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RZWQM simulated effects of crop rotation, tillage, and controlled drainage on crop yield and nitrate-N loss in drain flow

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Keywords

Management effects, System models, Water quality, Tile drainage, N leaching

Disciplines

Agriculture | Bioresource and Agricultural Engineering | Soil Science | Water Resource Management

Comments

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Accurate simulation of agricultural management effects on N loss in tile drainage is vitally important for understanding hypoxia in the Gulf of Mexico. An experimental study was initiated in 1978 at Nashua, Iowa of the USA to study long-term effects of tillage, crop rotation, and N management practices on subsurface drainage flow and associated N losses. The Root Zone Water Quality Model (RZWQM) was applied to evaluate various management effects in several previous studies. In this study, the simulation results were further analyzed for management effects (tillage, crop rotation, and controlled drainage) on crop production and N loss in drain flow. RZWQM simulated the observed increase in N concentration in drain flow with increasing tillage intensity from NT (no-till) to RT (ridge till) to CP (chisel plow) and to MP (moldboard plow). It also adequately simulated tillage effects on yearly drain flow and yearly N loss in drain flow. However, the model failed to simulate lower corn and soybean yields under NT than under MP, CP, and RT. On the other hand, RZWQM adequately simulated lower yearly drain flow and lower flow-weighted N concentration in drain flow under CS (corn–soybean) and SC (soybean–corn) than under CC (continuous corn). The model adequately simulated higher corn yield under CS and SC than under CC. Applying the newly suggested N management practice for the Midwest of controlled drainage, the model simulated a 30% reduction in drain flow and a 29% decrease in N losses in drain flow under controlled drainage (CD) compared to free drainage (FD). With most of the simulations in reasonably close agreement with observations, we concluded that RZWQM is a promising tool for quantifying the relative effects of tillage, crop rotation, and controlled drainage on N loss in drainage flow. Further improvements on simulated management effects on crop yield and N mineralization are needed, however.

Keywords: Management effects; System models; Water quality; Tile drainage; N leaching

1. Introduction

Subsurface drainage is a common practice used in the Midwest Corn Belt of the USA (Randall et al., 1997; Fisher et al., 1999) and is believed to contributing to hypoxia in the Gulf of Mexico (Kladivko et al., 2004). Many field studies have been conducted under subsurface drainage conditions with various management practices to reduce N loss in subsurface drainage flow (Randall and Iragavarapu, 1995; Fisher et al., 1999; Huggins et al., 2001; Vetsch and Randall, 2002, 2004; Kladivko et al., 2004). Computer models were also developed and used to evaluate these management effects on drain flow and N loss in drain flow, such as DRAINMOD (Skaggs et al., 1995), ADAPT (Davis et al., 2000), CERES-Maize (Garrison et al., 1999), and RZWQM (Bakhsh et al., 2004a,b). Root Zone Water Quality Model (RZWQM) was initially developed specifically for the Midwest soil conditions (Ahuja et al., 2000), and it simulates the physical, chemical, and biological responses of the soil system within the root zone under various agricultural management practices. The model has been extensively tested under various soil–weather-management conditions (Ma et al., 2000), and is now operational for assessment of agricultural management effects on crop production and water quality related issues.

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The RZWQM has been used extensively to simulate existing and alternative agricultural management practices. Ma et al. (1998a,b) correctly simulated manure management effects on crop production, N uptake, and nitrate leaching under Arkansas and Colorado conditions of the USA. Ma et al. (2003) and Nielsen et al. (2002) found that RZWQM had the capability of simulating corn and soybean responses to water stresses in a gradient irrigation system under semi-arid Colorado conditions. Cameira et al. (1998) compared single and multiple fertigation on water and nitrate movement in a Portuguese soil and found that RZWQM correctly simulated soil water content and soil nitrate-N under these N management practices. Azevedo et al. (1997a) conducted a sensitivity analysis of RZWQM for N leaching for moldboard plow (MP) and no-till (NT) under tile-drained conditions and found higher N loss in drainage under NT compared to MP. Farahani et al. (1999) simulated corn production under both irrigated and dryland conditions and found that RZWQM was adequate in simulating corn yield as long as soil water content was correctly simulated. As a water quality model, RZWQM has been used widely for addressing pesticide management issues (Ma et al., 1995; Ahuja et al., 1996, Azevedo et al., 1997b, Kumar et al., 1998; Ma et al., 2004; Malone et al., 2004a,b,c). Recently, the CROPGRO and CERES crop growth models of DSSAT v3.5 (Decision Support System for Agrotechnology Transfer) were linked to RZWQM, which provided additional options for simulating plant growth (Ma et al., 2005, 2006).

The MSEA (Management Systems Evaluation Areas)-RZWQM modeling project contributed significantly to the refinement of RZWQM as well (Watts et al., 1999). During the 4 years of RZWQM integration with MSEA field research, the model was tested for: 1) water and pesticide movement at the Minnesota MSEA site (Wu et al., 1999); 2) surface runoff, nitrate and pesticide losses to seepage and runoff, and crop yields at the Missouri MSEA site (Ghidey et al., 1999); 3) crop yield, and water, nitrate and pesticide movement at the Iowa MSEA site (Jaynes and Miller 1999); 4) crop yield, N uptake, plant biomass, leaf area index, soil water content, and soil N at the Nebraska MSEA site (Martin and Watts 1999); and 5) leaf, stem, and seed biomass of corn at the Ohio MSEA site (Landa et al., 1999). Although the model has been evaluated extensively under tile-drained conditions at Nashua, Iowa for estimating N loss and crop growth (Singh and Kanwar, 1995; Kumar et al., 1998; Bakhsh et al., 2004a,b), only a few years of data or a few treatments were used (Ma et al., 2007a).

In a recent study, Ma et al. (2007a) extended RZWQM applications to the Nashua study with data collected from 1978 to 2003. In this study, we further examined the management effects of crop rotation and tillage on crop yield and N load in drainage flow. These analyses for management effects were important for building a quality assured database using RZWQM and for evaluating the contribution of drainage flow to hypoxia in the Gulf of Mexico. Therefore, the objectives of this paper were to 1) analyze RZWQM simulated and measured management effects of crop rotations and tillage practices on corn and soybean yield and N loss in drainage flow; and 2) extend RZWQM applications beyond the current experimental management practices and evaluate possible long-term effects of crop rotation, tillage, and controlled drainage on crop production and N loss in drainage flow.

2. Materials and methods

2.1. Experimental site description

The experiment was conducted at Iowa State University's Northeast Research Center in 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, 1998).

The site consists of 36 one-acre plots. Drainage water from the center drain in each plot was collected and used for water quality analysis (Table 1). Three phases of study were conducted from 1978 to 1992, 1993 to 1998, and 1999 to 2003. From 1978 to 1993, the main focus of the study was on tillage practices (moldboard plow, chisel plow, ridge till, and no-till) and crop rotations (continuous corn, corn–soybean). Only crop yield was measured from 1978 to 1989. Data collected in 1990–1992 included drain flow, nitrate concentration in drain flow, residual N in soil, and crop biomass, yield, and N uptake. From 1993 to 1998, the main focus of the study was on N management including liquid swine manure, N application rate, and late spring N test. Tillage was reduced from four to two practices (chisel plow and no-till). Data collection included drainage flow, runoff, nitrate in drainage flow, soil nitrate, and crop N uptake, yield, and biomass. From 1999 to 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 corn–soybean rotation. Manure was applied either in the fall or spring. Chisel plow and no-till management practices were continued. Each cropping season received manure and/or UAN. Experimental measurements included drain flow, nitrate in drain flow, soil N, and crop N uptake, yield, biomass. Soil hydraulic conductivities and soil water retention curves were determined for all the three soil types using soil samples collected in 2001 from a nearby field (Ma et al., 2007b) (Table 2).

2.2. RZWQM simulation and data interpretation

RZWQM was calibrated using data from Plot 25 because the water table in this plot was recorded continuously and the plot had both continuous corn (CC) and corn–soybean (CS) rotations and both fertilizer and manure applications during the course of the 26 years of experiments (Ma et al., 2007a). In this study, we extended the RZWQM simulation results to evaluate different

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

Plot no [a]	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	NH3	SM	SM	CP	CP	CP
2, 16, 20	Readlyn/Kenyon	CS	CS	CS	NH3	UAN	SM	MP	NT	NT
3, 24, 28	Readlyn/Kenyon	SC	SC	SC	NH3	UAN (LSNT)	UAN	NT	NT	CP
4, 18, 33	Kenyon	SC	CS	CS	NH3	UAN	SM+UAN	CP	CP	CP
5, 21, 26	Readlyn/Kenyon	CC	CC	SC	NH3	UAN	SM	CP	CP	CP
6, 32, 36	Readlyn/Kenyon	CC	SC	SC	NH3	UAN	SM+UAN	RT	CP	CP
8, 9, 19	Readlyn/Floyd	CS	CS	CS	NH3	UAN (LSNT)	UAN (LSNT/LCD)	RT	CP	CP
10, 15, 29	Kenyon	CS	CS	CS	NH3	UAN (LSNT)	UAN	NT	NT	CP
11, 23, 27	Kenyon	SC	SC	SC	NH3	SM	SM	RT	CP	CP
12, 17, 34	Kenyon/Floyd	SC	SC	SC	NH3	UAN (LSNT)	UAN (LSNT/LCD)	MP	CP	CP
13, 22, 35	Readlyn/Floyd	CC	CC	CS	NH3	SM	SM	MP	CP	CP
14, 25, 31	Readlyn/Kenyon	CC	SC	SC	NH3	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; NH3: anhydrous ammonia; UAN: urea–ammonia-nitrate; LSNT: late spring N test; LCD: localized compaction and doming; SM: swine manure.
[a] Six plots (8, 17, 20, 27, 30, 31) were excluded from RZWQM simulations due to distinct differences in hydraulic properties.

tillage practices, crop rotations, and controlled drainage on crop production, drainage flow, and N loss to drainage flow. Of the 36 plots, six plots (#8, #17, #20, #27, #30, #31) had distinct soil hydraulic properties than the rest, which could not be explained by management effects. Thus, only 30 plots were used in the analyses (Ma et al., 2007b). However, there were at least two replicates for each treatment. Detailed simulations on N and water balances for the 30 plots were reported in Ma et al. (2007b).

In this study, we specifically analyzed the simulated and measured differences in yield, yearly drainage flow, yearly N loss in drainage flow, and yearly flow-weighted N concentration in drainage flow (yearly N loading/yearly drain flow amount) between various tillage practices and between crop rotations. Although the experiments were initiated in 1978, extensive sampling didn't commence until 1990. Also because the experiments went through three phases of studies, measured tillage effects could only be obtained from 1990 to 1992 for all the tillage practices and from 1993 to 1998 for NT and CP, provided that all the other management practices (e.g., crop rotation and N management) were the same (Table 1). By the same token, measured crop rotation effects (CC–CS or CC–SC) were available from 1990 to 1992 and then from 1993 to 1998. No data after 1998 could be used to analyze management effects of a single practice.

To evaluate management effects, we took the differences between two management practices, such as NT–MP, NT–CP, NT–RT, MP–CP, MP–RT, CP–RT for management effects and CC–CS, CC–SC for crop rotation effects. When both measured and simulated differences have the same sign, the model correctly simulated the response to that particular management. In the *x–y* plane of measured vs. simulated differences, a perfect response to that management practice would be all the data points in the 1st and 3rd quadrants along the 1:1 line. Any data points in the 2nd and 4th quadrants suggested opposite responses to the management practice as suggested from observed and simulated results. The percentage of data points in the 1st and 3rd quadrants was used to quantify goodness of management effect simulation. In this paper, emphasis was placed on simulated trends by taking differences between two management practices. Statistical comparisons between simulated and measured values were reported by Ma et al. (2007a). In a companion paper, Malone et al. (2007) analyzed N management effects, including late spring N test, manure application, and winter cover crop.

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)	Ksat (cm/h)	Soil water at 33 kPa (cm^3/cm^3)	Soil water at 1500 kPa (cm^3/cm^3)	Klat (cm/h)	λ
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).

2.3. Long-term simulations of tillage, crop rotation, and controlled drainage effects

Since the 36 plots have gone through three phases of study, observed crop rotation effects on water quality are only available for a short period of time (Table 1). Therefore, it is important to investigate long-term effects of crop rotation and tillage using a calibrated system model. To do so, we selected several management practices and ran the calibrated model from January 1, 1979 to December 31, 2002, using hydraulic properties from Plot 25. Corn or soybean was planted each year according to actual planting dates with planting density of 71,000 plants/ha and 494,000 plants/ha, respectively. Fertilizer as anhydrous ammonium was applied 2 weeks before corn planting at 202 kg N/ha for CC and 168 kg N/ha for CS or SC as implemented in the Nashua field study from 1978 to 1992 (Karlen et al., 1991). Tillage practices (MP, NT, and CP) were implemented a month after corn harvest. Results for corn–soybean rotation were reported as the averages for CS and SC rotation phases to account for possible weather effects.

Since controlled drainage has shown promise in reducing subsurface drainage discharge and nitrate-N loss in drainage water (Gilliam et al., 1979; Wahba et al., 2001; Wesstrom et al., 2003; Khan et al., 2003), in this study, we also tested controlled drainage effects on crop production and N loss in drain flow by assuming a drainage-control system managed as follows: control gate at 120 cm on March 15; raise to 60 cm on June 10; lower to 120 on September 10; raise to 30 cm on November 1; and lower to 120 cm on March 15, based on controlled drainage studies in the literature (Kalita and Kanwar, 1993; Drury et al., 1996; Wesstrom et al., 2003). This drainage-control system minimized nitrate-N losses in the winter, yet it optimized crop yield and water quality objectives during the cropping seasons (Kalita and Kanwar, 1993).

3. Results and discussion

3.1. Simulated and measured tillage effects

Figs. 1 and 2 show the simulated and measured differences in yearly nitrate-N loss to drain flow, flow-weighted nitrate-N concentration in drain flow, drain flow, and corn yield between specific tillage practices from 1990 to 1992. What we consider adequate simulation of the management effects is indicated by the points in Figs. 1 and 2 aligning with 1:1 line, or at least falling in the 1st and 3rd quadrants of the x–y plane. A good correlation was obtained between simulated and measured yearly drain flow with a majority of the data points along the 1:1 line and 70% of

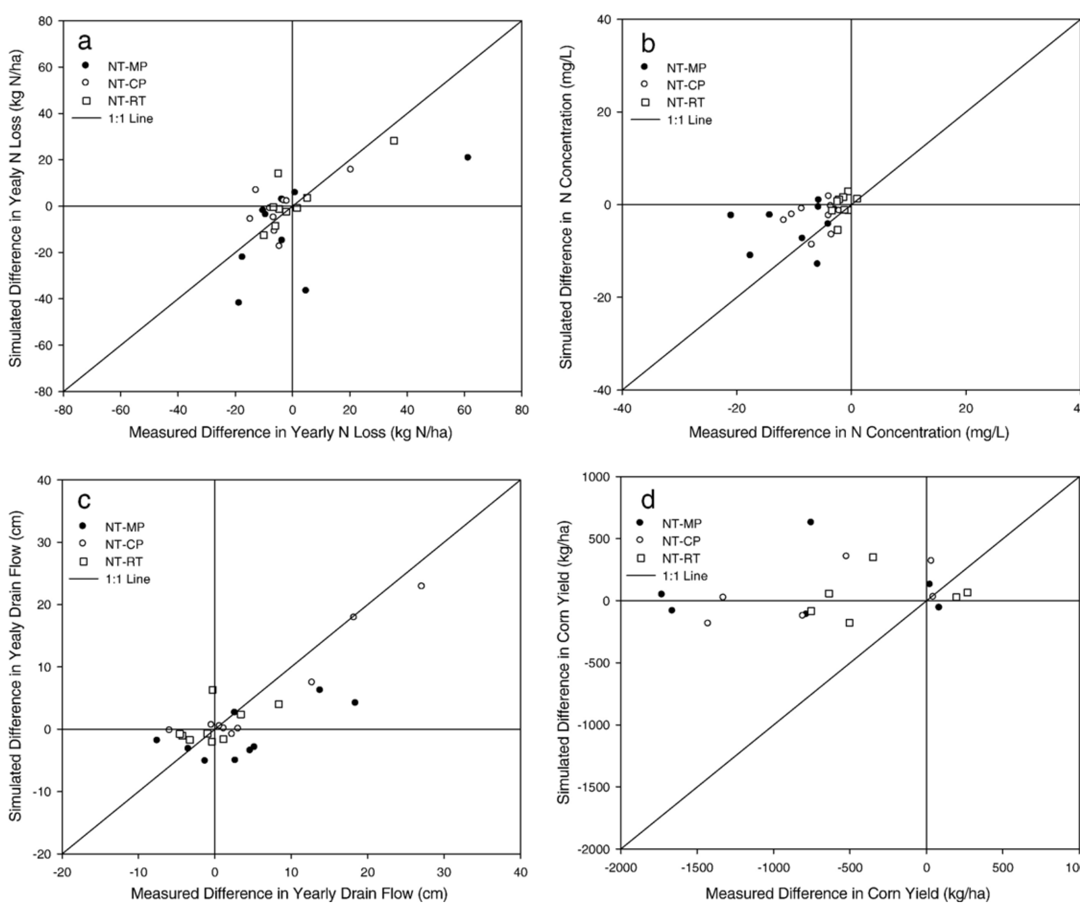

Fig. 1. Observed and simulated differences between NT and MP (NT–MP); NT and CP (NT–CP); and NT and RT (NT–RT) in yearly nitrate-N loss in drain flow (a), flow-weighted nitrate-N concentration in drain flow (b), yearly drain flow (c), and corn yield (d) at Nashua, IA, from 1990 to 1992. NT: no-till; MP: moldboard plow; CP: chisel plow; and RT: ridge till.

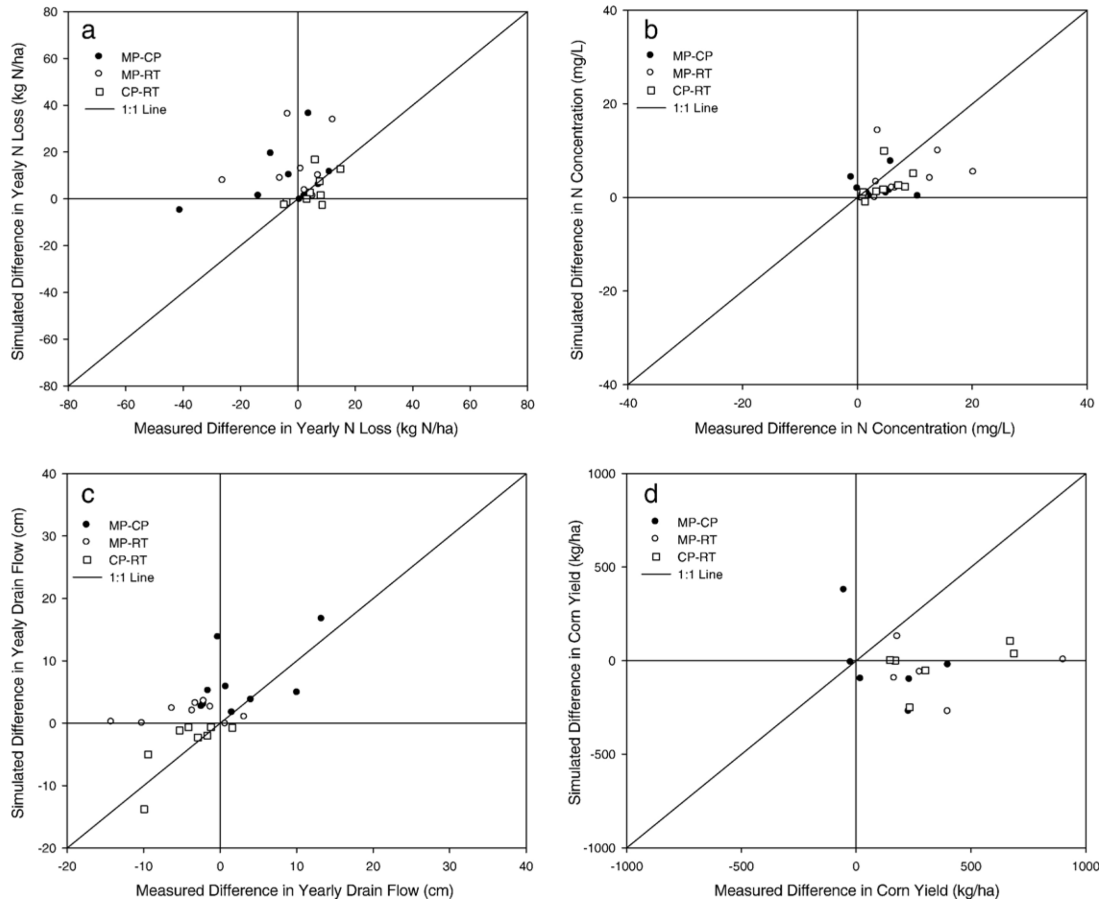

Fig. 2. Observed and simulated differences between MP and CP (MP–CP); MP and RT (MP–RT); and CP and RT (CP–RT) in yearly nitrate-N loss in drain flow (a), flow-weighted nitrate-N concentration in drain flow (b), yearly drain flow (c), and corn yield (d) at Nashua, IA, from 1990 to 1992. NT: no-till; MP: moldboard plow; CP: chisel plow; and RT: ridge till.

the data points in the 1st and 3rd quadrants when comparing NT with other tillage (MP, CP, and RT) (Fig. 1c). Thus, RZWQM can simulate year-to-year variation in drain flow as long as soil hydraulic properties are known, which was obtained in this study by calibrating the total drainage flow from 1990 to 2003 (Ma et al., 2007b). Simulated yearly drain flow between other tillage practices (MP, CP, and RT) was less satisfactory with only 56% of the data points in the 1st and 3rd quadrants (Fig. 2c). The effects of tillage practices on yearly N loss to drain flow were slightly better simulated with 74% (Fig. 1a) and 67% (Fig. 2a) of the data points in the 1st and 3rd quadrants. Tillage effects on flow-weighted N concentrations in yearly drain flow were equally simulated with 78% (Fig. 1b) and 85% (Fig. 2b) in the 1st and 3rd quadrants. Although flow-weighted N concentration in drain flow was lower with NT than with MP, CP and RT (Fig. 1b), yearly N loss in drain flow depended on the amount of drain flow (Fig. 1a). Similarly, measured tillage effects between MP, CP, and RT (MP–CP, MP–RT, and CP–RT) depended on yearly drain flow (Fig. 2). Figs. 1 and 2 also confirmed previous conclusions that no consistent tillage effects were observed for drain flow and nitrate-N loss in drain flow in the long-term field study (Weed et al., 1995; Weed and Kanwar, 1996). Consistently, the results showed an increase in flow-weighted N concentration with increasing tillage intensity from NT to RT to CP to MP. Although the measured results showed lower corn yield under NT for most of the years, the model did not adequately simulate the observed lower yield with only 61% of data points in the 1st and 3rd quadrants and majority of the data points away from the 1:1 lines (Fig. 1d). Simulated tillage effects on corn yield were worse between MP, CP, and RT with 39% of data points in the 1st and 3rd quadrants (Fig. 2d). Therefore, there is a need to improve tillage effects on crop yield, including residue cover effects on surface soil temperature and water content (Brandt, 1992; Aiken et al., 1997; Flerchinger et al., 2003). Similarly, the model did not simulate tillage effects on soybean yield well with majority of the data points close to the *x*-axis (Fig. 3).

Simulated tillage effects on crop production and N loss in drain flow for the second phase of study from 1993 to 1998 are shown in Fig. 4. Measured and simulated tillage effects were very similar to those in Figs. 1 and 2 for 1990–1992 with most data points in the 1st and 3rd quadrants; 71% for yearly N loss (Fig. 4a), 79% for drain flow (Fig. 4c), and 63% for flow-weighted N concentration (Fig. 4b). Given that the average standard deviation in observed yearly N loss in drain flow between replicated field plots was 4 kg N/ha with individual plots being as high as 25 kg N/ha, RZWQM simulated tillage effects were acceptable. Similarly, simulated tillage effects on flow-weighted N concentration in drain flow were in general

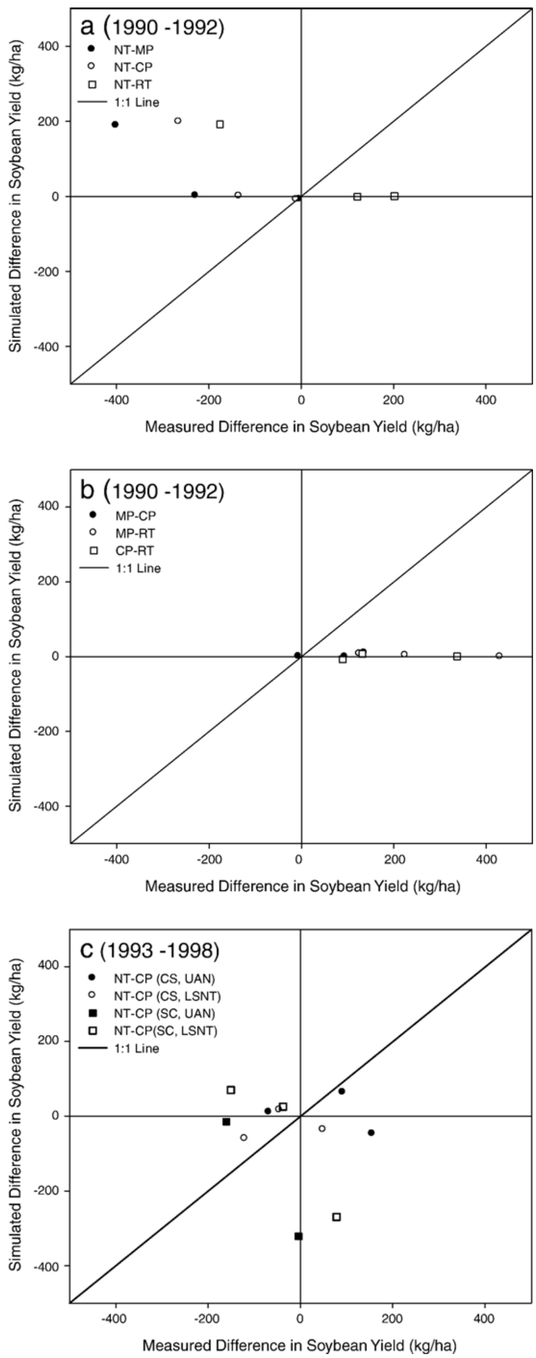

Fig. 3. Observed and simulated differences between various tillage practices in soybean yield at Nashua, IA, from 1990 to 1992 and from 1993 to 1998. NT: no-till; MP: moldboard plow; CP: chisel plow; RT: ridge till; UAN: urea–ammonium-nitrate; LSNT: late spring N test.

agreement with observed N concentrations in drain flow, given that measured standard deviations among replicated plots were as high as 8 mg/L and the average standard error was 1.7 mg/L. It was interesting to note that the simulated and measured tillage effects on yearly drain flow from 1993 to 1998 were different for the UAN and LSNT treatments (solid vs. open symbols). Again the model failed to simulate tillage effects on crop production (Fig. 4d), and on soybean production (Fig. 3c) with only 42% of data points in the 1st and 3rd quadrants and majority of the data points away from the 1:1 lines.

3.2. Simulated and measured crop rotation effects

Fig. 5 shows for the same 1990–92 period the impact of crop rotation on yearly nitrate-N loss to drain flow, nitrate-N concentration in drain flow, drain flow, and crop yield. For both nitrate-N loss to drain flow and flow-weighted N concentration in drain flow, the majority of data points are in the 1st and 3rd quadrants (83% for N loss and 88% for N concentration) with a few exceptions in the 4th quadrant (Fig. 5a, b). Differences in yearly drain flow are mostly in the 1st and 3rd quadrants (67%) with the rest in the 4th quadrant as well (Fig. 5c). Thus, crop rotation effects on yearly drain flow depend on tillage and year. RZWQM simulated and field observed corn yield differences between crop rotations are generally acceptable with 83% of the data points in the 1st and 3rd quadrants. However, majority of the data points are away from the 1:1 line (Fig. 5d). Similar results were reported by Saseendran et al. (2007) when the RZWQM–DSSAT hybrid model was used.

Simulated crop rotation effects for 1993–1998 (Fig. 6) were similar to 1990–1992 (Fig. 5). Percentages of data points in the 1st and 3rd quadrants were 58% for yearly N loss in drain flow (Fig. 6a), 54% for flow-weighted N concentration (Fig. 6b), and 71% for yearly drain flow (Fig. 6c). However, given that the observed standard deviation could be as high as 25 kg N/ha for yearly N loss in drain flow and 8 mg/L for flow-weighted N concentration, the simulated crop rotation effects were reasonable. For this period of time, simulated crop rotation effects on corn yield were considerably better with 92% of the data points in the 1st and 3rd quadrants and close to the 1:1 line (Fig. 6d).

3.3. Simulated long-term crop rotation and tillage effects

When the calibrated model was used for long-term simulation from 1979 to 2002 with uniform management practices, we averaged the results for CS and SC rotation phases and listed under CS in Tables 3 and 4. In general, less drain flow was simulated under CC compared to CS (Table 3). On average, RZWQM simulated a 14% reduction in drain flow under CC compared to CS. This is in agreement with other studies in the Midwest of the USA (Randall et al., 1997; Huggins et al., 2001), although Kanwar et al. (1997) observed greater amounts of drain flow under CC than under CS rotation using 3 years of data (1990–1992). As shown in Figs. 5 and 6, the crop rotation effects on drain flow depend on other management practices and weather conditions. These results also demonstrated the necessity of long-term experiments (Kladivko et al., 2004). The lower simulated drain flow under CC than under CS was due to higher evapotranspiration for corn. In fact, simulated ET values in Table 3 were very close to those measured by Huggins et al. (2001) in the Midwest. They also showed no difference in drain flow in years when ET was similar for corn and soybean. The NT system had higher drain flow than MP (7–14%) or CP (2–5%) (Table 3), which is in agreement with Randall and Iragavarapu (1995), and Bjorneberg et al. (1996). Again, tillage effects

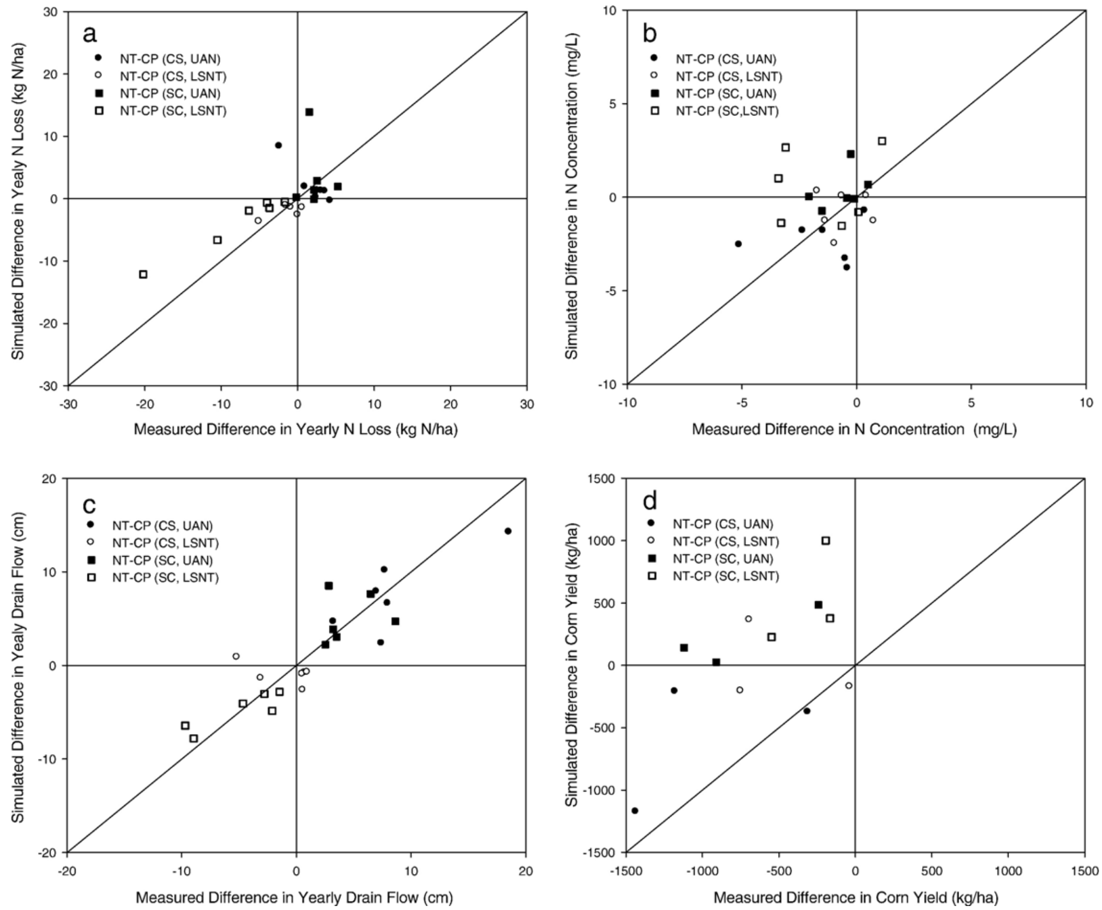

Fig. 4. Observed and simulated differences between NT and CP (NT–CP) in yearly nitrate-N loss in drain flow (a), flow-weighted nitrate-N concentration in drain flow (b), yearly drain flow (c), and corn yield (d) at Nashua, IA, from 1993 to 1998. NT: no-till; CP: chisel plow; UAN: urea–ammonium-nitrate; LSNT: late spring N test.

depend on other management and weather conditions (Figs. 1, 2 and 4).

Although N losses were higher under CC than under CS, N losses could be comparable to those under CS under certain circumstances (Figs. 5 and 6). Under the current scenario (202 kg N/ha for CC and 168 kg N/ha for CS), the model simulated a 9% decrease in nitrate-N loss in drain flow (Table 4), and a 30% reduction in flow-weighted nitrate-N concentration in drain flow under CS than under CC. However, if 150 kg N/ha was applied to corn for both CC and CS, the model simulated 42% lower in nitrate-N loss (7.3 vs. 12.6 kg N/ha/year) and 32% lower in flow-weighted nitrate-N concentration (7.6 mg/L vs. 11.1 mg/L) for CC than for CS. Therefore, lower nitrate-N loss under CS was partially due to lower N application rate (Karlen et al., 1991; Randall et al., 1997; Huggins et al., 2001; Kladivko et al., 2004). Tillage had minimum effects on N loss to drain flow under CC as reported by Randall and Iragavarapu (1995), with slightly lower N loss simulated under NT than under MP (5%) and CP (5%) under CS (Table 4). Weed and Kanwar (1996) also reported lower N losses in drain flow under NT from 1990 to 1992 than other tillage (MP, CP, and RT). In contrast, Bakhsh et al. (2002) observed the exact opposite tillage effects on N losses in drain flow from 1993 to 1998. As shown in Figs. 1, 2, and 4, tillage effects are mixed depending on other conditions. In general, tillage effects on N loss in drain flow were minimum compared with other management practices (Randall and Mulla, 2001).

The effects of crop rotation on corn yield were not simulated when averaging over the 24 years of simulation. Crop production was not affected by tillage either when taking averages over the 24 years of simulation (Table 3). Although higher yields were observed with MP compared to NT (Karlen et al., 1991; Chase and Duffy, 1991), these differences are due to factors not incorporated into the RZWQM model (Randall and Iragavarapu, 1995). Also, there was a strong tillage by year interaction and observed tillage effects varied from year to year (Vetsch and Randall, 2002, 2004).

Simulated runoff was not affected by either crop rotation or tillage (Table 3). Simulated lateral flow was higher under CS than under CC due to lower simulated ET for soybean, but was not affected by tillage. Simulated net N mineralization was about 45 kg N/ha higher under CS compared with those simulated under CC (Table 4). RZWQM simulated tillage and crop rotation effects on nitrate-N loss to lateral flow were closely following nitrate-N loss in drain flow (Table 4). Simulated N fixation for soybean was highest under MP, followed by CP and NT (Table 4) due to higher N uptake demand and higher soybean biomass. Increase in soil organic N was slightly higher with CS compared to CC, which is in agreement with experimental observations (Karlen et al., 1991, 1998). The slightly higher soil

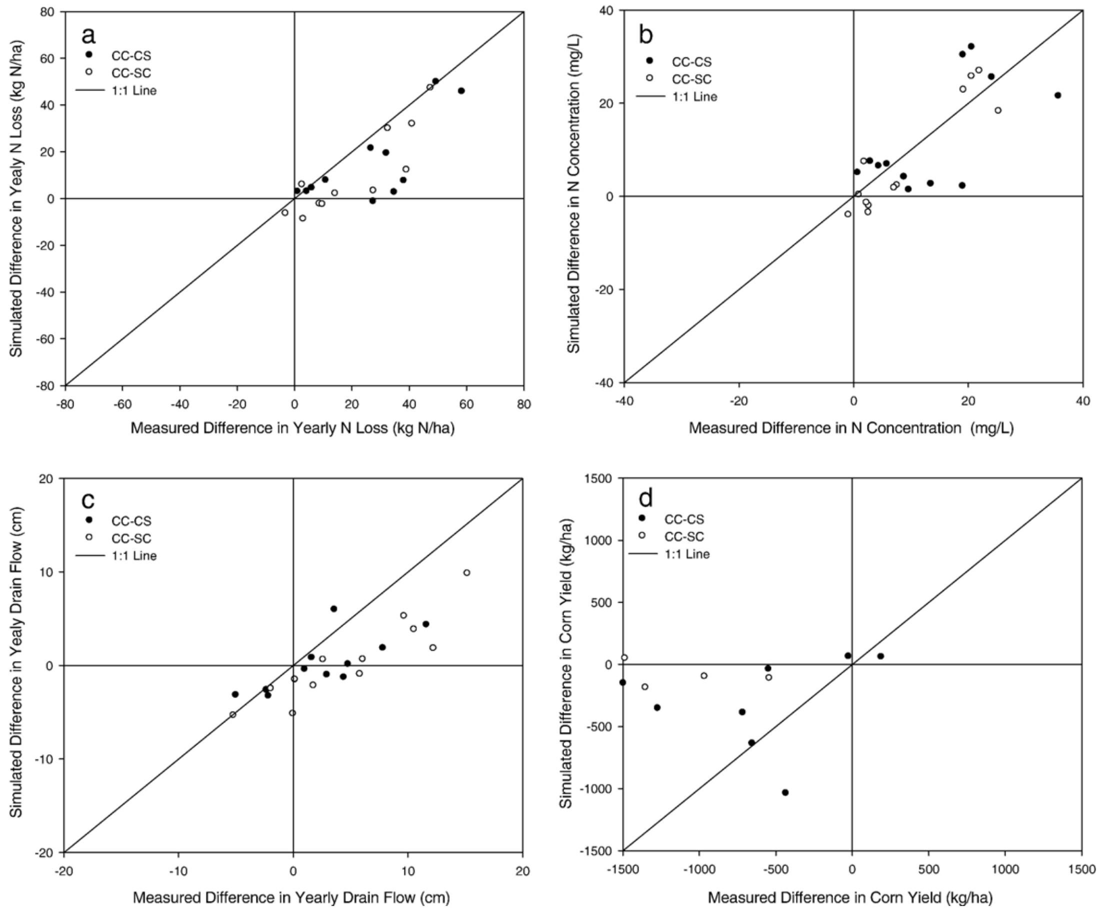

Fig. 5. Observed and simulated differences between CS and CC (CC–CS) and between SC and CC (CC–SC) in yearly nitrate-N loss in drain flow (a), flow-weighted nitrate-N concentration in drain flow (b), yearly drain flow (c), and corn yield (d) at Nashua, IA from 1990 to 1992. CS: corn–soybean rotation; SC: soybean–corn rotation; and CC: continuous corn.

organic N increase under MP for CS was due to higher soybean yield simulated under MP. In RZWQM, tillage practice only affects the soil hydraulic properties and mixes surface crop residue. It may be necessary to increase mineralization of organic N under MP or CP as suggested by McGechan et al. (2005) to simulate lower organic N under MP compared to NT (Karlen et al., 1998). Higher residual soil nitrate-N was simulated under CC than under CS during the 24 years of simulation.

3.4. Simulated controlled drainage (CD) effect

Controlled drainage (CD) had profound effects on water and N balance in the system (Tables 3 and 4). Drain flow simulated by RZWQM was reduced by 30% on average under CD than under free drainage (FD). As a consequence, N loss to drain flow was also reduced by 29%. However, yearly lateral flow increased by 17% under CD. Correspondingly, N losses to lateral flow increased by 17%. Flow-weighted N concentration in drain flow was increased by only 1–2% under CD compared to FD. Mineralization of organic N was slightly higher under FD than under CD, whereas denitrification was slightly lower under FD than under CD. Soil organic N was not affected by CD (Table 4).

These simulated results agreed well with experimental observations. In a study reported in Egypt, Wahba et al. (2001) found that drain flow was reduced by 28% and N losses to drain flow were reduced by 32% under CD during the winter season as is the case in this study. Similar results were observed by Gilliam and Skaggs (1986), Evans et al. (1995), and Drury et al. (1996). Of course, effectiveness of CD depends on soil type, rainfall, type of drainage system, and management intensity (Evans et al., 1995). When the water table was controlled throughout the year, drain flow and N losses in drain flow can be reduced by 40 to 95% (Lalonde et al., 1996; Wesstrom et al., 2001).

Wahba et al. (2001) also noticed lateral seepage from CD plots to FD plots and found that the amount of lateral seepage estimated from CD to FD plots equaled the reduced drain flow amount. Similarly, a comparable amount of N was lost in lateral seepage as in drain flow (Wahba et al., 2001). Although N concentrations were significantly lower with CD compared to FD in some studies (Drury et al., 1996; Mejia and Madramootoo, 1998; Wahba et al., 2001), reduction in N losses to drain flow was mainly due to reduction in drain flow under CD as the reduction in N concentrations was not significant (Gilliam et al., 1979). Our simulation results also showed no consistent decrease in overall N concentration in drain flow under CD (Tables 3 and 4).

A higher water table also promoted surface runoff (Evans et al., 1995) and N losses to runoff (Drury et al., 1996). However, N loss in runoff was minor compared with N losses through drain

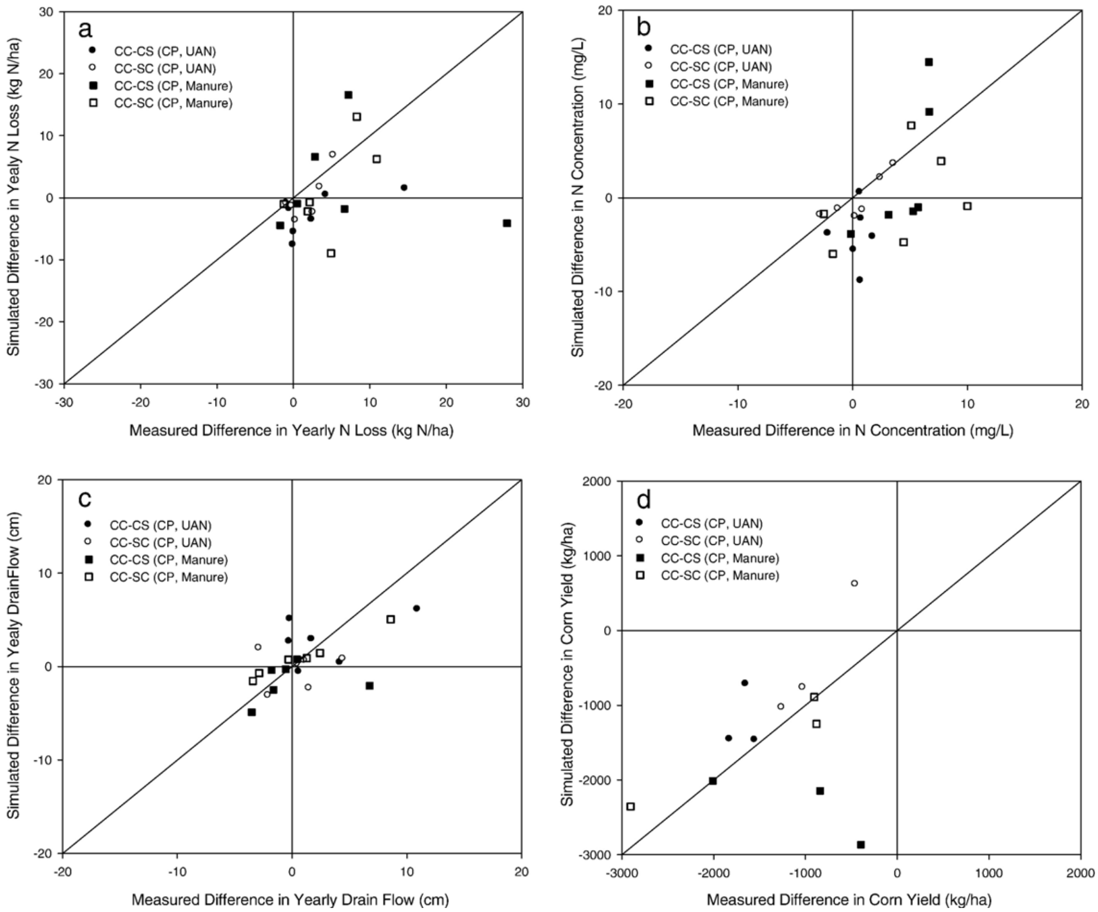

Fig. 6. Observed and simulated differences between CS and CC (CC–CS) and between SC and CC (CC–SC) in yearly nitrate-N loss in drain flow (a), flow-weighted nitrate-N concentration in drain flow (b), yearly drain flow (c), and corn yield (d) at Nashua, IA from 1993 to 1998. CS: corn–soybean rotation; SC: soybean–corn rotation; CC: continuous corn; RT: ridge till; UAN: urea–ammonium-nitrate; LSNT: late spring N test.

flow (Drury et al., 1996). These results are in agreement with our simulation results (Table 3). Although a few studies implied that lower N losses (or lower N concentration) under CD were partially due to denitrification (Evans et al., 1995; Wahba et al., 2001), denitrification was not a major factor based on our simulations and measured oxidation–reduction potentials made by others in the soil profile (Gilliam et al., 1979). Simulated N mineralization was not affected by CD either (Fisher et al., 1999). Simulated evapotranspiration increased slightly as suspected by Gilliam et al. (1979), but not enough to affect the water balance in the system (Table 3). Simulated crop yield was not affected by CD. Similar to our simulation results, Drury et al. (1996) did not find significant interaction between tillage (reduced tillage and MP) and drainage management (CD and

Table 3
Simulated yearly water balance and crop production averaged over 24 years for different crop rotation, tillage, and drainage scenarios

Scenarios	Drain flow (cm)	Lateral flow (cm)	Runoff (cm)	ET (corn, cm)	Corn yield (kg/ha)	Corn biomass (kg/ha)	ET (soybean, cm)	Soybean yield (kg/ha)	Soybean biomass (kg/ha)
CC-NT-FD[a]	12.2	13.2	6.8	57.0	7878.3	18,426.0	–	–	–
CC-MP-FD	10.6	11.4	6.8	60.4	7862.2	18,384.4	–	–	–
CC-CP-FD	11.7	12.7	6.8	58.0	7886.9	18,445.1	–	–	–
CC-NT-CD	8.7	15.2	7.4	57.8	7920.3	18,433.5	–	–	–
CC-MP-CD	7.2	13.4	7.3	61.3	7908.0	18,382.9	–	–	–
CC-CP-CD	8.3	14.7	7.4	58.8	7921.7	18,433.2	–	–	–
CS-NT-FD	13.8	15.5	6.9	57.6	7879.7	18,410.2	47.9	2971.5	8190.5
CS-MP-FD	12.8	14.4	6.9	58.9	7915.0	18,443.1	50.9	3052.2	8544.2
CS-CP-FD	13.5	15.2	6.9	57.9	7915.7	18,460.0	48.7	3001.3	8270.7
CS-NT-CD	9.8	18.2	7.6	58.4	7927.3	18,428.6	48.4	3024.4	8281.8
CS-MP-CD	8.7	17.1	7.5	59.7	7959.0	18,472.6	51.6	3098.3	8638.8
CS-CP-CD	9.5	17.9	7.6	58.8	7958.3	18,487.6	49.3	3052.2	8356.0

Results for corn–soybean rotation were taken as averages from CS and SC.
[a] CC: continuous corn; CS: corn–soybean rotation; NT: no-till; MP: moldboard plow; CP: chisel plow; FD: free drainage; CD: controlled drainage.

Table 4
Simulated yearly nitrogen balance under different crop rotation, tillage, and drainage scenarios

Scenarios	Flow-weighted N concentration (mg/L)	N loss in tile	N loss to lateral flow	Net mineralization	Denitrification	N uptake in corn biomass	N uptake in soybean biomass	N fixation	△ inorganic N (1979–2002)	△ organic N (1979–2002)
CC-NT-FD[a]	15.0	18.4	19.1	73.3	10.4	224.1	–	–	85.7	1642.6
CC-MP-FD	17.4	18.4	17.5	70.3	8.6	223.7	–	–	81.2	1637.6
CC-CP-FD	16.1	18.9	19.2	73.3	9.7	224.3	–	–	83.2	1639.6
CC-NT-CD	15.3	13.4	21.9	72.2	11.3	224.4	–	–	86.0	1647.6
CC-MP-CD	18.3	13.1	20.6	69.2	9.4	224.3	–	–	81.2	1641.6
CC-CP-CD	16.6	13.7	22.0	72.1	10.5	224.7	–	–	83.2	1644.6
CS-NT-FD	11.8	16.3	18.1	116.5	12.5	225.0	318.8	242.8	49.8	1672.7
CS-MP-FD	13.5	17.3	18.6	118.0	9.5	225.8	333.4	252.0	45.4	1793.6
CS-CP-FD	12.7	17.2	19.0	117.0	10.8	226.0	322.1	246.5	52.3	1679.9
CS-NT-CD	11.7	11.4	21.2	115.8	13.3	225.6	322.4	246.3	49.5	1727.6
CS-MP-CD	13.4	11.7	22.1	117.4	10.1	226.5	336.9	254.9	46.3	1798.6
CS-CP-CD	12.6	11.9	22.2	116.2	11.5	226.8	325.4	249.7	52.0	1684.7

Units are in kg N/ha unless stated otherwise. N application rate was 202 kg N/ha for CC and 168 kg N/ha on corn for CS and SC. Results for corn–soybean rotation were taken as averages from CS and SC.
[a]CC: continuous corn; CS: corn–soybean rotation; NT: no-till; MP: moldboard plow; CP: chisel plow; FD: free drainage; CD: controlled drainage.

FD), although we found slightly lower drain flow with MP, which was in agreement with that found by Drury et al. (1996).

4. Summary and conclusions

Using a calibrated RZWQM model, this study demonstrated how well are RZWQM simulated tillage effects and crop rotation effects on crop production, drain flow, and nitrate-N loss in drain flow. Both measured and simulated results showed an increase in flow-weighted nitrate-N concentrations in drain flow with increasing tillage intensity. Although total yearly drain flow and yearly nitrate-N loss in drain flow varied with crop rotation, the simulated tillage scenarios showed impacts that in general reflected observed tillage effects. However, the model failed to simulate the observed lower yield with NT compared to MP, CP, and RT. RZWQM correctly simulated lower N loss and lower N concentrations in drain flow under CS and SC than under CC rotation. Differences in yearly drain flow between CS or SC and CC were also correctly simulated. Observed higher corn yield under CS or SC than under CC was reasonably simulated from 1993 to 1998 and from 1990 to 1992. However, these simulated management effects varied from year to year, indicating a need to conduct long-term evaluation of system models.

Using long-term uniform management practices from 1979 to 2002 with N application rate of 202 kg N/ha for CC and 168 kg N/ha for CS, RZWQM simulated lower drain flow and higher flow-weighted N concentration in drain flow under CC compared to CS. The model also simulated minimum tillage effects on N loss in drain flow and flow-weighted N concentration in drain flow. Simulated corn and soybean yield was not affected by either tillage or crop rotation. CD reduced drain flow and N loss in drain flow by 30% and 29%, respectively. However, flow-weighted N concentration in drain flow was not affected by CD. Thus, reduction in N loss with CD was mainly due to the decrease in drain flow. CD also promoted lateral subsurface flow and associated N loss. Simulated N mineralization was not noticeably affected by CD and tillage, but increased 45 kg N/ha (63%) under CS compared with CC. Therefore, N application to corn after soybean was less compared to CC. Although N loss to runoff was very low under these management scenarios, the model did simulate higher amounts of runoff water with CD (7%). Simulated denitrification increased slightly under CD compared to FD.

Although RZWQM simulated the trends of tillage practices, crop rotation, and controlled drainage on yearly drain flow and yearly N loss in drain flow, their effects on corn yield were less adequately simulated. This study also identified areas that needed improvements in RZWQM, such as N fixation for soybean, plant N uptake, and enhanced mineralization after tillage. With explanations of hypoxia in the Gulf of Mexico focusing on N loss from tile-drained soils of the USA Midwest (Kladivko et al., 2004), there is a strong interest in improving/evaluating management practices to reduce nitrate-N loss in drain flow, such as controlled drainage, crop rotation, cover crops, and N management. In a companion paper, Malone et al. (2007) also showed that RZWQM was able to simulate cover crops and N management effects on nitrate-N loss in drain flow. Although this study was focused on Nashua, Iowa only, RZWQM has been applied in several States in the Midwest and can be extended to other soils and climate conditions (Ma et al., 2000, 2007b). By extending RZWQM to other water quality study sites in tile-drained soils in the Midwest States, it is possible to evaluate the benefits of agricultural practices for alleviating the hypoxia problem. Thus, we conclude that RZWQM can be used as a tool to evaluate the proposed management practices in the Midwest for their potential contributions to hypoxia in the Gulf of Mexico.

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