (2007-this issue).

2. Materials and methods

The experiment was conducted at Iowa State University's Northeast Research Center near Nashua, IA. The three dominant soils at this site are Floyd loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls), Kenyon silty-clay loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls), and Readlyn loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls). These soils are moderately well to poorly drained, lie over loamy glacial till, and belong to the Kenyon–Clyde–Floyd soil association. The seasonal water table fluctuates from 20 to 160 cm and subsurface drainage tubes/pipes (10 cm in diameter) were installed in the fall of 1979 at 120 cm depth and 29 m apart. A trenchless drain plow was used to install the center drain in each plot and a chain trencher was used to install the drains between the plots (Karlen et al., 1991).

The research site consists of 36 0.4-ha plots that are instrumented to collect drainage water from the center of each plot for water quantity and quality analysis (Fig. 1; Table 1). Drainage flow and N loss in drainage were monitored for each plot since 1990. The total flow from 1990 to 2003 for 30 of the

Table 2
Measured and default soil parameters used in RZWQM to simulate management effects

Soil depth (cm)	Bulk density (g/cm^3)	Porosity (cm^3/cm^3)	Saturated soil hydraulic conductivity (Ksat, cm/hr)	Soil water content at 33 kPa (cm^3/cm^3)	Soil water content at 1500 kPa (cm^3/cm^3)	Lateral saturated soil hydraulic conductivity (Klat, cm/hr)	λ (dimensionless)
0–20	1.45	0.442	3.60	0.300	0.145	3.60	0.086
20–41	1.51	0.430	6.05	0.270	0.132	6.05	0.070
41–50	1.51	0.430	8.50	0.260	0.127	8.50	0.070
50–69	1.60	0.405	11.50	0.234	0.116	11.50	0.092
69–89	1.60	0.405	14.50	0.234	0.116	14.50	0.092
89–101	1.69	0.372	1.80	0.260	0.127	9.41	0.060
101–130	1.80	0.333	1.80	0.280	0.136	17.22	0.060
130–150	1.80	0.333	0.01	0.280	0.136	0.01	0.060
150–200	1.80	0.333	0.01	0.280	0.136	0.01	0.060
200–252	1.80	0.333	0.01	0.280	0.136	0.01	0.060

λ is pore size distribution index used to describe the soil water retention curves. (from Ma et al., 2007b-this issue).

Table 3
Initial soil organic and soil microbial pools used in the simulations

Soil depth (cm)	Fast humus pool (μg C/g soil)	Transient humus pool (μg C/g soil)	Stable humus pool (μg C/g soil)	Aerobic heterotrophs (no./g soil)	Autotrophs (no./g soil)	Anaerobic heterotrophs (no./g soil)	NO_3–N Conc. (μg N/g soil)	NH_4–N Conc. (μg N/g soil)
0–20	0	0	15,000	1,300,021	6870	12,448	3.090	0.037
20–41	0	0	7184	255,601	1857	15,166	1.140	0.003
41–50	0	0	5355	220,965	935	14,437	0.495	0.002
50–69	0	0	3524	145,640	752	8875	0.369	0.002
69–89	0	0	2589	84,155	407	5789	0.298	0.002
89–101	0	0	1694	15,114	78	1207	0.250	0.001
101–130	0	0	1693	10,630	56	640	0.225	0.000
130–150	0	0	846	4707	32	251	0.249	0.000
150–200	0	0	592	3286	22	189	2.099	0.000
200–249	0	0	422	2375	18	148	3.558	0.000

36 plots ranged from 111 to 270 cm with an average of 185 cm. Three plots (Nos. 20, 30, and 31 in Fig. 1) have or are close to the poorly drained Clyde soil and therefore have had much higher tile drainage (335 to 505 cm between 1990 and 2003). Plot #8 also had higher than average tile drainage (385 cm) for the same period. Plots 17 and 27 had below average tile drain flow (43 cm to 56 cm for this period). These six plots were excluded in this study because of their distinctly different hydrology, but there were still at least two replicates for each treatment. The field study was conducted in three phases. From 1978 to 1992, the main focus was on tillage (moldboard plow, chisel plow, ridge till, and no till) and crop rotation (continuous corn, corn–soybean). Anhydrous ammonia was applied in 1990–1992 and UAN (urea–ammonium–nitrate) was applied in other years as fertilizer. Crop yield was the primary measurement from 1978 to 1989. Data for 1990 through 1992 included drainage flow; nitrate concentration in the drainage; residual N; crop biomass, grain yield, and N uptake. From 1993 through 1998, the main focus was on N management including liquid swine manure, N rates, and using the late spring nitrate test (LSNT) to determine the N fertilizer rate. The number of tillage practices was reduced from four to two practices (chisel plow and no till) in 1993 to accommodate the additional N management treatments. Data collection included tile drainage; runoff; soil nitrate; nitrate concentrations in the drainage water; crop N uptake, yield, and biomass. From 1999 through 2003, the main focus of the study was on manure application rate, timing, and method. Manure application rates were based on N or P needs for both phases of a corn–soybean rotation, either in the fall or spring. Chisel plow and no till management practices were continued. Each cropping season received manure and/or UAN liquid fertilizer. Experimental measurements included drainage; nitrate concentrations in the drainage water; N concentration in the soil; crop N uptake, yield, and biomass. Soil hydraulic conductivities and soil water retention curves were determined using soil samples collected in 2001 from a nearby field (Ma et al., 2007b-this issue) (Table 2). Weather data (solar radiation, daily rainfall) were derived from an on-site weather

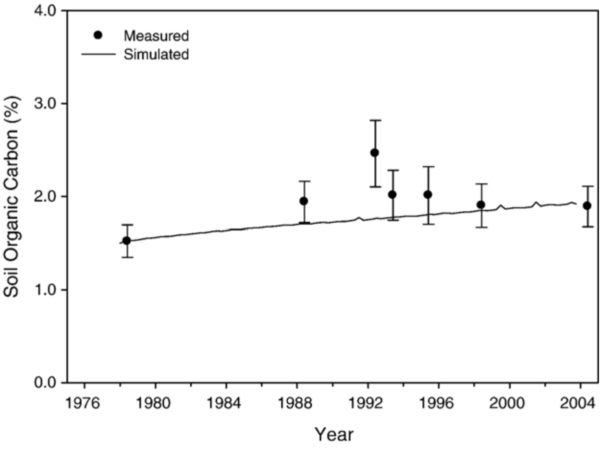

Fig. 2. Average measured soil organic carbon (OC) from 1978 to 2004 for the 36 plots in the top 20 cm soil profile, in comparison with simulated soil OC. The bars are one-standard derivation from the means.

Table 4
Calibrated plant model parameter values of RZWQM for corn and soybean

Parameter name	Corn	Soybean
Minimum leaf stomatal resistance (s/m)*	100	100
Maximum active N uptake per plant (g N/plant/day)*	1.5	0.4
Photosynthesis rate at reproductive stage compared to vegetative stage (fraction)*	1.0	0.9
Photosynthesis rate at seeding stage compared to vegetative stage (fraction)*	1.0	0.85
Coefficient to convert leaf biomass to leaf area index, CONVLA (g/LAI)*	10.0	0.7
Plant population on which CONVLA is based (plants/ha)*	71,114	494,000
Maximum rooting depth (m)*	1.5	1.0
Maximum plant height (m)	2.5	0.5
Aboveground biomass at ½ maximum height (g)	30	5
Aboveground biomass of a mature plant (g)	250	15
Minimum time needed from planting to germination (days)	4	4
Minimum time needed from germination to emergence (days)	10	10
Minimum time needed from emergence to 4-leaf stage (days)	12	6
Minimum time needed from 4-leaf stage to end of vegetative growth (days)	38	30
Minimum time needed from end of vegetative to end of physiological maturity (days)	38	40

Parameters with an asterisk are suggested calibration parameters by the model developers.

Table 5
Simulated plant growth, total water and nitrogen balances during the simulation period for plot 25

	Total balance accumulated over 26 years	Annual range	Annual average
N balance (kg N ha^{-1})			
Fertilizer application	3772		
N fixation	1280	196–336	256
Net mineralization	2847	67–223	109
Denitrification	402	6.5–46.4	15.4
Volatilization	28	0.0–9.4	1.1
N uptake (corn+soybean)	6354		
N loss in tile flow	483	0.6–128.1	18.6
N loss in lateral flow	528	5.8–61.2	20.3
Change in soil N storage	102		
Runoff+deep seepage	1		
Water balance (cm)			
Rainfall	2267	40.8–123.9	88
Tile flow	328	0.4–36.1	12.6
Lateral flow	352	5.7–23.7	13.5
Runoff	173	0.9–13.2	6.6
Evapotranspiration (corn or soybean)	1420	39.4–67.4	54.6
Change in soil water storage	−4		
Plant growth			
Corn yield (kg ha^{-1})		3772–10875	7580
Corn aboveground biomass (kg ha^{-1})		13184–21807	18207
Maximum LAI for corn (dimensionless)		5.8–9.8	8.6
Corn N uptake in aboveground biomass (kg N ha^{-1})		108–211	184
Soybean yield (kg ha^{-1})		3335–3512	3397
Soybean aboveground biomass (kg ha^{-1})		7338–10332	8722
Maximum LAI for soybean (dimensionless)		3.6–4.8	4.1
Soybean N uptake in aboveground biomass (kg N ha^{-1})		252–349	295

station for most of the years with missing data filled from nearby weather stations (Saseendran et al., 2007-this issue).

RZWQM was calibrated using data from Plot #25 because the water table in this plot was recorded continuously and the plot had all crop rotations (continuous corn and both phases of the corn–soybean rotation), inorganic fertilizer and manure applications during the 26 years of research at this site. The calibrated soil and plant parameters from Plot #25 were subsequently used for the other 29 plots with different rotation, tillage, and N management treatments, with the same plant parameters, initial soil nutrient condition, and soil hydraulic properties, except for the lateral hydraulic gradients for subsurface flow, which were adjusted for each plot (Ma et al., 2007b-this issue).

3. Results and discussion

3.1. Model calibration

Model calibration was conducted following the procedure outlined by Ma et al. (2003). Measured soil hydraulic properties were used for the 10 soil layers (Table 2). Since the lateral saturated soil hydraulic conductivity (Lksat) was not sensitive except for the layers immediately above (#6) and between (#7) the tile drains, Lksat was therefore assumed to be the same as the vertical saturated soil hydraulic conductivity (Ksat) for all the layers except the two (#6 and #7) layers. Lksat for these two layers were optimized and listed in Table 2 (Ma et al., 2007b-this issue). Soil carbon pools were calibrated based on measured data assuming all the carbon was in the slow humus pool since the site had very low fertility when the experiments were started in 1978 (Karlen et al., 1991, 1998). Microbial population was initialized by running the model using current management practices for Plot #25 and weather data for a course of 26 years. The calibrated values are listed in Table 3. The estimated soil organic pools can only be tested with soil organic carbon (OC) in the top 20 cm soil profile. As shown in Fig. 2, simulated soil OC from 1978 to 2003 was close to measured values. The model simulated a 0.40% increase in soil OC compared to a 0.40% observed increase from 1978 to 2003. However, simulated OC levels failed to repeat the initial rapid change from 1978 to 1988 and then the steady-state from 1988 to 2003. The high measured soil OC in 1992 was more likely due to a sampling error because a new laboratory technician was hired to collect and analyze those samples and the resultant values were considerably higher than expected or subsequently re-measured in 1993. Simulated yearly N mineralization from swine manure

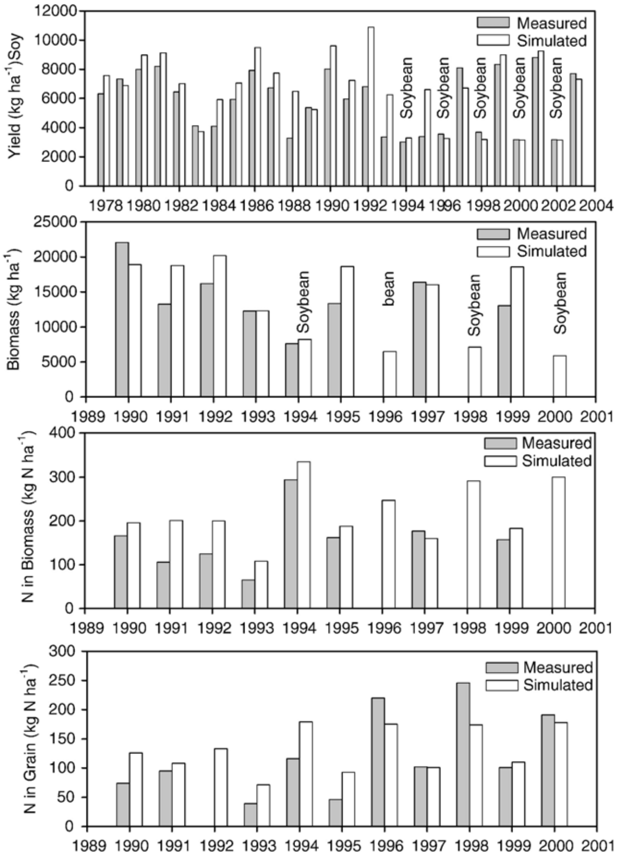

Fig. 3. Simulated and measured yield, biomass, and N uptake for Plot #25.

was about 51% in the first year, which is in agreement with commonly hold assumptions (Karlen et al., 2004).

Plant growth was calibrated last by adjusting the parameters (Table 4) as suggested by Ma et al. (2003). Although corn and soybean varieties have been changed throughout the 26 years of experiments (Karlen et al., 1991), only one set of plant parameters was used for either corn or soybean. Since some of the plant parameters were inter-dependent, the values in Table 4 might be best viewed as a set of parameters that provided reasonable simulations of plant growth. Grain yield was the only complete measurement (along with a few years of above ground biomass data), so we adjusted the parameters manually by trial and error until the model simulated reasonable maximum leaf area index and selected growth stages (e.g., germination, beginning of reproductive growth). Table 5 shows calibrated plant growth along with water and N balances. On average, the model over-predicted corn yield by 17% with RMSE (root mean square error) of 1757 kg ha^{-1} or CV (coefficient of variation) of 0.28 and under-predicted soybean yield by 4% with RMSE of 295 kg ha^{-1} or CV of 0.09. The high RMSE for corn was mainly due to over-prediction in years 1992, 1993 (flood damage), and 1995 (hail damage). The reason for the low yield in 1992 was unknown except for low rainfall in May (5.3 cm), June (5.4 cm), and August (6.7 cm). Eliminating these 3 years from statistics resulted in an over-prediction of 11% and CV of 0.19. Correlation between measured and simulated corn yield from year to year was low with $r^2 = 0.48$ when all the years were included and improved with $r^2 = 0.61$ when 1992, 1993 and 1995 were excluded (Fig. 3). Although soybean yield were simulated well with RMSE of 295 kg ha^{-1}, it did not

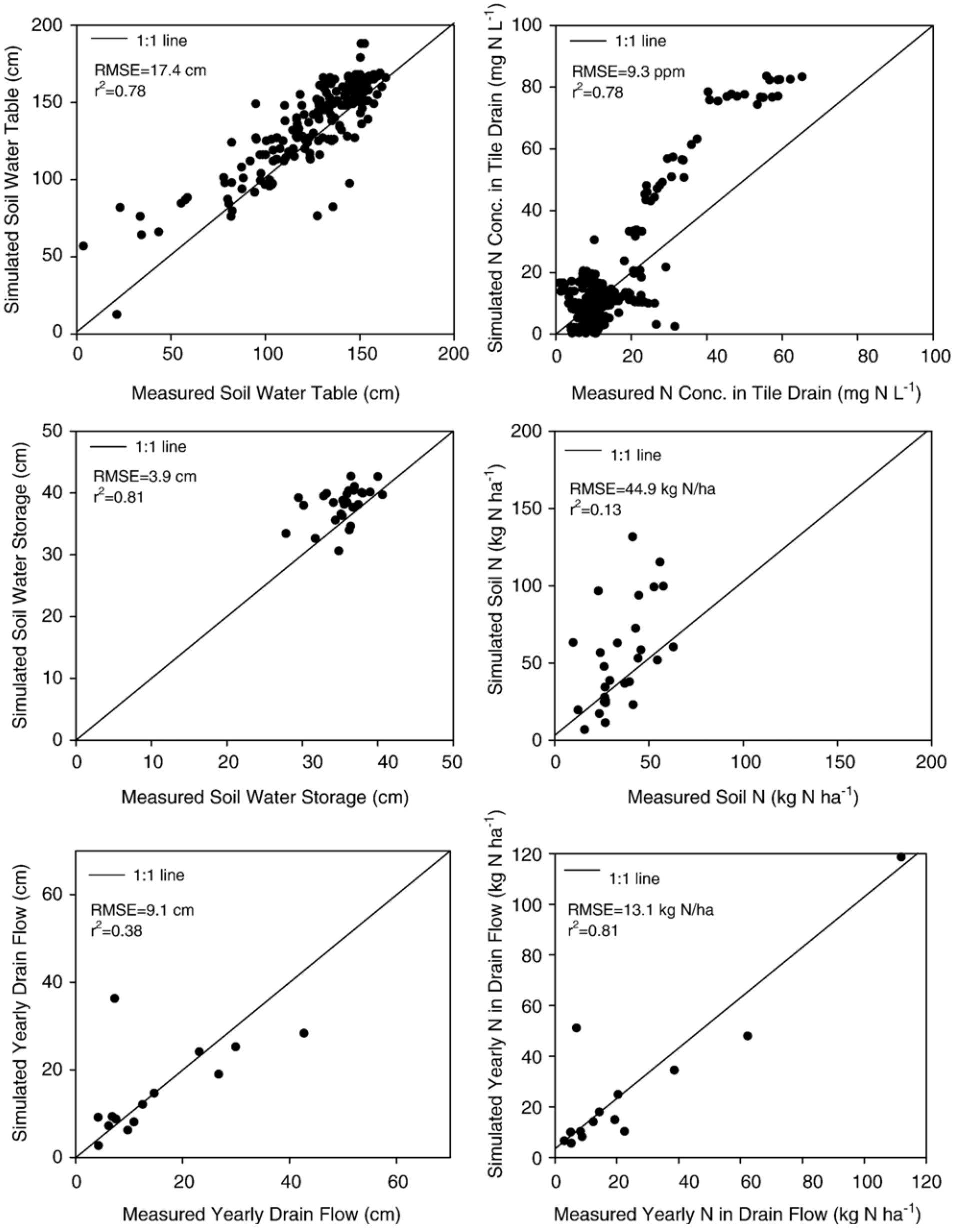

Fig. 4. Simulated and measured soil water and N balances for Plot #25. Soil water storage and soil N are measured in the top 120 cm soil profile.

respond to yearly variation with r^2 close to zero. The reason for the no response was a very low annual variation in measured soybean yield (standard derivation of 290 kg ha^{-1}). Corn biomass was over-predicted by 15% with CV of 0.27. Biomass measurements for soybean were available for 1994 only (7590 kg ha^{-1}), but overall the simulated value was reasonable (8217 kg ha^{-1}) with only 8% over-prediction (Table 5). However, measurement of soybean biomass was very difficult because of sloughed leaves and aborted pods.

Simulated total tile drainage flow from 1990 to 2003 was 209 cm which matched the measured flow (209 cm) for the same period. Simulated total N loading was 321 kg N ha^{-1} from 1990 to 2003, which was also close to the measured value of 343 kg N ha^{-1}. It should note that sometimes there were recorded drainage flows without associated N concentrations. As an approximation, we took the average of measured N concentrations available before and after the missing event to fill the missing data. Therefore, actual total N loss might be slightly different from what is reported in this paper. Also shown in Fig. 4 are simulated and measured depths to water table with r^2 of 0.78; soil water storage in the top 120 cm soil profile with a RMSE of 3.6 cm and r^2 of 0.20; and simulated yearly drainage flow with a RMSE of 9.1 cm. The high RMSE of simulated annual tile flow was due primarily to the higher prediction in 1999 (36.1 cm vs. 7.4 cm) when flooding occurred and flow measuring equipment failed. As a result, drainage N loss was also over-predicted for 1999 with an overall RMSE of 13.1 kg N ha^{-1} (Fig. 4). If the 1999 data was omitted, RMSE for simulated tile flow was reduced to 5.3 cm with an r^2 of 0.87, and RMSE for simulated yearly N loss in tile flow was decreased to 7.0 kg N ha^{-1} with r^2 of 0.97. Although measured N concentration in tile flow was over-predicted for high N loss events, a high correlation between measured and simulated concentrations was observed (r^2 = 0.78). Total soil nitrate-N in the 120 cm soil profile was also generally over-predicted with RMSE of 44.9 kg N ha^{-1} and r^2 of 0.13 only (Fig. 4). Poor simulations in soil N may be partially due to extremely dry weather in 1989, which caused difficulty in both modeling and soil sampling. Biomass N was over-predicted by 29% for corn and 14% for soybean on average. Grain N uptake was over-predicted by 33% for corn and under-predicted by 8% for soybean on average. Therefore, there is a need to improve plant N uptake and its effects on growth in RZWQM.

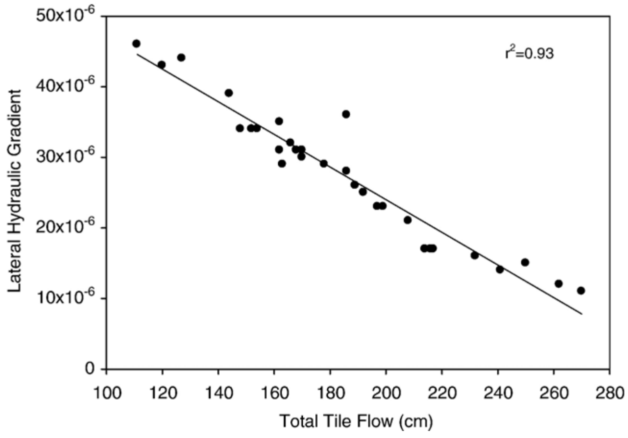

Fig. 5. Correlation between calibrated lateral hydraulic gradient (LHG) and measured total tile flow.

Table 6
Goodness of simulation across all the plots and years in terms of root mean square errors (RMSE) and coefficient of variation (CV)

Variables	RMSE (between measured and simulated)	Coefficient of variation (CV)	RMSE between replicates
Soil water storage in the 120 cm soil profile (cm)	3.0	0.08	3.0
Water table (cm)	22.1	0.18	22.4
Yearly tile flow (cm)	5.6	0.44	5.7
Yearly N loading in tile flow (kg N ha^{-1})	16.8	0.79	7.8
Soil nitrate-N (kg N ha^{-1})	47.0	0.91	38.8
Yearly flow weighted N concentration (mg N L^{-1})	8.9	0.52	3.0
Corn yield (kg ha^{-1})	1386	0.19	406
Soybean yield (kg ha^{-1})	674	0.25	139
Corn biomass (kg ha^{-1})	2692	0.16	1664
Soybean biomass (kg ha^{-1})	2438	0.27	878
Corn N uptake in biomass (kg N ha^{-1})	48	0.28	25.3
Soybean N uptake in biomass (kg N ha^{-1})	67	0.23	40
Corn N in grain (kg N ha^{-1})	40	0.41	7.6
Soybean N in grain (kg N ha^{-1})	45	0.25	14.1

An advantage of using system models to analyze field studies is that processes or properties that were not measured due to technical issues or resource limitations can be examined. One such process is mineralization of organic carbon. RZWQM simulated an average mineralization rate of 109 kg N ha^{-1} yr^{-1} with a range from 67 to 223 kg N ha^{-1} yr^{-1} (Table 5). This is within the range reported in the literature for manure and non-manure field studies (Vigil et al., 2002, Schepers and Mosier, 1991). The model also simulated about 51% of organic N being mineralized the first year, which is in agreement with common assumption in manure fertilization (Karlen et al., 2004). However, N fixation was high (196–336 kg N ha^{-1}) in our simulations (Table 5) compared to that reported by Schepers and Mosier (1991) who listed from 57 to 94 kg N ha^{-1} for the U.S. Midwest- and 73 to 218 kg N ha^{-1} for Southeastern-conditions. This presumably occurs because RZWQM does not simulate N fixation *per se* but rather the difference between soybean N demand and soil N supply is assumed to be met through fixation. Simulated denitrification loss averaged 15.4 kg N ha^{-1} yr^{-1}, which accounts for 7 to 13% of input inorganic fertilizer and is within the range given by Meisinger and Randall (1991) for somewhat poorly drained soils. Simulated soil inorganic N before spring fertilization ranged from 75 to 175 kg N ha^{-1} except for the extremely dry year, which was close to that reported by Sanchez and Blackmer (1988). However, RZWQM did not simulate a high percentage of ammonium N in early spring as reported by Sanchez and Blackmer (1988), suggesting that further improvement in simulating nitrification during winter seasons is needed (Ma et al., 1988).

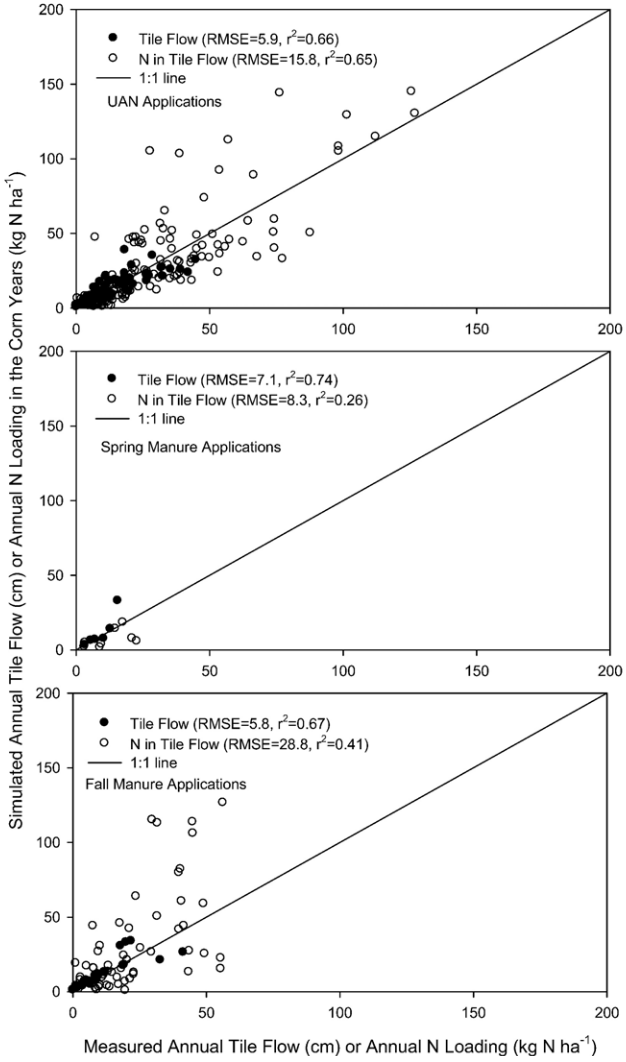

Fig. 6. Simulated and measured annual tile flow and annual N loading in tile flow from all the 30 plots for the corn years with UAN, spring manure, and fall manure applications.

Although there was no measurement of lateral subsurface flow below the tiles, RZWQM simulated an amount comparable to tile flow (352 vs. 328 cm) (Table 5). This is reasonable based on the study of Wahba et al. (2001). Simulated yearly evapotranspiration (54.6 cm) was close to that reported by Jaynes and Miller (1999) for Iowa conditions, who observed ET from 45 to 50 cm during the crop growing season in normal rainfall years. Simulated average maximum leaf area index for corn and soybean was 8.6 and 4.1, respectively, which again are in agreement with literature values (Lizaso et al., 2003; Pedersen and Lauer, 2004; Jones et al., 2003). Runoff was very site-specific. RZWQM simulated yearly runoff ranging from 0.9 to 13.2 cm with average value of 6.6 cm. Estimates of measured surface runoff from Plots 21, 22, 31, and 32 for 1993 through 1995 ranged from 0.1 to 1.7 cm. The main reason for higher simulated values was due to the fact that no surface roughness/detention storage was considered in RZWQM so all rainfall exceeding saturated hydraulic conductivity and macropore flow was assumed to be runoff. If rainfall intensity used in RZWQM was higher than actual rainfall intensity, higher runoff was simulated. Nonetheless, runoff was a small percentage of the overall soil water budget (7.5% of rainfall).

3.2. Model evaluation

Calibrated lateral hydraulic gradients (LHG) for each plot are shown in Fig. 1. Spatial distribution of LHG was not obviously correlated to soil type or the elevation. It was more or less randomly distributed and affected by the combination of soil and landscape within each plot (Bakhsh and Kanwar, 2004). Since LHG was obtained by matching total tile flow from 1990 through 2003 in each plot, the calibrated values were highly correlated to tile flow (r^2 = 0.93, Fig. 5). Table 6 lists RMSEs across all plots and years for several water, N and plant growth valuables. In general, RZWQM simulations were within the experimental errors among replicates of each treatment, especially for soil water storage, depth to water table, and yearly tile

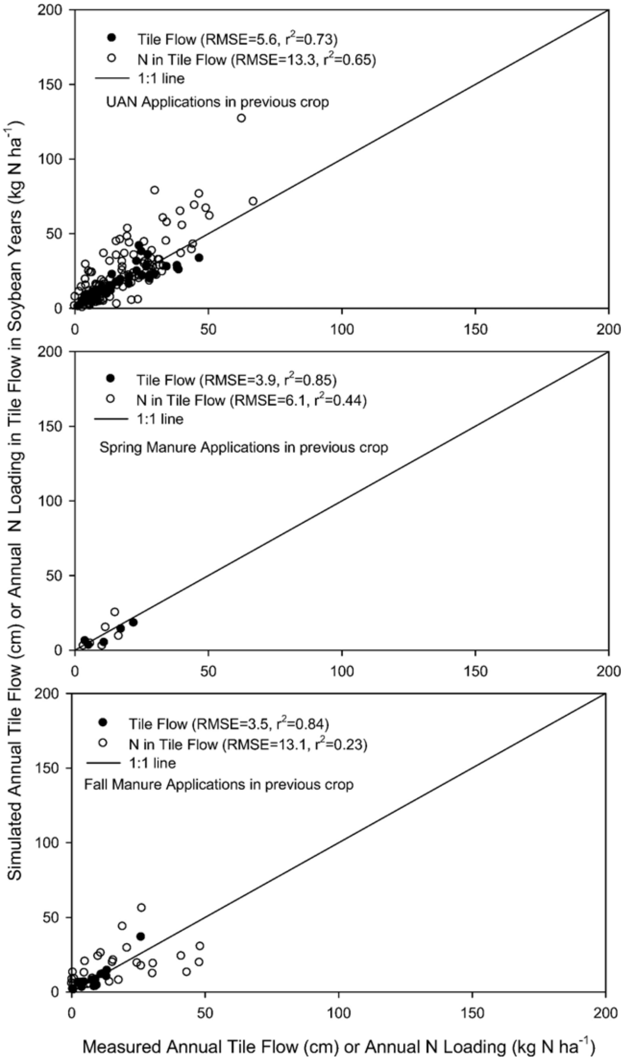

Fig. 7. Simulated and measured annual tile flow and annual N loading in tile flow from all the 30 plots for soybean years with previous UAN, spring manure, and fall manure applications in the corn years.

flow (Table 6). Nitrogen loading in tile flow and flow weighted N concentration in tile flow were reasonable with r^2 as high as 0.70 although simulated RMSE was twice the average RMSE among replicates. Although soil water storage simulations in the 120 cm soil depth were within the experimental errors, the correlation between simulated and measured soil water storage was low ($r^2 = 0.46$). Soil residual N has a RMSE of 47 kg N ha^{-1} with a CV of 0.91. However, the RMSE between replicates in field measured soil N can be as high as 140 kg N ha^{-1}. High RMSE and high CV associated with plant growth and N uptake warrant improvement in plant N uptake simulation in RZWQM. However, RMSE among replicates for biomass N uptake can be as high as 55 kg N ha^{-1} (CV = 0.32) for corn and 173 kg N ha^{-1} (CV = 0.59) for soybean, and RMSE among replicates for biomass can be as high as 3800 kg ha^{-1} (CV = 0.22) for corn and 2900 kg ha^{-1} (CV = 0.32) for soybean.

Simulated yearly tile flow and N loading in the corn years are shown in Fig. 6. There were no noticeable differences in annual tile flow among N treatments, but N loading was much higher when UAN (or anhydrous ammonia, AA) was applied than when swine manure was applied in the spring. Fall manure application had higher N loading than spring applications primarily due to the high percentage of NH_4–N in the swine manure (as high as 90% of NH_4–N in swine manure) that was subject to mineralization and subsequent leaching during the winter months. The model simulated much higher N leaching in 1999 (especially after fall manure, Fig. 6) due to a loss of tile samples after an equipment failure. We also found that simulated annual N loading was improved if we ignored the drainage samples without N concentration measurements rather than using average N concentrations from drainage samples before and after. Similarly, when UAN was applied to the previous corn crop, a higher N loading was expected in drainage in the subsequent soybean year (Fig. 7). However, N loading was generally lower in soybean years than in the corn years. Flow weighted N concentrations (yearly N loading/yearly tile flow amount) were higher in the corn years than in the soybean years when UAN was applied, but were comparable when

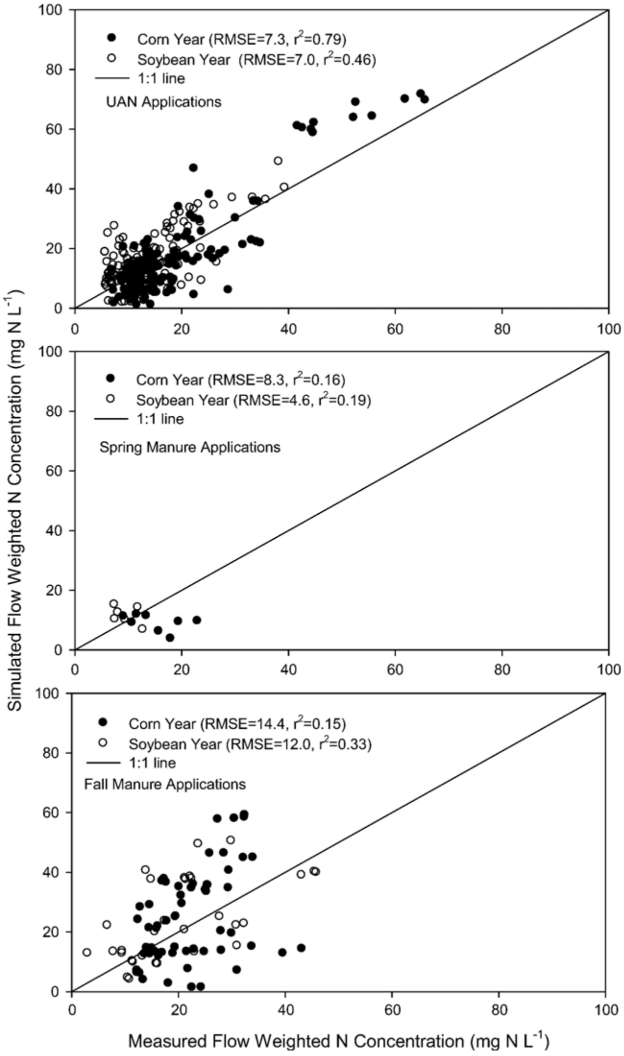

Fig. 8. Simulated and measured annual flow weighted N concentrations in tile flow from all the 30 plots for all years with UAN, spring manure, and fall manure applications.

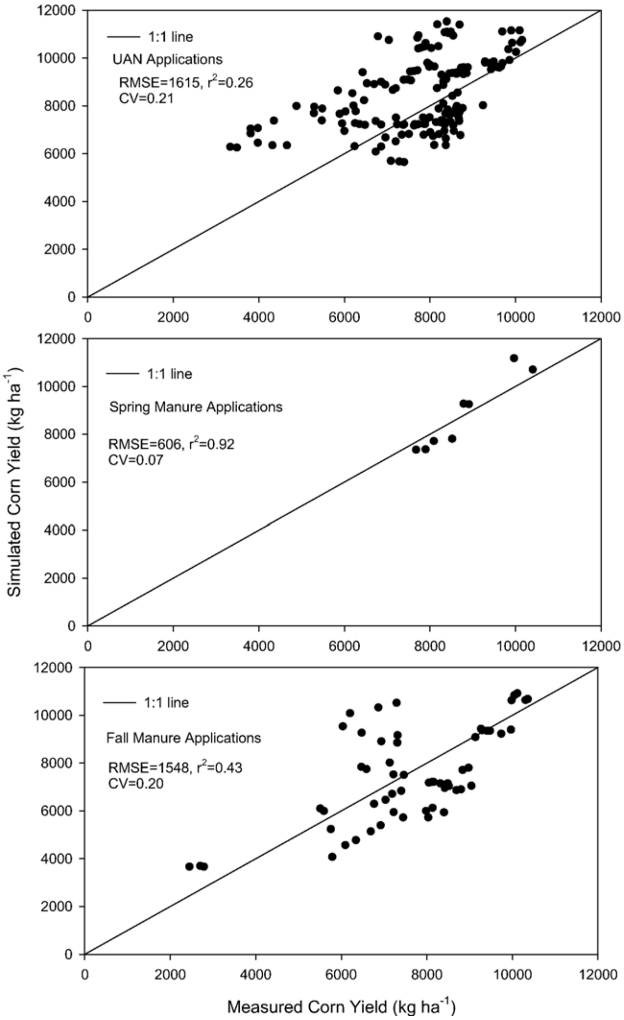

Fig. 9. Simulated and measured corn yields from all the 30 plots for years with UAN, spring manure, and fall manure applications.

manure was applied (Fig. 8). These management effects were demonstrated by both field measurements and simulation results.

Simulated corn yield was over-predicted when UAN (or AA) was applied, but was under-predicted when manure was applied in the fall (Fig. 9). The high measured yield for manure plots may also be due to factors other than N availability (Singer et al., 2004). Corn biomass was over-predicted as well when UAN was applied, but was reasonably simulated when swine manure was applied (Fig. 10). However, correlations between simulated and measured corn yield and biomass were improved if 1993 and 1995 data were excluded. Soybean yield was predicted reasonably well without biases, but soybean biomass simulation failed to follow the experimental trends (Fig. 11). Here we should mention that soybean biomass was difficult to measure and only a few biomass measurements were taken. The reported soybean biomass might contain considerable error. For example, in Plot #10 in 1991, 1997 and 1999, measured soybean biomass was from 11,400 to 12,700 kg ha^{-1} and yield was from 2900 to 3200 kg ha^{-1} with harvest index of only 0.25. Simulated corn N uptake did not change as observed when UAN (or AA) was applied (Fig. 12), but there was an N uptake response when manure was applied. Soybean N uptake was always met by N fixation in RZWQM. Therefore, maximum N concentrations in biomass and grain were simulated at all times (Fig. 11). Since average yearly N loading in tile flow was only 21.3 kg N ha^{-1}, high simulated RMSE (48 to 67 kg N ha^{-1}) in N uptake contributed inevitably to errors in simulated N loading and residual soil N (Table 6).

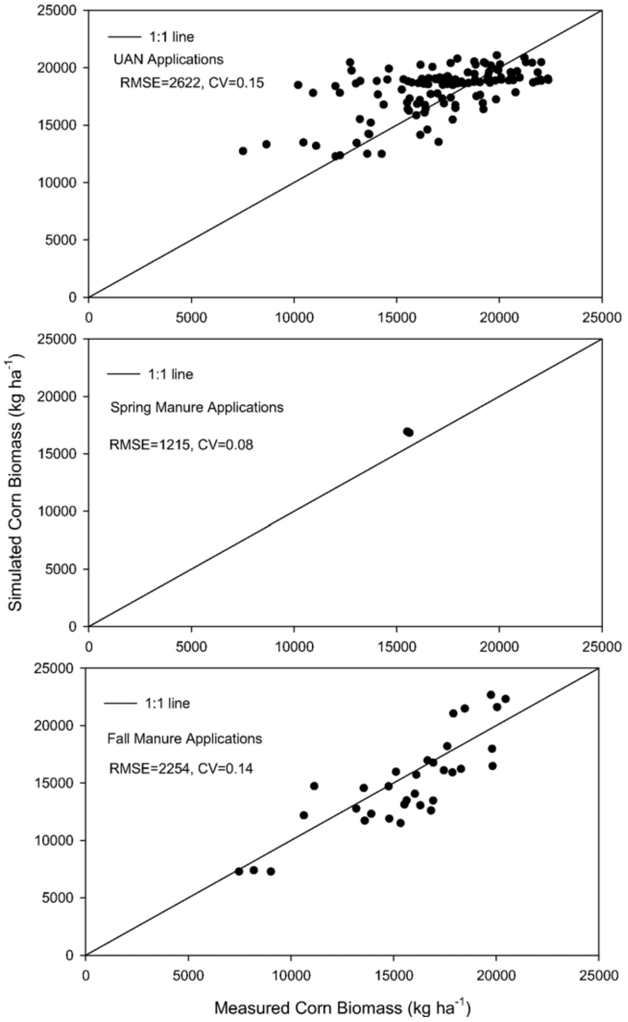

Fig. 10. Simulated and measured corn biomass from all the 30 plots for years with UAN, spring manure, and fall manure applications.

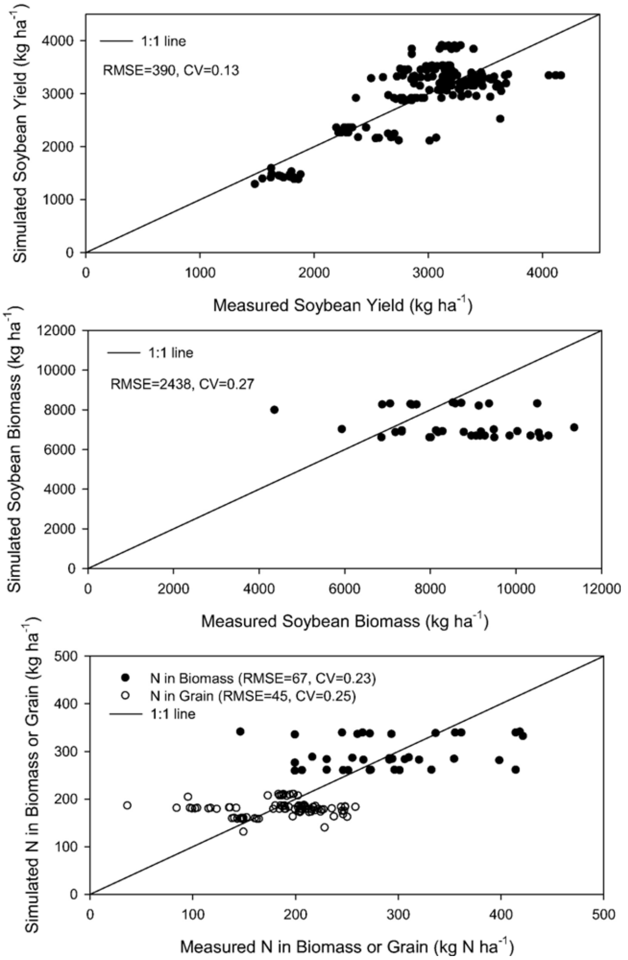

Fig. 11. Simulated and measured soybean yield, biomass, and N uptake from all the 30 plots for all the years.

Simulated management effects across years for tillage and crop rotation were reported by Ma et al. (2007a-this issue) and for nitrogen and manure by Malone et al. (2007-this issue). However, it was also important to compare measured and simulated weather effects when averaged across all treatments. On average, RZWQM responded to weather patterns well in terms of yield, annual tile flow, and N loading in tile flow (Fig. 13). With the exception of 1979, 1989, and 1997 when corn yield was predicted to decrease but actually increased compared to the previous year, the model correctly simulated the trends of yield from 1978 to 2003. The model started to simulate considerable N stress in 1997 when UAN was applied at a much lower rate (110 kg N ha^{-1} vs. 202 kg N ha^{-1}). The simulated corn yield was higher in 1993 because the model did not account for damage due to excessive rainfall that year. For soybean, simulated yields were considerably different from measured values in only 2 years (1981 and 1983). These discrepancies between simulated and measured yields resulted in low r^2 values (0.52 for corn and 0.37 for soybean) for both crops. Yearly tile flow also followed the measured temporal trend (Fig. 13). Simulated high annual tile flow in 1999 was mainly due to a loss in tile flow samples caused by equipment failure. Also, 1993 was a flood year and the measured high tile flow could be due to overland flow from adjacent fields. Nonetheless, a high r^2 (0.74) was obtained. Simulated yearly N loading and flow weighted N concentrations also responded to the weather pattern, with r^2 values of 0.71 and 0.69, respectively (Fig. 13). Since 1990 was the first year when tile flow and N concentration in the drainage water were recorded after an extremely dry year (40 cm rainfall in 1989), measured N loading in tile flow varied considerably among replicates. Differences among replicates were as high as 61 kg N ha^{-1} in that year. Therefore, 1990 data should not be weighted too much in evaluating model performance. However, the discrepancies between measured and simulated yearly N loading in 1990, 1993, and 1999 became less important when flow weighted concentration was taken.

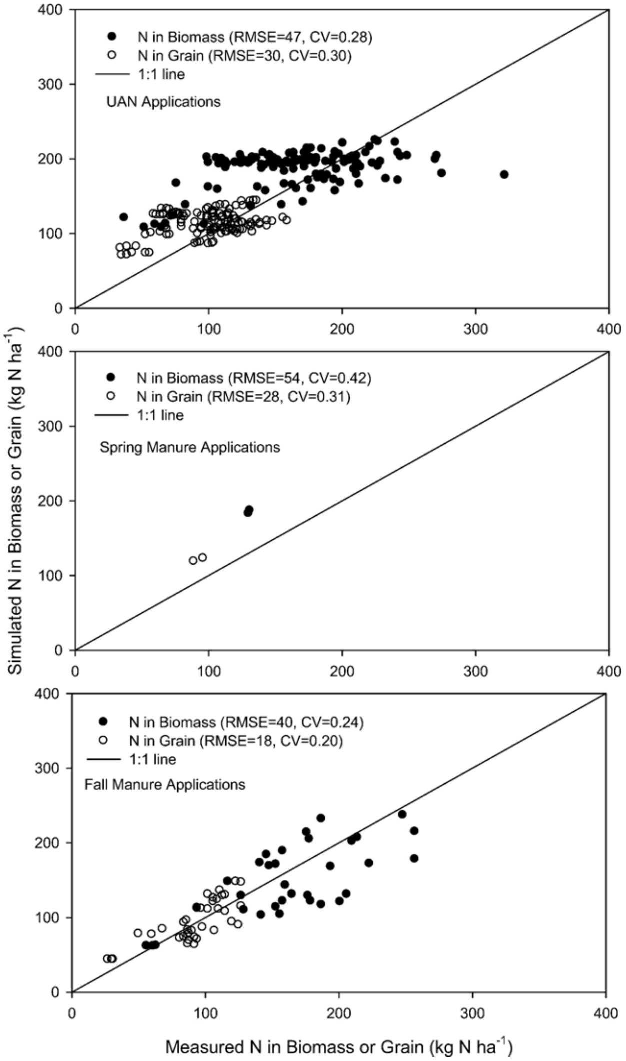

Fig. 12. Simulated and measured corn N uptake from all the 30 plots for the years with UAN, spring manure, and fall manure applications.

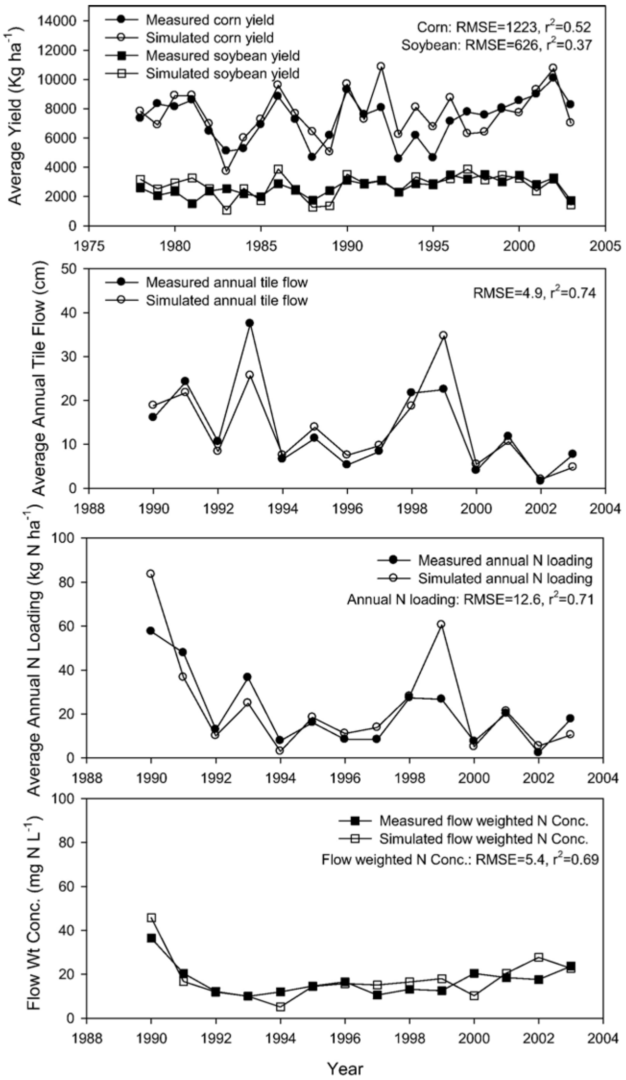

Fig. 13. Simulated and measured average corn and soybean yield, yearly tile flow, yearly N loading in tile flow, and flow weighted N concentration in tile flow across all treatments.

4. Summary and conclusions

We evaluated RZWQM using long-term (1978 to 2003) field data for 30 out of 36 plots. RZWQM was calibrated using data for Plot No. 25 and then used with the same soil and plant parameters, except for lateral hydraulic gradient, to simulate responses for the other 29 plots. Simulated water and N balances and crop production were compared to experimental measurements whenever possible. In general, the model correctly simulated year to year variations in tile flow and N loading in the tile flow. Simulated and measured average annual tile flows were 13.5 cm, which was expected because total tile flow was calibrated from plot to plot to capture the difference in flow characteristics. Simulated average annual N loading in tile flow was 21.3 kg N ha^{-1} compared to measured value of 17.6 kg N ha^{-1}. Simulated and measured average yearly flow weighted N concentrations in tile flow were 13.3 and 13.8 mg N L^{-1}, respectively. Simulated soil water storage in the 120 cm soil profile had the same RMSE (3.0 cm) as experimental errors (RMSE) between replicates. Similarly, simulated water table depth (22.1 vs. 22.4 cm) and yearly tile flow (5.6 vs. 5.7 cm) were within experimental RMSEs among replicates.

However, RZWQM over-predicted corn yield when spring UAN or anhydrous ammonium was applied, but it under-predicted corn yield when fall swine manure was applied. Simulated N uptake did not respond to N management. High simulated errors for plant N uptake were related to both large errors in simulated soil residual N (supply) and simulated plant N concentration (demand). Simulated N fixation for soybean was high compared to literature values. However, across all plots and years, corn yield was over-predicted by 5% (331 kg ha^{-1}) and soybean yield was over-predicted by 3% (or 68 kg ha^{-1}). Corn biomass was over-predicted by 2% (392 kg ha^{-1}) and soybean biomass was under-predicted by 17% (1544 kg ha^{-1}). Less than satisfactory results for plant growth were partially due to uncertainty in soil condition from plot to plot; lack of consideration for pest, hail, and flood damage in the model; missing weather data on the experimental site, and changes in corn and soybean varieties during 26 years of experiments. To improve plant simulations in this study, RZWQM needs to: (1) account for subsurface lateral flow below the tile between adjacent plots so that lateral flow out of one plot can be routed to other plots; (2) simulate N fixation rather than supplying all N needed by soybean; (3) improve simulation of plant N uptake; (4) take into account of surface roughness/detention storage in runoff estimation; and (5) reduce winter nitrification so that there is more soil NH_4–N at planting.

The questions now are: what is the usefulness of this simulation exercise and what do we learn from it? We calibrated RZWQM for one plot by trial and error without using a mathematically sound optimization scheme. During the calibration process, we also had difficulty to select criteria for goodness-of-calibration, and variables or parameters to calibrate. The calibrated model by no mean was the best, rather it was reasonable. We tried to match total tile flow and total N loading in tile flow for the calibrated plot, but there was an equipment failure in 1999. When the model was evaluated on the other 29 plots, we found that N uptake simulation was generally unacceptable and simulations of biomass and yield had much higher RMSE than experimentally observed. In spite of these discrepancies between simulated and measured results, we went ahead and examined the management effects on tile flow, N loading in tile flow, and crop yield. As shown by Ma et al. (2007a-this issue) and Malone et al. (2007), simulated management effects seemed to be reasonable on N loading in tile flow, regardless of poor simulations of plant N uptake and N fixation. As shown in this study, the model also responded reasonably to yearly variations in yield, tile flow, N loading in tile flow when taking average across treatments. Since this study was one of the very few on simulating management effects using more than 10 years of experimental data, it identified many knowledge gaps in agricultural system modeling, including: (1) How should a system model be calibrated for a long-term experimental data? Should it be calibrated by plot or by year? (2) What are the criteria for the goodness-of-calibration? Can we define an objective function to include both plant and soil measurements? How can we objectively calibrate a system model? (3) How should modeling results be interpreted and used? Is it acceptable to focus on simulated differences between management practices even if simulation results have large errors? (4) How should we deal with missing data (weather, soil, and plant) in calibrating a system model for long-term experiments? It is hoped that this study reveals the complexity in system modeling and its applications to long-term experiments. More applications of system models to long-term comprehensive field studies are needed, and performance of system models should be evaluated for all the system components (soil, water, nutrient, and plant growth), rather than a single component.

References

Ahuja, L.R., Rojas, K.W., Hanson, J.D., Shaffer, M.J., Ma, L., 2000. The Root Zone Water Quality Model. Water Resources Publications LLC, Highlands Ranch, CO. 372 pp.

Azevedo, A.S., Kanwar, R.S., Singh, P., Ahuja, L.R., Pereira, L.S., 1997. Simulating atrazine using root zone water quality model for Iowa soil profiles. J. Environ. Qual. 26, 153–164.

Bakhsh, A., Kanwar, R.S., 2004. Spatio-temporal analysis of subsurface drainage flow volumes. Trans. ASAE 47, 1427–1436.

Bakhsh, A., Kanwar, R.S., Ahuja, L.R., 1999. Simulating the effect of swine manure application on NO_3–N transport to subsurface drainage water. Trans. ASAE 42, 657–664.

Bakhsh, A., Hatfield, J.L., Kanwar, R.S., Ma, L., Ahuja, L.R., 2004a. Simulating nitrate losses from Walnut Creek Watershed. J. Environ. Qual. 33, 114–123.

Bakhsh, A., Ma, L., Ahuja, L.R., Hatfield, J.L., Kanwar, R.S., 2004b. Using RZWQM to predict herbicide leaching losses in subsurface drainage water. Trans. ASAE 47, 1415–1426.

Ghidey, F., Alberts, E.E., Kitchen, N.R., 1999. Evaluation of RZWQM using field measured data from the Missouri MSEA. Agron. J. 91, 183–192.

Jaynes, D.B., Miller, J.G., 1999. Evaluation of RZWQM using field measured data from Iowa MSEA. Agron. J. 91, 192–200.

Jones, B.P., Holshouser, D.L., Alley, M.M., Roygard, J.K.F., Anderson-Cook, C.M., 2003. Double-crop soybean leaf area and yield responses to Mid-Atlantic soils and cropping systems. Agron. J. 95, 436–445.

Karlen, D.L., Berry, E.C., Colvin, T.S., Kanwar, R.S., 1991. Twelve-year tillage and crop rotation effects on yields and soil chemical properties in northeast Iowa. Commun. Soil Sci. Plant Anal. 22, 1985–2003.

Karlen, D.L., Kumar, A., Kanwar, R.S., Cambardella, C.A., Colvin, T.S., 1998. Tillage system effects on 15-year carbon-based and simulated N budgets in a tile-drained Iowa field. Soil Tillage Res. 48, 155–165.

Karlen, D.L., Cambardella, C.A., Kanwar, R.S., 2004. Challenges of managing liquid swine manure. Appl. Eng. Agric. 20, 693–699.

Kumar, A., Kanwar, R.S., Ahuja, L.R., 1998a. RZWQM simulation of nitrate concentrations in subsurface drainage from manured plots. Trans. ASAE 41, 587–597.

Kumar, A., Kanwar, R.S., Ahuja, L.R., 1998b. Evaluation of preferential flow component of RZWQM in simulating water and atrazine transport to subsurface drains. Trans. ASAE 41, 627–637.

Kumar, A., Kanwar, R.S., Singh, P., Ahuja, L.R., 1999. Evaluation of the root zone water quality model for predicting water and NO_3–N movement in an Iowa soils. Soil Tillage Res. 50, 223–236.

Landa, F.M., Fausey, N.R., Nokes, S.E., Hanson, J.D., 1999. Evaluation of the root zone water quality model (RZWQM3.2) at the Ohio MSEA. Agron. J. 91, 220–227.

Lizaso, J.J., Batchelor, W.D., Westgate, M.E., 2003. A leaf area model to simulate cultivar-specific expansion and senescence of maize leaves. Field Crops Res. 80, 1–17.

Ma, L., Shaffer, M.J., Boyd, J.K., Waskom, R., Ahuja, L.R., Rojas, K.W., Xu, C., 1988. Manure management in an irrigated silage corn field: experiment and modeling. Soil Sci. Soc. Am. J. 62, 1006–1017.

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 root zone water quality model (RZWQM). Adv. Agron. 71, 233–292.

Ma, L., Nielsen, D.C., Ahuja, L.R., Malone, R.M., Anapalli, S.S., Rojas, K.W., Hanson, J.D., Benjamin, J.G., 2003. Evaluation of the RZWQM under various irrigation levels in Eastern Colorado. Trans. ASAE 46, 39–49.

Ma, L., Malone, R.W., Heilman, P., Jaynes, D., Ahuja, L.R., Saseendran, S.A., Kanwar, R.S., Ascough II, J.C., 2007a. RZWQM simulated effects of crop rotation, tillage, and controlled drainage on crop yield and nitrate-N loss in drain flow. Geoderma 140, 260–271 (this issue). doi:10.1016/j.geoderma.2007.04.010.

Ma, L., Malone, R.W., Heilman, P., Ahuja, L.R., Meade, R., Saseendran, S.A., Ascough, J.C. II, Kanwar, R.S., 2007b. Sensitivity of tile drainage flow and crop yield on measured and calibrated soil hydraulic properties. Geoderma 140, 284–296 (this issue). doi:10.1016/j.geoderma.2007.04.012.

Malone, R.W., Ma, L., Heilman, P., Karlen, D.L., Kanwar, R.S., Hatfield, J.L., 2007. Nitrogen management effects on crop production and water quality. Geoderma 140, 272–283 (this issue). doi:10.1016/j.geoderma.2007.04.011.

Martin, D.L., Watts, D.G., 1999. Application of the root zone water quality model in central Nebraska. Agron. J. 91, 201–211.

Meisinger, J.J., Randall, G.W., 1991. Estimating nitrogen budgets in soil–crop systems. In: Follett, R.F., Keeney, D.R., Cruse, R.M. (Eds.), Managing Nitrogen for Groundwater Quality and Farm Profitability. SSSA, Inc. Madison, WI, USA, pp. 85–124.

Pedersen, P., Lauer, J.G., 2004. Soybean growth and development in various management systems and planting dates. Crop Sci. 44, 508–515.

Sanchez, C.A., Blackmer, A.M., 1988. Recovery of anhydrous ammonia-derived nitrogen-15 during three years of corn production in Iowa. Agron. J. 80, 102–108.

Saseendran, S.A., Ma, L., Malone, R.W., Heilman, P., Ahuja, L.R., Kanwar, R.S., Karlen, D.L., Hoogenboom, G., 2007. Simulating management effects on crop production, tile drainage, and water quality using RZWQM-DSSAT. Geoderma 140, 297–309 (this issue). doi:10.1016/j.geoderma.2007.04.013.

Schepers, J.S., Mosier, A.R., 1991. Accounting for nitrogen in nonequilibrium soil–crop systems. In: Follett, R.F., Keeney, D.R., Cruse, R.M. (Eds.), Managing Nitrogen for Groundwater Quality and Farm Profitability. SSSA, Inc. Madison, WI, USA, pp. 125–138.

Singer, J.W., Kohler, K.A., Liebman, M., Richard, T.L., Cambardella, C.A., Buhler, D.D., 2004. Tillage and compost affect yield of corn, soybean, and wheat and soil fertility. Agron. J. 96, 531–537.

Singh, P., Kanwar, R.S., 1995a. Modification of RZWQM for simulating subsurface drainage by adding a tile flow component. Trans. ASAE 38, 489–498.

Singh, P., Kanwar, R.S., 1995b. Simulating NO_3–N transport to subsurface drain flows as affected by tillage under continuous corn using modified RZWQM. Trans. ASAE 38, 499–506.

Singh, P., Kanwar, R.S., Johnsen, K.E., Ahuja, L.R., 1996. Calibration and evaluation of subsurface drainage component of RZWQM v2.5. J. Environ. Qual 25, 56–63.

Vigil, M.F., Eghball, B., Cabrera, M.L., Jakubowski, B.R., Davis, J.G., 2002. Accounting for seasonal nitrogen mineralization: an overview. J. soil water Conserv. 57, 464–469.

Wahba, M.A.S., El-Ganainy, M., Abdel-Dayem, M.S., Gobran, A.T.E.F., Kandil, H., 2001. Controlled drainage effects on water quality under semi-arid conditions in the western delta of Egypt. Irrig. Drain. 50, 295–308.

Watts, D.G., Fausey, N.R., Bucks, D.A., 1999. Background of the MSEA-RZWQM modeling project. Agron. J. 91, 169–170.

Wu, L., Chen, W., Baker, J.M., Lamb, J.A., 1999. Evaluation of RZWQM field measured data from a sandy soil. Agron. J. 91, 177–182.