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Modeling the effects of controlled drainage, N rate and weather on nitrate loss to subsurface drainage

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ABSTRACT

Controlled subsurface drainage can reduce nitrate loss to tile flow, but the effects may vary with different N application rates and weather conditions. Interactions between these factors can be understood better via combinations of field experiments and modeling. Using an automated parameter estimation method (PEST), the Root Zone Water Quality Model (RZWQM2) was calibrated with measured monthly tile flow, N loss and flow weighted nitrate-N concentration (FWNC) from 2006 to 2008 in a corn and soybean rotation system with free drainage (FD) management. Similar data from 2006 to 2008 with controlled drainage (CD) management were used to evaluate the model. Changing from FD to CD reduced the annual N loss in tile flow by 22 and 32% based on measured and RZWQM2 simulated results, respectively. The model over-predicted the CD effect possibly because of the slope of the field, which reduces the effect of CD but is not simulated by the model. Long-term RZWQM2 simulations (1996–2008) suggest that N loss can be reduced by about 40% in both FD and CD by decreasing N rate from 245 to 140 kg N ha^{-1} with little effect on corn yield. A further reduction in N loss of 39% (9.3 kg N ha^{-1}) was simulated by implementing CD at the reduced N rate, and the reduced N loss to tile flow was mainly associated with increased N loss to seepage (lateral flow) and crop N uptake. The percent of N loss reduction using CD relative to FD was magnified with increased rainfall (from approximately 20 to 50% with annual rainfall ranging from 600 to 1100 mm), but the reduction varied only between 38 and 40% under different N rates (0–250 kg N ha^{-1}). The results indicate that RZWQM2 accurately responded to CD compared to field measurements, and CD management in combination with reduced N application rates can substantially reduce N loss to the environment with little negative effect on corn yield.

1. Introduction

Subsurface drainage has been practiced widely in the Midwest Corn Belt, USA (Randall et al., 1997; Hatfield et al., 1998; Randall, 1998; Zucker and Brown, 1998; Fisher et al., 1999). This practice shows benefit to both agricultural production and the environment (Baker et al., 2004; Singh et al., 2007). However, studies suggest that nitrate loss through tile drainage was the main source of nitrate in surface water (David et al., 1997; Goolsby et al., 2001; Jaynes and Colvin, 2006) and a leading cause of hypoxia in regions such as the northern Gulf of Mexico (Goolsby et al., 1999; Rabalais et al., 2001).

Many studies have been carried out to investigate the effect of agricultural management practices (e.g., N fertilization, cropping system, buffer crops, and cover crops) on nitrogen (N) loss to subsurface drainage (Randall and Mulla, 2001; Dinnes et al., 2002). In Sweden, research has focused on alternative cropping and soil management practices to reduce nitrate leaching under subsurface drainage conditions (Wesstrom et al., 2001; Wesstrom and Messing, 2007).

An innovative water table management technique, controlled drainage (CD), has been studied and practiced in many countries, such as USA, Australia, Canada and Sweden (Skaggs et al., 1994; Lalonde et al., 1996; Wesstrom et al., 2003; Elmi et al., 2004; Ayars et al., 2006; Zebarth et al., 2009). The practice utilizes a control structure at the end of subsurface drainage lines to vary the depth of the drainage outlet and has potential for improving grain yield and benefiting the environment by reducing tile flow and nitrogen loss. As summarized by Dinnes et al. (2002), controlled drainage management can reduce nitrate loss to the environment by increasing

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denitrification with higher soil anaerobic activity, decreasing tile drainage and soil profile depth. Singh et al. (2007) summarized that controlled drainage could reduce tile drainage discharge volume from 25 to 44%, compared with free drainage (FD). The reductions in nitrate loss by CD varied greatly (13–95%) with soil type, climate (rainfall) conditions, crop system and other management practices (Drury et al., 1996; Lalonde et al., 1996; Amatya et al., 1998; Kroger et al., 2008). The groundwater table depth, drain spacing, time of implementation and duration of the controlled drainage also showed great influence on nitrate loss to tile drainage and crop production (Jacinthe et al., 1999; Kladivko et al., 1999; Fisher et al., 1999; Ale et al., 2010). Thorp et al. (2008) used the Root Zone Water Quality Model (RZWQM2) to estimate that CD reduces nitrate in subsurface drainage by 35–50% across the Midwest, but the model was not tested for CD using field data.

Improper N management has also been considered as a main contribution to increased nitrate load in the Midwest of USA (Dinnes et al., 2002). Improved timing and rates of N application based on weather conditions and crop demand can reduce nitrate loss to tile drainage, but the variation is high with different climate and soil conditions (Randall and Mulla, 2001; Jaynes et al., 2004). Effective combinations of N management may be different among FD and CD due to different soil water availability (Drury et al., 2009). The high temporal and spatial variability in soil and climate results in difficult interpretation of results when experiments are conducted for only a few sites and years. Also few studies were carried out to evaluate the coupled effects of drainage management (FD or CD) and N rate on nitrate losses, soil water, and nitrogen balance across different climate conditions. Such results are essential to adapting better agricultural water and N management practices to reduce nitrate loss effectively to benefit surface waters and the environment.

Combining model simulation and experimental results is an effective method to evaluate the impact of alternative management on water quality at different scales and climate conditions (Youssef et al., 2006; Ma et al., 2007; Nangia et al., 2008). Many system models have been developed and evaluated for simulating nitrate losses in tile flow and crop production such as DRAINMOD (Skaggs et al., 1995; Singh et al., 2006; Youssef et al., 2006; Salazar et al., 2009), ADAPT (Davis et al., 2000; Nangia et al., 2008), CERES-Maize (Garrison et al., 1999), DNDC (Tonitto et al., 2007), GLEAMS (Chinkuyu and Kanwar, 2001; Bakhsh et al., 2000) and RZWQM/RZWQM2 (Kumar et al., 1998; Bakhsh et al., 2001, 2004; Thorp et al., 2007, 2008). Davis et al. (2000) used the ADAPT model to simulate a greater reduction in nitrate loss by reducing N application rate compared to adjusting tile drain depth or spacing. Using the same model, Nangia et al. (2008) predicted a reduction of 13% in nitrate loss by reducing N rates from 180 to 123 kg N ha^{-1} and a further 9% reduction by switching N application time from fall to spring. Singh et al. (2007) applied DRAINMOD in a corn rotation system in Iowa, and found a tradeoff between subsurface drainage and surface runoff under controlled drainage and possible higher excess water stress on crop production. These system model analyses provided useful information on evaluating agricultural management effects on crop, soil hydrology and chemical properties and environment problems, and they improve our understanding of soil water and nitrogen processes under different variations of subsurface drainage systems.

RZWQM2 was utilized for simulating long-term fertilizer effects on crop production and nitrate loss in the Midwest of USA (Ma et al., 2007; Thorp et al., 2008; Malone et al., 2010) and shows promise as a tool for quantifying the relative effects of agricultural management on nitrate losses in drainage flow. Ma et al. (2007) successfully used RZWQM2 to simulate the effects of crop rotation, tillage and controlled drainage on crop yield and nitrate loss in drain flow. Bakhsh et al. (2001) and Thorp et al. (2007) evaluated the model for

Table 1
Management practices at the experiment site from 1996 to 2008 (adapted from Thorp et al., 2007).[a]

Year	Crop	Spring tillage		Planting	Nitrogen fertilizer application					Summer tillage		Harvest	Fall tillage		Drainage management[e]	
		Type	DOY	DOY	Method[b]	DOY	Rate (kg N ha^{-1})			Type	DOY	DOY	Type	DOY	FD (plots 4,5, 6)	CD (plots 1, 2, 3)
							H	M	L						Calibration	Evaluation
1996	Corn	FC	114	115	AA and NPK	109 and 114[c]	210	143	75	RCC	164	307	MP	315	FD	–
1997	Soybean	FC	113	125[d]	–	–	–	–	–	–	–	274	MP	283[d]	FD	–
1998	Corn	FC	115	116	32% UAN	134	172	114	57	RCC	166[d]	264	CP	273	FD	–
1999	Soybean	FC	112	125[d]	–	–	–	–	–	–	–	264	CP	290	FD	–
2000	Corn	FC	115[d]	116	28% UAN	131	199	138	69	RCC	161	265	–	–	FD	–
2001	Soybean	–	–	125[d]	NPK	298[d]	8	8	8	–	–	289	CP	298[d]	FD	–
2002	Corn	FC	109[d]	110	28% UAN	141	199	138	69	RCC	160[d]	287	–	–	FD	–
2003	Soybean	–	–	125[d]	–	–	–	–	–	–	–	281	CP	290[d]	FD	–
2004	Corn	FC	109[d]	110	28% UAN	154	199	138	69	RCC	160[d]	283	–	–	FD	–
2005	Soybean	–	–	125[d]	–	–	–	–	–	–	–	265	CP	274[d]	FD	–
2006	Corn	FC	102	103	28% UAN	143/170[c]	202	134	67/67[c]	RCC	102	276	CP	283	FD	CD
2007	Soybean	–	–	128	–	–	–	–	–	–	–	270	CP	278	FD	CD
2008	Corn	FC	128	125	28% UAN	143/197[c]	157	157	67/90[c]	RCC	123	283	–	–	FD	CD

[a] DOY: day of year; H: high rate (plots 1 and 4); M: medium rate (plots 2 and 5); L: low rate (plots 3 and 6); N: nitrogen; FC: field cultivator; AA: anhydrous ammonia; NPK: nitrogen, phosphorus, and potassium; RCC: row-crop cultivator; MP: moldboard plow; UAN: urea ammonium nitrate; and CP: chisel plow.

[b] Fertilizer was injected into the soil.

[c] AA was applied on DOY 109 at rates of 202 (1), 135 (2), and 67 (3) kg N ha^{-1}; NPK was applied to all plots at 8 kg N ha^{-1} on DOY 114; UAN was applied separately for 3 treatment in 2006 (on DOY 143 and 170) and 2008 (on DOY 143 and 197).

[d] Estimated date.

[e] Drainage management includes free drainage (FD) at plots 4, 5, and 6, and controlled drainage (CD) at plots 1, 2 and 3.

Table 2
Water table management for controlled drainage practices from 2006 to 2008 at the experimental site and for the long-term simulations from 1996 to 2008.

Experiment from 2006 to 2008				Long-term simulation from 1996 to 2008			
Date	Day of year	Gate above tile (cm)	Water table depth from surface (cm)	Date[a]	Day of year	Gate above tile (cm)	Water table depth from surface (cm)
1-Jan-2006	0	0	145	1-Apr-1996	91	0	145
23-May-2006	142	61	84	30-May-1996	150	85	60
26-Sep-2006	268	0	145	8-Oct-1996	281	0	145
12-Oct-2006	284	122	23	29-Oct-1996	302	115	30
7-Apr-2007	96	0	145	27-Apr-1997	117	0	145
30-May-2007	149	61	84	15-Jun-1997	166	85	60
9-Nov-2007	312	122	23	22-Sep-1997	265	0	145
				13-Oct-1997	286	115	30
11-Apr-2008	102	0	145	1-Apr-1998	92	0	145
24-Jun-2008	176	61	84	30-May-1998	151	85	60
7-Oct-2008	281	0	145	8-Oct-1998	282	0	145
20-Oct-2008	294	61	84	29-Oct-1998	303	115	30
24-Nov-2008	329	122	23				

[a] CD management data from 1996 to 2008 were repeated in a periodic pattern according to the management data across the three years from1996 to 1998.

simulating tile flow and nitrate-N loss with different N application rates under free drainage management at the same site. The RZWQM2 has not yet been evaluated for controlled drainage using field data in the Midwest. Most of above studies calibrated the models via the trial and error method, which is usually difficult and time consuming when measurement data sets for calibration are large. A more efficient and objective method for RZWQM2 parameter optimization can be obtained using automatic parameter estimation methods (Fang et al., 2010; Nolan et al., 2010; Malone et al., 2010).

Clearly reducing N loss to streams and rivers from Midwest U.S.A. corn and soybean production is an important and complex research issue. Agricultural system models can improve our understanding and quantification of important conservation practices that reduce N loss such as fertilizer application rate and controlled drainage under different conditions such as weather and management. The RZWQM2 has been used to quantify the effect of controlled drainage under limited conditions. However, RZWQM2 has not been thoroughly evaluated for its ability to respond to controlled drainage using field data and little research has been devoted to the interactive effect of drainage management under different fertilizer application rates and rainfall conditions. The objectives of this study are to (1) test RZWQM2 for simulating tile flow volume and N loss in tile flow for a corn and soybean rotation production system in central Iowa with CD and different N application rates; and (2) predict the effects of CD and different N rates on nitrate loss using a 13-year simulation period.

2. Materials and methods

2.1. Experimental site, management and data collection

The experimental site is near Story City (42.2°N, 93.6°W), Iowa with mostly Kossuth silty clay loam and Ottosen clay loam soil types (Brevik et al., 2003). The details of the site, experiment, data collection, and RZWQM2 processes are described in Thorp et al. (2007) and the associated references but we will briefly overview them here.

This study included a corn–soybean rotation with corn planted in even years and soybean planted in odd years (Table 1). The fertilizer treatments included different rates and timing of N application. Three N rates (high, medium and low) were applied to corn from 1996 to 2005 and after 2005 the rates and timing of fertilizer varied (Table 1). For soybean years, approximately 8 kg N ha^{-1} was added to all treatment plots as NPK fertilizer in 2001, and no further fertilizer was applied to soybean. Over the course of the thirteen-year study period, tillage transitioned from intensive conventional tillage to more conservation tillage practices (Table 1). Except for N fertilizer applications and harvest, all management decisions were made by the owner–operator of the farm. Three plots (1, 2, and 3) included controlled drainage from 2006 to 2008 (Table 2). The water table management is reasonable for the study area and reduces nitrate-N loss in the winter.

A weather station positioned less than 0.5 km from the site provided hourly rainfall, maximum and minimum daily temperature, wind speed, solar radiation, and relative humidity. Soil properties, including bulk density, field capacity at 33 kPa, and sand, silt, and clay percentages, were measured to a depth of 1.2 m at 42 sampling sites across the 22 ha field (Bakhsh et al., 2000) (Table 3). Bakhsh et al. (2001) and Thorp et al. (2007) used these soil properties for simulations in RZWQM2, and our study made use of them as well. Soil organic carbon (SOC) measurements at the site were used to establish initial conditions for the three organic matter pools within the nutrient component of RZWQM2, and the levels of SOC were greater in comparison to many soils in the Midwest (Jaynes et al., 2001).

Other measurements included crop yield, crop N uptake, monthly tile drainage, and nitrogen loss and flow weighted nitrate concentration (FWNC) in tile flow. A field-plot combine modified to automatically collect grain weight and moisture information (Colvin, 1990) was used to harvest the crop and collect yield information for each plot. Water samples were automatically collected from drainage sumps and were returned to the laboratory on a biweekly basis for analysis of nitrate-N content in drainage effluent (Jaynes et al., 2001). After harvest each year, grain yield was measured in each plot using the procedure outlined by Jaynes et al. (2001). Grain samples were analyzed for protein content, which was used to estimate grain N (e.g., Jaynes and Colvin, 2006). Jaynes et al. (2001) and Jaynes and Colvin (2006) describe the equipment and procedures used to automatically measure flow from drainage sumps and to compute the depth of water drained from each plot on a daily basis.

2.2. RZWQM2 inputs and initialization

The RZWQM2 is a comprehensive agricultural system model that simulates the processes of mineralization, immobilization, nitrification, denitrification, volatilization, urea hydrolysis, methane production, organic matter decay, microbial growth and decay, soil water dynamics, evapotranspiration, subsurface drainage and fluctuating water tables, and plant growth. The simulated processes and the model parameters are described in detail elsewhere (e.g., Ahuja et al., 2000; Malone et al., 2003). Here, the Brooks–Corey equations (Brooks and Corey, 1964) and parameters used in the RZWQM2 are defined for reference, and these

Table 3
Soil parameters calibrated for RZWQM2.[a]

Layer	Depth (cm)	BD ($g\,cm^{-3}$)	Soil water retention[b]				Lateral K_{SAT} ($cm\,h^{-1}$)	K_{SAT}[b] ($cm\,h^{-1}$)	SRGF for corn[c]	SRGF for soybean[c]
			θ_s ($cm^3\,cm^{-3}$)	θ_r ($cm^3\,cm^{-3}$)	t_b (cm)	λ				
1	0–2	1.20	0.5417 (0.56, 0.52–0.58)	0.04	3.84 (15, 1–15)	0.08923 (0.1, 0.05–0.15)	5.00 (5)	3.50 (3.5, 2–8)	1	1
2	2–15	1.20	0.4925 (0.56, 0.49–0.58)	0.04	1.92 (15, 1–15)	0.08923 (0.1, 0.05–0.15)	5.00 (5, 2.5–7.5)	3.50 (3.5, 2–6)	1	1
3	15–150	1.50	0.3906 (0.42, 0.38–0.46)	0.04	2.53 (15, 1–15)	0.0615 (0.1, 0.05–0.15)	5.00 (5, 2.5–7.5)	3.50 (1.5, 2–4)	0.9328, 0.8862, 0.6646, 0.0366	0.72, 0.56, 0.42, 0.25
4	150–160	1.80	0.3047 (0.32, 0.30–0.35)	0.04	4.00 (15, 1–15)	0.080 (0.1, 0.05–0.15)	0.10 (0.2, 0.01–5)	0.90 (0.1, 0.01–1.0)	0	0
5	160–297	1.80	0.350 (0.35)	0.04	15.00 (15)	0.100 (0.1)	0.6 (0.6)	0.01 (0.01)	0	0

[a] BD: bulk density; θ_s: saturated soil water content; θ_r: residual soil water content; t_b: bubbling pressure; λ: pore size distribution index; K_{SAT}: vertical saturated hydraulic conductivity; Lateral K_{SAT}: horizontal K_{SAT} used in the Hooghoudt equation for tile flow; SRGF: soil root growth factor. The numbers in bracket are initial values from Thorp et al. (2007) and their calibration ranges used by the parameter estimation method (PEST).

[b] Soil parameters θ_s, θ_r, t_b, λ and K_{SAT} are used in Brooks–Corey equations (Eqs. (1a), (1b), (2a), (2b)), and other required parameters include A1 (set to zero), B, N1 (set to zero), N2 ($2+\lambda$) and K2 were computed using the RZWQM2 default constraint for all layers (Ahuja et al., 2000).

[c] Soil root growth function (SRGF) was calibrated for 15–30, 30–45, 45–60, 60–90 cm soil layers, respectively, and SRGF values for other soil depths (90–297 cm) were from Thorp et al. (2007) and Malone et al. (2010).

definitions are similar to those in Fang et al. (2010). The Brooks–Corey equations used to relate volumetric soil water content (θ) and matric suction head (ψ, where $\psi > 0$ for negative soil-water pressures) are:

$$\theta = \theta_s \quad \text{for}\ \psi < \psi_b \tag{1a}$$

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{\psi}{\psi_b}\right)^{-\lambda} \quad \text{for}\ \psi \geq \psi_b \tag{1b}$$

where θ_s and θ_r are saturated and residual soil water contents, ψ_b is the air-entry water suction (negative “bubbling pressure”), and λ is the absolute value of the slope of the $\log(\theta) - \log(\psi)$ curve or the “pore-size distribution index”. Similarly, assuming the log–log slope of the water retention curve is linearly related to the log–log slope of the unsaturated conductivity curve, the hydraulic conductivity K vs suction head is:

$$K(\psi) = K_{SAT} \quad \text{for}\ \psi < \psi_b \tag{2a}$$

$$K(\psi) = K_{SAT}\left(\frac{\psi}{\psi_b}\right)^{-(2+3\lambda)} \quad \text{for}\ \psi \geq \psi_b \tag{2b}$$

where K_{SAT} is the saturated hydraulic conductivity. Therefore, the Brooks–Corey parameters for both soil water retention and conductivity include K_{SAT}, θ_s, θ_r, ψ_b, and λ. The soil profile was divided into five layers and simulated to a depth of 297 cm (Table 3). Soil porosity was calculated from bulk density using the default particle density of 2.65 $g\,cm^{-3}$ in each layer. Saturated soil water content was assumed equal to porosity. Necessary parameters to describe the soil water retention curves include θ_s, θ_r, λ, τ_b, lateral saturated hydraulic conductivity (K_{SAT}), and lateral hydraulic gradient parameters (LHG). These parameters were initialized based on values listed in Thorp et al. (2007, 2008) and Malone et al. (2010). Other required parameters, including the intercepts and exponents for hydraulic conductivity curves, were computed from the soil water retention parameters using the RZWQM2 default constraints. To maintain a water table in the soil profile, the K_{SAT} value of the lower layers was tapered down to 0.01 $cm\,h^{-1}$ and deep seepage was assumed to be zero (Ma et al., 2007; Thorp et al., 2007).

Soil nutrient parameters were obtained based on stabilized soil nutrient and micro-organism pools after about 10 year of initialization, which has been described by Ma et al. (1998) and applied in other studies (Thorp et al., 2007; Fang et al., 2008). Other parameters for hydrology and nutrient components were mostly initialized from Thorp et al. (2007, 2008) and Malone et al. (2010).

Crop cultivar parameters include corn and soybean parameters, and most of these parameters were calibrated similar to procedures outlined in Thorp et al. (2007) (Table 4). Management practices such as planting date and density, fertilization, tillage, and water table management are described in Tables 1 and 2.

2.3. Model calibration and evaluation

Model parameterization is a time-consuming process and it is often difficult to obtain the true optimized result due to non-linear co-relations between parameters. Automated calibration procedures provide a more efficient way to calibrate a complex model, such as hydrological models (Madsen, 2003). In this study, the automatic parameter estimation software (PEST) was used (Doherty, 2004), which is a useful method to calibrate RZWQM2 (Fang et al., 2010; Nolan et al., 2010; Malone et al., 2010).

Most of the input parameters were the same or similar to Thorp et al. (2007), Ma et al. (2008), and/or Malone et al. (2010). Parameters that were adjusted from these values or RZWQM2 default values are listed in Tables 3 and 4. We used a combination of manual and PEST optimization that was similar to Malone et al. (2010).

Table 4
Crop cultivar coefficients for corn and C/N and hydrology parameters used by RZWQM2.[a]

Parameter	Description	Calibrated value	Initial values and ranges
Corn growth model			
P1	Thermal time from seedling emergence to the end of the juvenile phase during which the plant is not responsive to changes in photoperiod (DD_8)	225	240 (200, 255)
P2	Extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (d)	0.75	0.75 (0.65, 0.85)
P3	Thermal time from silking to physiological maturity (DD_8)	760	(760)
G2	Maximum possible number of kernels per plant	730	750 (650, 850)
G3	Kernel filling rate during the linear grain filling stage and under optimal conditions ($mg\,d^{-1}$)	7.63	8.2 (5.5, 9.0)
PHINT	Phylochron interval between successive leaf tip appearances (DD)	51	(51)
Hydrology component			
LHG	Lateral hydraulic gradient	1E−5	5E−6 (1E−6, 2E−5)
Nutrient component			
R14	Slow residue to soil intermediate organic matter pool transfer coefficient	0.6	0.3 (0.2, 0.8)
R23	Fast residue to soil fast organic matter transfer coefficient	0.85	0.6 (0.5, 0.9)
R34	Fast soil organic matter to intermediate organic matter pool transfer coefficient	0.6	0.6 (0.2, 0.8)
R45	Soil intermediate organic matter pool to slow organic matter transfer coefficient	0.7	0.7 (0.2, 0.8)
DENR	Denitrification reaction rate coefficient	4.81E−14	1E−13 (5E−14, 5E−13)
SODR	Slow organic matter pool decay rate coefficient	1.0E−9	4.5E−10 (1E−10, 1E−9)

[a] DD_8: degree days above a base temperature of 8 °C; DD: degree days. The numbers in bracket are initial values from Thorp et al. (2007), Ma et al. (2008) and Malone et al. (2010).

The 2006–2008 monthly measured tile drainage, nitrogen loss to tile flow, and FWNC in tile flow from three plots (4, 5, and 6) with FD were used for calibration along with annual corn yield and N uptake from 1996 to 2005 for the three N application rates (plots for corn yield and N uptake data are 4, 5, and 6). We used 1996–2005 corn yield and N uptake data for optimization because of the limited data in 2006–2008, and our objectives do not include testing RZWQM2 for simulation of crop production. The model was thoroughly tested at this Story City site for response to N application rate by Thorp et al. (2007). Although we do not formally test the model for response to corn yield and N uptake, we briefly discuss the corn yield and N uptake simulations because of their influence on water quality.

Similar data from three other plots (1, 2 and 3) from 2006 to 2008 under CD management were used for model evaluation. Additionally, we tested the calibrated model for response to N rate using N loss, FWNC, and tile flow data from plots 4, 5, and 6 (1996–2005, FD management). However, the main purpose in the model testing component of this research is to determine if a previously calibrated and tested RZWQM-DSSAT on this site (e.g., Thorp et al., 2007; Ma et al., 2008) responds to CD compared to FD treatments. Therefore, we report and discuss model comparisons to observed data from individual treatments such as nitrate loss from CD in 2006–2008 and FD in 1996–2005, but the observed and RZWQM2 differences between CD and FD are the most important comparisons. This model testing technique is similar to previous work by Li et al. (2008).

The measured monthly tile flows were very similar across these plots under FD or CD management, and were not sensitive to N application and nutrient management (Jaynes and Colvin, 2006; Thorp et al., 2007). Therefore, the averaged monthly tile drainage from these plots (FD or CD management) was used for calibration and evaluation.

2.4. Model evaluation criteria

Several model calibration criteria were used to evaluate the simulation results for an individual treatment (FD or CD), including: Percent bias (Pbias), Root Mean Squared Error (RMSE), and Nash–Sutcliffe model efficiency (NSME).

$$\text{Pbias} = \frac{1}{n}\sum_{i=1}^{n}\frac{O_i - P_i}{O_{\text{avg}}} \times 100 \tag{3}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}} \tag{4}$$

$$\text{NSME} = 1.0 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - O_{\text{avg}})^2} \tag{5}$$

where P_i is the ith predicted value, O_i is the ith observed value, O_{avg} is the average of observed values, respectively, and n is the number of data pairs. Based upon guidelines from Moriasi et al. (2007), model simulations can be considered satisfactory under a monthly time step if NSME > 0.5, RMSE/mean < 0.7, Pbias is within ±25% for stream flow, and Pbias is within ±70% for N loss. The values of RMSE and NSME when model estimates perfectly match observed data are 0 and 1.0, respectively. An NSME value less than zero indicates that the mean of observed measurements were a better estimator than the model. The effects of controlled drainage on nitrate loss and tile drainage amount were also evaluated using measured and simulated differences between treatments.

2.5. Model applications and analysis

The calibrated and tested RZWQM2 was then used to study the long-term effects of weather, subsurface drainage management (FD and CD), and N application rate on nitrate loss to tile flow in a corn and soybean rotation. The model was run from 1960 to 2008 for both phases on the corn–soybean rotation (corn in odd or even years), both CD and FD, and for eight N application rates (0, 35, 70, 105, 140, 175, 210, and 245 kg N ha^{-1}). Although the model runs began in 1960, the analysis includes only the model results from 1996 through 2008, which allowed the initial soil C and N pools to stabilize. The long-term CD management was set as: lower control gate to 145 cm on April 1; raise to 60 cm on May 30; lower

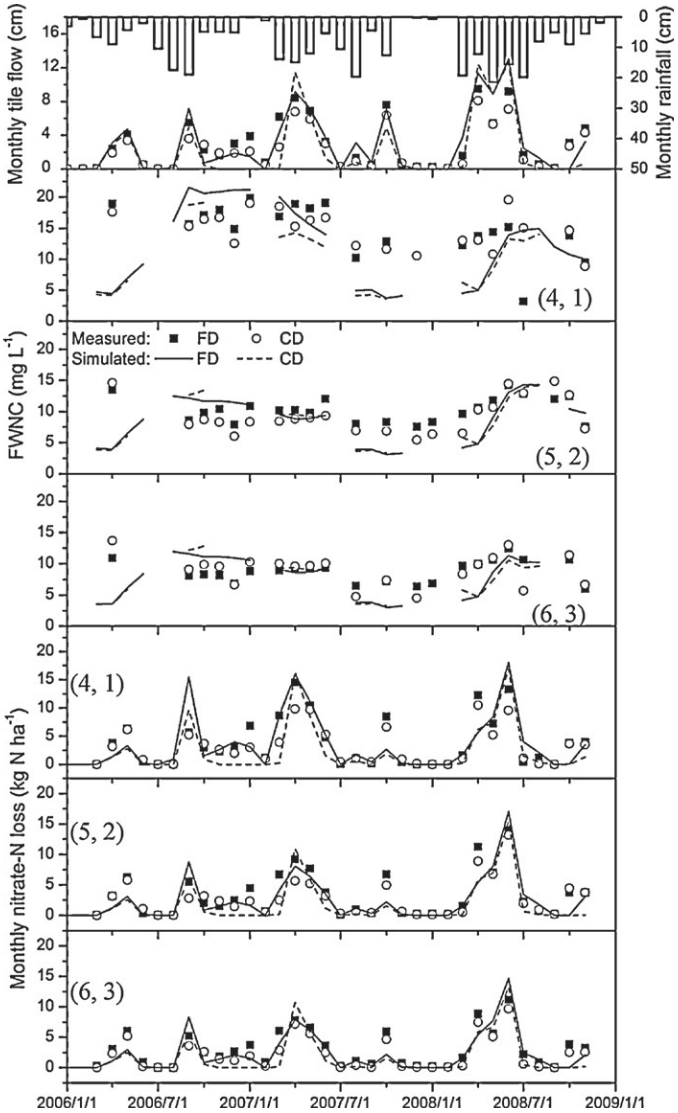

Fig. 1. Measured and simulated monthly tile flow, flow weighted nitrate-N concentration (FWNC), and nitrate-N losses. These are averaged from plots 4, 5, 6 under free drainage (FD: 2006–2008) and from plots 1, 2, 3 under controlled drainage (CD: 2006–2008) conditions. For FWNC, some of the measured and simulated data with low tile flow were removed due to low impact on simulated and observed N loss (plot numbers are shown in brackets (FD plot, CD plot)).

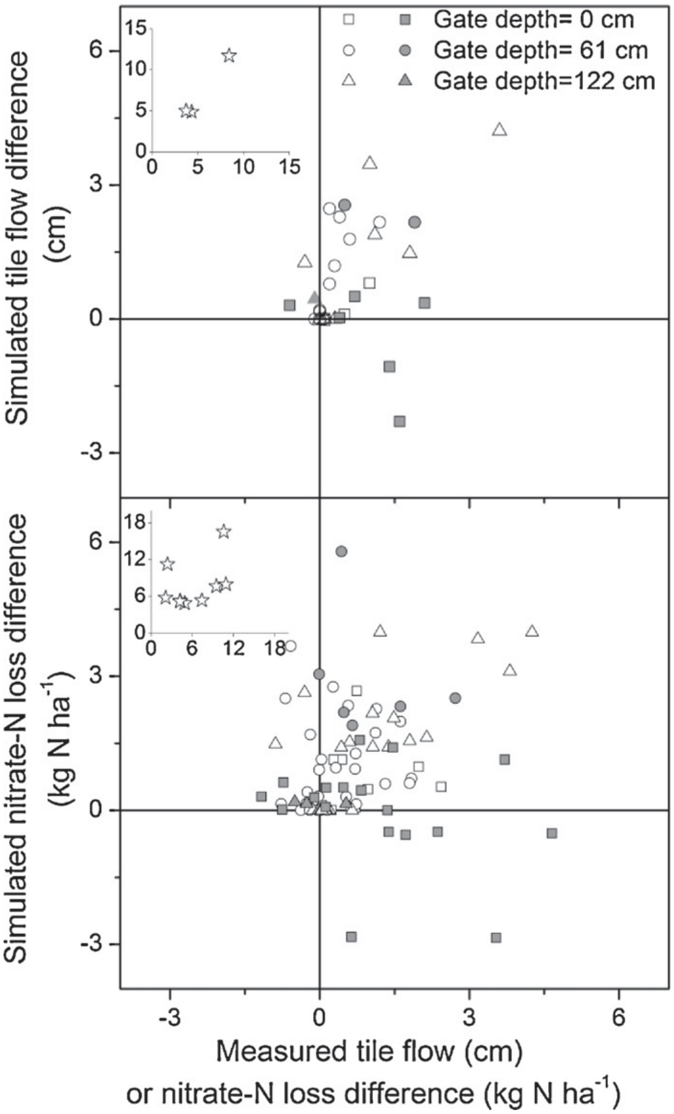

Fig. 2. Measured and simulated annual and monthly difference in tile flow and nitrate-N loss to tile flow between free drainage (FD: plots 4, 5 and 6) and controlled drainage (CD: plots 1, 2, and 3) from 2006 to 2008. Tile flow was averaged from the three plots under FD or CD conditions. Gate depth is the height above the tile. Filled symbols represent measured or simulated data when the gate depth was changed during that month. The inset graphs (star symbols) show annual difference in tile flow (cm) or annual nitrate-N loss (kg N ha^{-1}) from 2006 to 2008 where data were removed during the months when gate depths were changed.

to 145 on October 8; raise to 30 cm on October 29; and lower to 145 cm on April 27 next year, raise to 60 cm on June 15; lower gate to 145 on September 22; and raise to 30 cm on October 13, based on Thorp et al. (2008) and the current water table management at the experimental field. Detailed information is described in Table 2.

3. Results and discussion

3.1. Model calibration

The main evidence that the model has been acceptably calibrated is that the NSME is greater than 0.5 for monthly tile flow (median = 0.83) and nitrate loss (median = 0.72) on the calibration plots (Table 5 and Fig. 1; Moriasi et al., 2007). The NSME was less than zero for FWNC, which is common for agricultural system models (e.g., Youssef et al., 2006; Singh et al., 2006). Despite low NSME values for FWNC, Li et al. (2008) and Thorp et al. (2007) concluded that the calibrated model was acceptable for estimating the relative effects of different management under different conditions on nitrate loss in subsurface drainage.

Also, the model accurately predicted yield differences between N application rates. For example, the simulated and observed corn yields differences between high and low N rates from 1996 to 2005 were 1830 and 1619 kg ha^{-1}, respectively. The overall corn and soybean grain N uptake from 1996 to 2005, however, was under-predicted by 17.6% (Table 5). In contrast, Thorp et al. (2007) found grain N uptake was over-predicted by between 15 and 40%. Thorp et al. (2007) discusses RZWQM2 problems with crop N uptake simulations in detail.

3.2. Model evaluation

The observed and simulated average annual nitrate loss difference between CD and FD were −22 and −32% (Table 5). More than 90% of the monthly observed and simulated nitrate loss

Table 5
Measured and simulated tile flow (mm), nitrate loss (kg N ha^{-1}) and flow weighted nitrate concentration (FWNC, mg L^{-1}), crop yield (kg ha^{-1}) and N uptake (kg N ha^{-1}) for plots 4, 5 and 6 under free drainage (FD: calibration) and for plots 1, 2, and 3 under controlled drainage (CD: evaluation).[a]

Item	N rate	Time	Measured mean	Simulated mean	Pbias (%)	RMSE	NSME
Calibration (plots 4, 5, 6 from 2006 to 2008)							
Tile flow	All N rates	Monthly	27.3	28.8	−5.32	1.45	0.76
		Yearly	318.7	335.6	−5.32	4.65	0.72
Nitrate loss	All N rates	Monthly	3.40	2.95	13.16	2.12	0.62
		Yearly	36.60	31.79	13.16	6.68	0.55
FWNC	All N rates	Monthly	11.44	10.21	10.75	3.35	−1.91
		Yearly	11.51	10.34	10.13	0.28	0.56
Corn yield	All N rates	Yearly	9969	9870	0.99	429	0.87
Evaluation (plots 4, 5, and 6 from 1996 to 2005)							
Tile flow	All N rates	Monthly	16.3	14.4	11.49	0.84	0.90
		Yearly	195.6	173.1	11.49	4.07	0.83
Nitrate Loss	High N	Monthly	5.14	3.99	22.50	2.20	0.77
		Yearly	37.04	28.70	22.50	11.46	0.65
	Low N	Monthly	3.00	2.56	14.82	1.41	0.71
		Yearly	20.12	17.14	14.82	7.28	0.90
	Middle N	Monthly	3.79	2.98	21.37	1.63	0.76
		Yearly	26.53	20.86	21.37	8.22	0.70
FWNC	High N	Monthly	18.70	15.38	17.75	3.80	−1.70
		Yearly	16.78	14.05	16.26	2.12	0.63
	Low N	Monthly	9.98	9.00	9.77	2.01	−0.87
		Yearly	8.82	8.14	7.67	1.25	0.63
	Middle N	Monthly	13.36	11.57	13.38	2.52	−0.95
		Yearly	11.90	10.26	13.74	1.41	0.72
Soybean yield	All N rates	Yearly	2960	2926	1.15	277	0.61
	High N	Yearly	9121	9498	4.14	1106	0.53
Corn yield	Low	Yearly	7291	7879	8.07	875	0.69
	Middle N	Yearly	8853	9121	3.03	876	0.61
	All N rates	Yearly	8421	8832	−4.88	959	0.61
Grain N uptake	All N rates	Yearly	131	108	17.59	33	0.43
Evaluation (plots 1, 2, and 3 from 2006 to 2008)							
Tile flow	All N rates	Monthly	21.6	21.0	2.72	2.05	0.29
		Yearly	251.7	244.8	2.72	4.80	0.44
Nitrate loss	All N rates	Monthly	2.69	2.01	25.14	2.13	0.40
		Yearly	28.70	21.49	25.14	2.36	−0.21
FWNC	All N rates	Monthly	11.15	8.92	20.00	3.03	−2.23
		Yearly	11.87	9.67	18.65	0.56	−0.63
Corn yield	All N rates	Yearly	10,339	9920	4.05	519	0.86

[a] MD, RMSE, and NSME are mean deviation, root mean square error, and Nash–Sutcliffe model efficiency, calculated from Eqs. (3), (4), and (5), respectively.

differences fall in 1st quadrant of the x–y plane or near zero ($r^2 = 0.1$, $n = 99$, slope = 0.41, $P = 0.0013$; Fig. 2). If we removed the data for the months when the gate depths were changed, the r^2 increased to 0.47 with a slope of 0.91 ($n = 69$, $P < 0.00001$). The most obvious anomaly between the RZWQM2 and observed CD effect on nitrate loss was for April 2007 and 2008 when the gate was lowered to zero to allow the fields to drain for the May soybean planting (Figs. 1 and 2). This all suggests that the model reasonably responded to the CD management.

The model may overpredict the effect of CD because only one control structure was implemented on each field and RZWQM2 does not currently simulate the field slope (0.8%) effect associated with controlled drainage. A sloped field reduces the effect of CD on nitrate loss to tile drainage (Evans and Skaggs, 1989; Frankenberger et al., 2006). The range of N loss reduction by CD is similar to the results reported by Jacinthe et al. (1999) and Wahba et al. (2005).

The observed and simulated average annual tile flow difference between CD and FD were −67 mm (−21%) and −91 mm (−27%) (Table 5). Almost all of the monthly observed and simulated tile flow differences fall in the 1st quadrant of the x–y plane except months when the tile gate depths were changed ($r^2 = 0.14$, $n = 35$, slope = 0.61, $P = 0.015$; Fig. 2). If the months when the tile gate depth was changed were removed, the r^2 increases to 0.54 ($n = 25$, slope = 1.00, $P < 0.00001$).

The observed and simulated average annual nitrate loss differences between high and low N rates (1996–2005) were about 46 and 40%, assuming the high rate as the control treatment (Table 5). The nitrate loss differences between different fertilizer rates were due to concentration differences rather than tile flow differences (Table 5). Thorp et al. (2007) discuss the response of RZWQM2 to N rates in detail and conclude that RZWQM-DSSAT can be used to quantify the long-term effects of different N application rates on subsurface drainage nitrate loss on the current Story City experiment site. Our results also suggest that the PEST calibrated model responds acceptably to N application rates.

The monthly tile flow was under-predicted by 2.72% under CD with an NSME of 0.29 (Fig. 1 and Table 5; 2006–2008). The low NSME is partially due to the model not simulating the tile flow during the gate depth adjustments. The least accurate simulations generally occurred when the tile-gate depth was changed from zero, such as April in 2007 and April to May in 2008 (Fig. 1). For the evaluations with FD data from 1996 to 2005, the average measured and simulated monthly tile flow were 16.3 and 14.4 mm with an NSME of 0.90 (Table 5). These results are comparable with the DRAINMOD-N results in North Carolina reported by Youssef et al. (2006) and the previous results from the RZWQM2 study at the current Story City experiment site (Thorp et al., 2007).

The predicted CD monthly nitrate loss to tile flow was 25% (0.68 kg N ha^{-1}) lower than the measured data with an NSME of 0.40 (Table 5). Similar to the monthly tile flow for CD, this result is partially due to the field slope effect and the gate depth adjustment effect that the model did not accurately simulate. Other studies simulating monthly nitrate-N loss under CD using calibrated models have reported negative or near zero values of NSME (Wu et al., 1998; Davis et al., 2000; Youssef et al., 2006; Singh et al., 2006).

The difference between the predicted and observed average monthly FWNC from 2006 to 2008 for the three CD plots were $-2.23\ \text{mg L}^{-1}$(Pbias = 20%) with an NSME of −2.23. The observed and simulated monthly FWNC differences between CD and FD were −2.8 and −12.6%. Some field experiments also showed a lower FWNC under CD compared to FD (Drury et al., 1996; Mejia and Madramootoo, 1998; Wahba et al., 2001). However, the main contribution to reducing nitrate-N loss under CD is the reduction in tile flow, which was also reported in other studies (Gilliam et al., 1979; Ma et al., 2007). Therefore, the CD effect on nitrate loss was mainly due to tile flow reduction rather than FWNC differences. The low or negative NSME values for predicting monthly FWNC for both calibration and evaluation were partly due to the relatively stable nitrate-N concentration across time (low observed variance). Other studies on predicting nitrate-N concentration in tile flow also resulted in negative NSME values (Thorp et al., 2007; Nangia et al., 2008). The high errors in monthly FWNC predictions suggested a further improvement in simulating the very complex processes of N uptake by the crops, soil N cycling and transformations between the different C and N pools (Thorp et al., 2007).

3.3. *Simulated soil water and nitrogen balances under FD and CD*

Detailed information on soil water and nitrogen balances under FD and CD can help our understanding of these management practices across different conditions. Furthermore, looking in additional detail at the measured and simulated water balances under FD and CD and comparing the simulated water balance to selected previous studies can help add confidence and understanding to the current model simulations.

Table 6 shows the annual water balances for FD and CD across the three years (2006–2008) and the long-term simulations from 1996 to 2008. Measured and simulated controlled drainage reduced tile flow by about 21 and 27%, respectively, from 2006 to 2008, which were lower than the CD effect of the long-term simulations (about 38%). Experimental studies also report similar tile flow reductions under CD compared to FD (20–60%; Lalonde et al., 1996; Wesstrom et al., 2001, 2003; Thorp et al., 2008; Drury et al., 2009). Simulated surface runoff, ET, and water seepage to lateral flow increased by 43, 3 and 21% across the three years under CD. These values were 86, 5 and 38% for the long-term simulations (1996–2008), respectively. Similar results were reported from other simulation studies (Ma et al., 2007; Singh et al., 2007) and field experiments (Evans et al., 1995; Drury et al., 1996; Wahba et al., 2001). The long-term simulation results showed a higher CD effect on tile flow reduction than the three-year (2006–2008) results, which was mainly associated with the slightly different water table management (Table 2).

Measured and simulated tile flows increased from a normal year (2006) to a wet year (2008), and were reduced from FD to CD by 17 and 34% in 2006, and 18 and 19% in 2008. Measured and simulated tile flows averaged for the three plots under FD accounted both for 22% of annual rainfall in 2006 and 31 and 37% of the annual rainfall in 2008. These were reduced to 18 and 14% of annual rainfall in 2006 and 25 and 30% of annual rainfall in 2008 under CD condition. The simulated tile flows average from the long-term simulation (1996–2008) accounted for 26 and 16% of annual rainfall under FD and CD, respectively (Table 6).

Evapotranspiration (ET) is one of the most important components in the water balance, and accounts for about 50% of annual rainfall under both FD and CD across the three years. The long-term simulated ET (1996–2008) accounted for about 58 and 61% of the rainfall under FD and CD, which are close to the values (59 and 61%) in 2006 with similar annual rainfall. Measured ET values were not available at the experimental site, but the simulated values were consistent with the results from Thorp et al. (2007) where ET estimated from nearby field measurements were compared to simulated ET.

The simulated annual N output pathways for the three years simulation (2006–2008) and long-term simulations (1996–2008) were summarized in Table 7. Plant N uptake was the main component of the N budget, accounting for about 75–81% of total N loss. Therefore, the errors in N uptake predictions can have a substantial influence on other components of the N budget. The long-term simulations showed about 3.7% increase in plant N uptake ($12\ \text{kg N ha}^{-1}$ at 210 kg N application rate) from FD to CD mainly due to the higher simulated corn yield of about 3% under CD, which was consistent with Thorp et al. (2008).

Nitrogen loss pathways not measured at the field include mineralization, denitrification, runoff, and seepage to lateral flow below tile flow (not captured by the tiles). The values of simulated soil denitrification account for 6–15% of the applied N rate, which are comparable with other values of 10% predicted by ADAPT at Minnesota (Nangia et al., 2008) and 10–25% estimated from field experiments (Meisinger and Randall, 1991). The high predicted soil denitrification in 2006 was probably due to the high N application rate ($202\ \text{kg N ha}^{-1}$) and high mineralization rate. Average soil denitrification across the three plots was simulated to slightly increase with CD by 1.5% and net soil mineralization decreased by 5.7% ($6.2\ \text{kg N ha}^{-1}$) (Table 7). Thorp et al. (2008) also found that CD reduced N mineralization by about $9\ \text{kg N ha}^{-1}$ using RZWQM2 and was the greatest contributor to the increase in stored soil N. But the long-term simulations (1996–2008) showed no significant difference in N mineralization and an increase of about 24% ($1.4\ \text{kg N ha}^{-1}$) in soil denitrification between FD and CD at 210 and $70\ \text{kg N ha}^{-1}$ application rates. Similar results were reported from Fisher et al. (1999) and Ma et al. (2007). These different results suggest that CD effect on soil N mineralization or denitrification vary with soil water conditions as influenced by climate and soil conditions. Malone et al. (2010) showed that RZWQM2 simulated the highest soil organic matter decay at 59% of water filled pore space of soil and this decay decreased as soil water content increased. The simulated increase in runoff, seepage and lateral flow contributed little (0.2 and $2.8\ \text{kg N ha}^{-1}$ at the high N application rate from 2006 to 2008, Table 7) to N losses under CD, which is consistent with the result from Ma et al. (2007). But the long-term simulation (1996–2008) showed a higher increase in N loss to seepage and lateral flow ($6.2\ \text{kg N ha}^{-1}$ at $210\ \text{kg N ha}^{-1}$ application rate) under CD. These results show that CD can increase N loss to pathways other than tile flow such as lateral flow and this effect can vary with N application rate, soil and climate conditions. The long-term simulation showed that CD N loss reduction to tile flow was mainly associated with increased N loss to seepage and lateral flow and crop N uptake under the simulated climate and soil conditions.

3.4. *Simulated long-term CD effects on N loss in tile flow and corn yield*

Fig. 3 shows annual N loss in tile flow accelerating and corn yield leveling-off with the increased N rate under FD and CD from 1996 to 2008. If average corn yield is targeted as 95% or more of maximum yield, an N application rate of $140\ \text{kg N ha}^{-1}$ is selected for the corn–soybean (CS) rotation and $105\ \text{kg N ha}^{-1}$ for the soybean–corn (SC) rotation. These application rates resulted in about 50 and 40% of the maximum N loss (N rate of $245\ \text{kg N ha}^{-1}$) for CS and SC rotations, respectively. This result for reduced N rates was comparable with other studies from Nangia et al. (2008), Baksh et al. (2004), Thorp et al. (2007) and Davis et al. (2000), who found reductions in nitrate-N loss by 13, 22, 27 and 93%, respectively, depending on the decrease in N rate. A further reduction in N loss of 42% ($10.2\ \text{kg N ha}^{-1}$) for CS rotation or 37% ($8.4\ \text{kg N ha}^{-1}$) for SC rotation can be achieved by implementing CD management at the targeted

Table 6
Simulated water balances (mm) and measured tile drainage (mm) for plots 4, 5, and 6 under free drainage (FD) conditions, and for plots 1, 2, and 3 under controlled drainage (CD) condition, and for the long-term simulation under FD and CD conditions by RZWQM2.[a]

Drainage	Year	Rainfall	Runoff	Evaporation	Transpiration	Measured tile drainage	Tile drainage	Seepage
Model calibration and evaluation								
	Mean[b]	770	18	183	302	196	173	84
FD	2006	882	25	189	335	195	193	102
Plots 4, 5, 6	2007	1036	48	196	282	398	374	115
	2008	1182	86	205	322	363	440	112
	Mean[c]	1033	53	196	313	319	336	110
	2006	882	34	197	341	161	127	107
CD	2007	1036	84	225	248	297	251	161
Plots 1, 2, 3	2008	1182	110	225	311	297	357	126
	Mean[c]	1033	76	216	300	252	245	132
Long-term simulation from 1996 to 2008								
FD	Mean[d]	830	26	182	302	–	218	92
CD	Mean[d]	830	48	196	310	–	135	126

[a] Because the nitrogen fertilizer application rate had little influence on the water balance, water balance and its components were averaged from the three N application rates (Table 1), and 70, 140 and 210 kg N ha^{-1} application rates for the long-term simulations from 1996 to 2008.

[b] Mean values were calculated from 1996 to 2005 under FD conditions and were included to correspond to plots 4, 5, and 6 evaluation years (see Table 5).

[c] Mean values were calculated from 2006 to 2008 under FD or CD conditions.

[d] Mean values were calculated from 1996 to 2008 under FD or CD conditions based on the long-term simulation.

(reduced) N rate. Fig. 3 also showed that higher corn yield under CS was associated with lower N loss in tile flow mainly due to increased corn N uptake from the soil, which is consistent with Malone and Ma (2009).

As recommended by Mitsch et al. (2001), a reduction in nitrate-N loss by 30% may be required to reduce hypoxia in the Gulf of Mexico. The N loss in tile flow was reduced by 39% from FD to CD averaged from 1996 to 2008 for all the N rates and the two rotations. This

Table 7
Effects of drainage management practices (free, FD and controlled, CD drainage) and fertilizer application rates on annual N budget (kg N ha^{-1}), including fertilizer input (I), rainfall (R), mineralization (M), fixation (F), denitrification (D), runoff + volatilization (RV), immobilization (IM), tile flow (T), seepage + lateral flow (S) and plant N uptake (P) simulated by RZWQM2 during the model calibration, evaluation and long-term simulation.

Drainage	Year	I	R	M	F	D	RV	IM	Measured T	Simulated T	S	P
Model calibration and evaluation												
Plot 4												
	Mean[a]	101	10.2	117	122	6.4	1.2	3.9	37.0	29.0	13.0	300
	2006	202	12.1	126	0	31.5	1.6	5.6	24.7	29.3	13.6	243
FD	2007	0	12.7	115	309	5.5	0.6	2.8	56.5	49.1	17.0	408
	2008	157	14.6	98	0	12.0	2.3	1.2	43.7	43.4	11.9	202
	Mean[b]	120	13.1	113	103	16.3	1.5	3.2	41.7	40.6	14.1	285
Plot 1												
	2006	202	12.1	121	0	29.4	1.7	6.5	23.7	14.7	15.2	260
CD	2007	0	12.7	108	334	6.7	1.0	3.5	42.4	29.2	21.9	431
	2008	157	14.6	97	0	13.8	2.3	1.9	34.8	33.9	13.6	206
	Mean[b]	119.7	13.1	109	111	16.6	1.7	3.9	33.6	25.9	16.9	299
Long-term simulation from 1996 to 2008												
210 kg N ha^{-1} application rate												
FD	Mean[c]	105	10.9	122	139	11.2	1.4	4.1	–	35.6	14.0	316
CD	Mean[c]	105	10.9	121	146	13.9	1.7	4.2	–	22.0	20.2	328
Drainage	Year	I	R	M	F	D	RV	IM	Measured T	Simulated T	S	P
Model calibration and evaluation												
Plot 6												
	Mean[a]	37	10.2	107	132	3.0	0.3	3.5	20.1	17.3	9.5	253
	2006	134	12.1	117	0	14.3	0.5	5.6	22.4	16.8	8.8	231
FD	2007	0	12.7	107	322	3.9	0.5	3.4	37.5	26.7	10.3	404
	2008	157	14.6	95	0	5.8	1.0	1.4	37.7	35.2	8.5	215
	Mean[b]	97	13.1	106	107	8.0	0.7	3.5	32.5	26.2	9.2	283
Plot 3												
	2006	134	12.1	108	0	13.2	0.4	5.9	16.4	10.1	9.9	221
CD	2007	0	12.7	96	333	4.5	0.8	4.1	25.7	19.5	14.6	413
	2008	157	14.6	90	0	6.6	1.0	1.9	28.5	26.6	8.9	217
	Mean[b]	97	13.1	98	111	8.1	0.7	4.0	23.5	18.7	11.1	283
Long-term simulation from 1996 to 2008												
70 kg N ha^{-1} application rate												
FD	Mean[c]	35	10.9	112	150	4.5	0.5	3.8	–	18.8	6.7	276
CD	Mean[c]	35	10.9	112	157	5.6	0.8	3.9	–	11.3	9.6	286

[a] Mean values were calculated from 1996 to 2005 under FD condition.

[b] Mean values were calculated from 2006 to 2008 under FD or CD condition.

[c] Mean values were calculated from 1996 to 2008 under FD or CD conditions based on the long-term simulation.

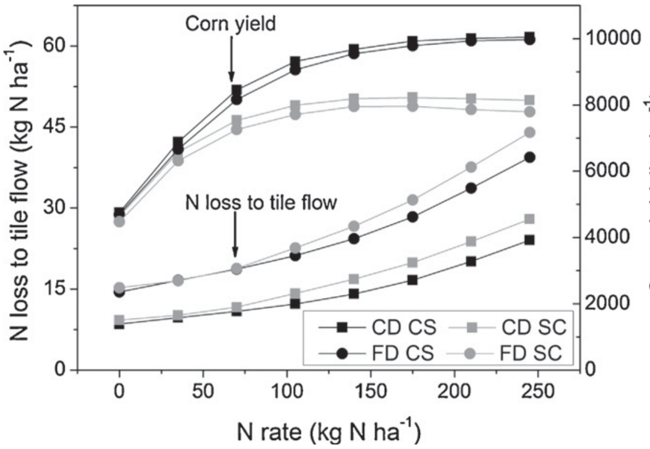

Fig. 3. Simulated average corn yield and N loss to tile flow from 1996 to 2008 in response to N rate and drainage type (free, FD; controlled, CD) in corn–soybean (CS) or soybean–corn (SC) rotations based on the long-term simulations from 1960 to 2008.

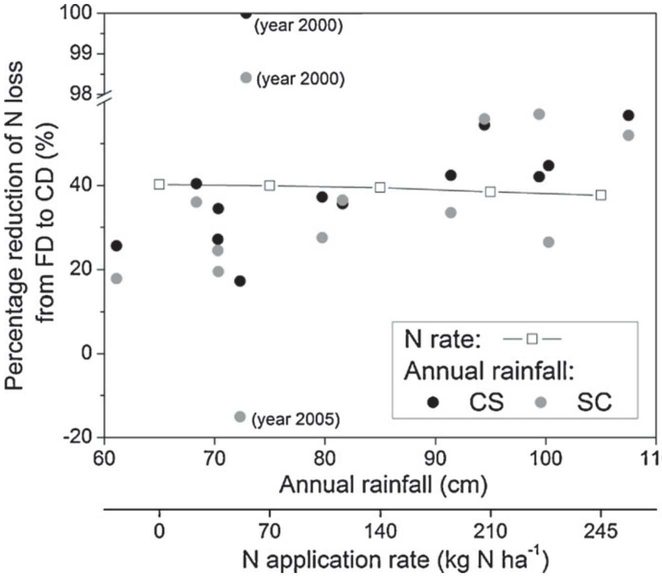

Fig. 4. Simulated controlled drainage effects on N loss to tile flow (percentage reduction of N loss from free drainage, FD, to controlled drainage, CD) in response to N rate or annual rainfall. The data were calculated from 1996 to 2008 for both corn–soybean (CS) and soybean–corn (SC) rotations at 140 kg N ha^{-1} application rate based on the long-term simulations from 1960 to 2008. Abnormal data have the year reported in parentheses.

result was comparable with the result (35–50%) from Thorp et al. (2008), but was higher than the field conditions (22%, 2006–2008, Table 6), mainly due to the slight difference in water table management between the long-term simulation and field experiment (Table 2). This suggests that careful management of the timing and depth of gate management is very important to optimize reduced N loss to the environment using CD.

Controlled drainage generally resulted in slightly higher (3%) average corn yield from 1996 to 2008 than free drainage (Fig. 3). Some field experiments report an increase in crop yield under CD, such as in a sandy loam soil in Canada (Mejia et al., 2000; Ng et al., 2002) and in Ohio, USA (Fisher et al., 1999). Other field experiments found that drainage type was not a significant factor for crop yield (Zhou et al., 2000; Grigg et al., 2003). The effects of CD on crop yield varied with the specific groundwater table management practices and environmental conditions (Ale et al., 2009).

The N loss and corn yield differed considerably between the two rotations (CS and SC), especially at the high N application rates (Fig. 3). This result was due to the simulated low corn yield (less than 5000 kg ha^{-1}) in 2001 and 2007 under the SC rotation. Many studies found below average July and August temperatures and above average July and August rainfall are generally associated with higher corn yield (Thompson, 1969, 1986; Wilhelm and Wortmann, 2004; Hu and Buyanovsky, 2003). For the simulation period (1996–2008), the lowest July and August rainfall (62% of average value) occurred in the 2001 corn season, and the highest July and August temperature (107% of average value) occurred in the 2007 corn season. The lowest simulated corn water stress indexes (higher value indicates lower stress) were for July and August in 2001 and 2007 (0.42 and 0.26), compared with the average value of 0.60 from1996 to 2008. If the water routines were closed in the model (no water stress), the corn yield in 2001 and 2007 increased to 8047 and 8967 kg ha^{-1}. The lower N loss to tile flow under CS compared to SC was associated with higher corn yield and N uptake as discussed above.

Fig. 4 shows the CD effect on N loss to tile flow from 1996 to 2008 under variable N rate and annual rainfall. The CD effect on N loss increased with increased rainfall (from 17 to 50%, not including year 2000 and 2005), but decreased slightly (from 40 to 38%) with increased N application rates. The two abnormal data in Fig. 4 (near to 100%) occurred in 2000 (CS and SC rotations) due to the simulated low N loss to tile flow (less than 0.1 kg N ha^{-1}). Another abnormal data (negative value) for SC rotation in 2005 was mainly due to the low N loss to tile flow (47% of the average value from 1996 to 2008, 7.9 kg N ha^{-1} vs 16.8 kg N ha^{-1}) and most of it (75% of total annual N loss) occurring in the tile gate transition month (May in 2005, Table 2). The slightly reduced CD effect on N loss to tile flow under increasing N rates was mainly due to increased N loss with high N rates.

4. Summary and conclusions

Calibration and evaluation of RZWQM2 were completed using thirteen years of data from a corn–soybean cropping system that included different N application rates and two drainage management practices (FD and CD). The model performed reasonably well when comparing measured and simulated tile flow, nitrate-N loss and crop yield. Consistent effects of CD and N application rate on tile flow and nitrate-N loss were found for both measured and simulated data. For example, the average annual reductions in nitrate loss using CD compared with FD were 22 and 32% based on observed and simulated results, respectively. One possible reason for the over-prediction is associated with the land-surface and tile drain slope (0.8%), which the model does not simulate. The predicted soil water and nitrogen balance were consistent with measured data and literature values. This all suggests that RZWQM2 can be used to predict tile flow and nitrate-N loss to tile flow under FD and CD after rigorous calibration with field data using PEST.

Based on the long-term simulations, more than 50% (FD and CD) reductions in annual N loss in tile flow were predicted by reducing N rate from 240 to 140 kg N ha^{-1} (SC) or to 105 kg N ha^{-1} (CS), and a further reduction by about 39% (9.3 kg N ha^{-1}) can be achieved by changing FD to CD management at the reduced N rates, which resulted in less than a 5% reduction in corn yield. The CD effect on N loss in tile flow increased (from about 20 to 50%) with increased annual rainfall, but decreased slightly (from about 40 to 38%) with increased N rates. CD also increased N loss to pathways other than tile flow, which varied with N application rate, soil and climate conditions. The long-term simulated reduction in N loss to tile flow using CD was mainly associated with increased N loss to seepage and crop N uptake (e.g., 6.2 kg N ha^{-1} loss to seepage and 12 kg N ha^{-1} for crop N uptake at the 210 kg N ha^{-1} application rate).

The present simulations using RZWQM2 helped increase the state of knowledge concerning N transport processes and mass balances, and the interactions between factors affecting N loss to tile drains in both FD and CD systems. The potential for improved N and tile-drain management is great, having important implications for off-site N loading to streams and hypoxia at large scales.

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