SIMULATING LONG-TERM IMPACTS OF WINTER RYE COVER CROP ON HYDROLOGIC CYCLING AND NITROGEN DYNAMICS FOR A CORN-SOYBEAN CROP SYSTEM

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ABSTRACT. *Planting winter cover crops into corn-soybean rotations is a potential approach for reducing subsurface drainage and nitrate-nitrogen (NO_3-N) loss. However, the long-term impact of this practice needs investigation. We evaluated the RZWQM2 model against comprehensive field data (2005-2009) in Iowa and used this model to study the long-term (1970-2009) hydrologic and nitrogen cycling effects of a winter cover crop within a corn-soybean rotation. The calibrated RZWQM2 model satisfactorily simulated crop yield, biomass, and N uptake with percent error (PE) within ±15% and relative root mean square error (RRMSE) <30% except for soybean biomass and rye N uptake. Daily and annual drainage and annual NO_3-N loss were simulated satisfactorily, with Nash-Sutcliffe efficiency (NSE) >0.50, ratio of RMSE to standard error (RSR) <0.70, and percent bias (PBIAS) within ±25% except for the overestimation of annual drainage and NO_3-N in CTRL2. The simulation in soil water storage was unsatisfactory but comparable to other studies. Long-term simulations showed that adding rye as a winter cover crop reduced annual subsurface drainage and NO_3-N loss by 11% (2.9 cm) and 22% (11.8 kg N ha^{-1}), respectively, and increased annual ET by 5% (2.9 cm). Results suggest that introducing winter rye cover crops to corn-soybean rotations is a promising approach to reduce N loss from subsurface drained agricultural systems. However, simulated N immobilization under the winter cover crop was not increased, which is inconsistent with a lysimeter study previously reported in the literature. Therefore, further research is needed to refine the simulation of immobilization in cover crop systems using RZWQM2 under a wider range of weather conditions.*

Keywords. *Corn-soybean rotation, Hydrology, Nitrogen, RZWQM2, Subsurface drainage, Winter rye.*

Agricultural nutrient loading to the Mississippi River is a main contributor to the hypoxia zone in the Gulf of Mexico (Rabalais et al., 2001). Approximately 24.5% of agricultural land is artificially drained in Iowa (Baker et al., 2004), and subsurface drainage is the main source of NO_3-N loss from agricultural fields, with losses being closely related to the volume of subsurface drainage flow (Baker et al, 1975; Cambardella et al., 1999). The time period from April through June, when the row crops have not been planted or are otherwise still in the early growth stages, was found to be the main subsurface drainage period. A 15-year study indicated that nearly 70% of the annual drainage occurred within these three months in north-central Iowa (Helmers et al., 2005). Growing winter cover crop is one of the strategies that may reduce NO_3-N losses in tile-drained Midwestern soils (Dinnes et al., 2002). Strock et al. (2004) found that using rye as a winter cover crop in Minnesota reduced subsurface drainage volume by 11% and NO_3-N load by 13%. In Iowa, confined lysimeter studies suggested that winter rye cover crops significantly reduced subsurface drainage volume (Qi and Helmers, 2010b) and nitrate loss (Logsdon et al., 2002; Parkin et al., 2006). In field studies, Kaspar et al. (2007) reported that rye cover did not reduce the cumulative annual drainage but significantly decreased the flow-weighted average NO_3-N concentration by 59% and NO_3-N load by 61%, whereas Qi et al. (2008, 2011b) documented that NO_3-N concentrations in the soil profile while growing winter rye prior to soybean were significantly reduced, but annual drainage volume and NO_3-N load were not significantly reduced by rye.

Agricultural systems models are promising tools for evaluating the effects of emerging agricultural practices on hydrologic cycling and nitrogen dynamics within agricultural fields. DRAINMOD was calibrated and validated to simulate the effects of drainage design and management on hydrologic components (Singh et al., 2006). Other models, such as GLEAMS (Groundwater Loading Effects of Agricultural Management Systems), APSIM (Agricultural Production Systems Simulator), DNDC (Denitrification- Decomposition), and CERES (Crop Environment Resource Synthesis) have been utilized to evaluate the impacts of crop system and fertilization rate on Iowa's subsurface drainage water quality and crop production with reasonably good performance (Garrsion et al., 1999; Paz et al., 1999; Bakhsh and Kanwar, 2001; Li et al., 2006; Malone et al., 2007b).

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The Root Zone Water Quality Model (RZWQM2) describes the physical, biological, and chemical processes occurring within the soil-plant-atmosphere system and from this simulates plant growth, water movement, and fate of nutrient and pesticides. Thorp et al. (2007) found that RZWQM2 performed reasonably in simulating corn yield and nitrogen dynamics for a crop production field near Story City, Iowa. The calibrated model was subsequently adopted by Li et al. (2008) and successfully used to simulate NO_3-N loss under winter rye cover crop at a site in Boone County, Iowa. However, Li et al. (2008) only tested RZWQM2 at high N rates (235 to 247 kg N ha^{-1}), which were much higher than the recommended N application rates of 112 to 168 kg N ha^{-1} for the study area (Blackmer et al., 1997). Moreover, the simulation of various scenarios was limited to five years of weather conditions, from 2001 to 2005.

With an increased concern about the effectiveness of winter cover crops on improving water quality in the Midwest, there is a need to investigate the long-term impacts of adding winter rye cover crops to corn-soybean rotations on the hydrologic and nitrogen cycling through models tested using comprehensive field-measured data over a wide range of weather and soil conditions. This may also help identify directions for further research. One of the primary values of a water quality model is to illuminate which aspects of a system are most in need of further study (Oreskes et al., 1994). Previous research with RZWQM2 has included as the main objective to identify areas of further research (Malone et al., 2004). The objectives of this research were to: (1) parameterize and evaluate the performance of RZWQM2 in simulating subsurface drainage, NO_3-N loss, soil water content, crop growth, and N uptake; and (2) predict the long-term subsurface drainage and NO_3-N loss for a corn-soybean rotation with and without a winter rye cover crop.

MATERIALS AND METHODS

RZWQM2 OVERVIEW

RZWQM2 (version 2.0.2010) is a one-dimensional agricultural system model consisting of hydrology, nutrition and pesticide transport and transformation, plant growth, and management practice components (Ahuja et al., 2000; Ma et al., 2005; Ma et al., 2006). Infiltration from rainfall, irrigation, or snow melt is computed by a modified Green-Ampt approach, and the water redistribution in the soil profile, considering plant uptake as a sink, is simulated by the Richards equation. Tile drainage flux is calculated using the steady-state Hooghoudt equation. Lateral flow is quantified by the user-defined parameters of lateral hydraulic gradient. The nutrient chemistry processes model incorporated in RZWQM2 is OMNI (Shaffer et al., 2000), a state-of-the-art model for carbon and nitrogen cycling in soils. The coupled DSSAT family (Jones et al., 2003) of crop growth models enhances the capability of RZWQM2 in describing crop establishment and water and nutrient uptake. The crop root water uptake can be conveniently adjusted by the user by changing the soil root growth factor for each calculated soil layer.

FIELD EXPERIMENTS

The field study was conducted at the Agricultural Drainage Water Quality - Research and Demonstration Site (ADWQ-RDS, former Agricultural Drainage Well Site) near Gilmore City in Pocahontas County, north central Iowa. Predominant soils are Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludoll), Webster (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls), Canisteo (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls), and Okoboji (Fine, smectitic, mesic Cumulic Vertic Endoaquolls) (USDA, 1985). This site has 78 individually drained plots in total, with the same layout. The design of this drainage site and the layout of the plots are described in greater detail by Lawlor et al. (2008).

This five-year field experiment was initiated in the fall 2004 with a completely randomized block design. All 78 plots were blocked by drainage characteristics based on the long-term drainage performance. The four blocks were classified as high (H), medium-high (MH), medium-low (ML), and low (L) drainage. Land cover treatments in this study were: winter rye growth prior to corn in odd years and prior to soybean in even years (TRT1), winter rye cover crop growth prior to soybean in odd years and prior to corn in even years (TRT2), corn in odd years and soybean in even years without cover crop (CTRL1), and soybean in odd years and corn in even years without cover crop (CTRL2). One plot in each block was randomly selected for each treatment application in this study. Plot numbers and the cropping systems during the monitoring years from 2005 through 2009 are listed in table 1.

The experimental phase that included winter cover crop for corn and soybean (TRT1 and TRT2) was initiated in October 2004 by planting of rye as a winter cover crop after corn and soybean harvest. In subsequent years, a winter rye cover crop continued to be planted after corn and soybean within the commonly adopted corn-soybean rotation cropping system in Iowa. Agronomic field activities were completed in a timely manner prior to and during the crop season beginning in October 2004 with plot tillage and seeding. ‘Rymin’ rye (*Secale cereale*) was drill seeded at a rate of 100 kg ha^{-1} (3,638,000 seeds ha^{-1}). Glyphosate-resistant corn (*Zea mays*) and soybean (*Glycine max*) were used, and planting dates were dictated by field conditions. Seeding rates were 77,000 seed ha^{-1} for corn (Dekalb 50-45) and 439,750 seed ha^{-1} for soybean (Pioneer 92M40 Group 2 middle season). Rye was terminated by glyphosate in the following April or

Table 1. Plots selected and cropping systems for the calibration and validation of crop parameters for RZWQM2.

	Calibration	Validation		
	TRT1	CTRL1	TRT2	CTRL2
Year	Plots 7-1, 8-3, 18-2, 1-2	Plots 14-3, 24-2, 18-1, 10-2	Plots 13-3, 6-3, 18-3, 26-3	Plots 8-1, 20-3, 22-2, 1-1
2005	Rye-Corn	Corn	Rye-Soybean	Soybean
2006	Rye-Soybean	Soybean	Rye-Corn	Corn
2007	Rye-Corn	Corn	Rye-Soybean	Soybean
2008	Rye-Soybean	Soybean	Rye-Corn	Corn
2009	Rye-Corn	Corn	Rye-Soybean	Soybean

Table 2. Agronomic management for all the treatments.

Activity	2004[a]	2005	2006	2007	2008	2009
Rye growth termination prior to corn	--	30 Apr.	24 Apr.	30 Apr.	6 May	8 May
Field cultivating and corn planting[b]	--	10 May	4 May	14 May	15 May	19 May
Field cultivating and soybean planting[c]	--	18 May	10 May	17 May	23 May	20 May
Rye growth termination prior to soybean	--	20 May	16 May	23 May	26 May	31 May
N fertilization to corn (140 kg N ha^{-1})	--	25 May	18 May	5 June	4 June	30 June
Corn and soybean harvest	10 Oct.	10 Oct.	7 Oct.	22 Oct.	20 Oct.	3 Nov.
Chisel/disk plow and field cultivating[d]	12 Oct.	10 Oct.	10 Oct.	24 Oct.	20 Oct.	--
Rye planting	15 Oct.	11 Oct.	12 Oct.	25 Oct.	21 Oct.	20 Nov.

[a] Field management dates prior to corn and soybean harvest in 2004 was not listed.

[b] Field cultivating was only applied to CTRL1 and CTRL2 plots.

[c] Soybean planting dates were adjusted later than rye growth termination in the modeling because RZWQM2 does not work when intercropping. Field cultivating was only applied to CTRL1 and CTRL2 plots.

[d] Chisel plow was applied to CTRL1 and CTRL2 plots, and disk plow and field cultivating were applied to TRT1 and TRT2 plots. In fall 2009, no tillage was conducted due to the wet weather condition in October and November.

May. Aqueous ammonia-nitrogen was applied at 140 kg N ha^{-1} to corn in spring, closely following corn emergence. Recommended N application rates for the study area are 112 to 168 kg N ha^{-1} (Blackmer et al., 1997). Detailed field management activity and timing since October 2004 are listed in table 2.

DATA COLLECTION

Weather and Soil Data

An automatic meteorological weather station at the site recorded rainfall, air temperature, solar radiation, relative humidity, and wind speed at 5 min intervals. Missing daily rainfall data were obtained from a National Climate Data Center (NCDC) weather station at Humboldt, Iowa (Station No. 076), about 20 km east of the site. Daily snowfall data were not measured at the site but were available at the Humboldt weather station. Snowfall depth was converted into water depth by dividing the snowfall depth by a factor of 10. Weather information for 2004 through 2009 were prepared using these site-specific measured data, whereas the long-term weather data from 1960 through 2003, including hourly precipitation, air temperature, solar radiation, wind speed, and humidity, were from another Iowa weather station in the Walnut Creek watershed in central Iowa because long-term weather observations at the study site were not available.

Soil hydraulic properties, including bulk density, particle size distribution, saturated hydraulic conductivity, and soil water characteristic curve, were determined from undisturbed soil cores. Bubbling pressure (P_b) and pore size distribution (λ) were fit using the Brooks-Corey equation over the pressure range of 0 to 1500 kPa. Residual water content was estimated by extrapolating each of the soil water characteristic curves to a point at which the gradient ($d\theta/dh$) approached zero. Soil moisture at matrix potentials of 10, 33, and 1500 kPa was either interpolated or extrapolated from the soil water characteristic curves. Saturated hydraulic conductivity was measured using the falling head method with three runs for each soil core.

Hydrology and NO_3-N loss

A flowmeter was used to measure the subsurface drainage flow volume, and the meter reading was manually recorded on a weekly or biweekly basis. Starting in April 2006, the flowmeter was switched to a magnetic meter, which was connected to an electronic data logger, facilitating the measurement of drainage flow volume in increments of 14 L (0.5 cubic foot), which represented a drainage flow depth of 0.005 cm. A fraction of the drainage flow was directed to a 20 L carboy through a plated orifice nozzle. Subsamples of the drainage water were collected after approximately every 1.3 cm of drainage flow and thereafter were stored in a cooler at 4°C until analyzed. NO_3-N concentration was analyzed in the Wetland Research Laboratory, Iowa State University, using the second-derivative spectroscopy technique. The NO_3-N concentration of each drainage event was multiplied by the representative drainage volume to calculate NO_3-N loss.

A PR2 Profile probe and a Theta probe (Delta-T Devices, Cambridge, U.K.) were used to measure the soil permittivity starting in fall 2005. The PR2 probe was calibrated by *in situ* soil sampling in two consecutive years (Qi and Helmers, 2010a). The permittivity output of the Theta probe was converted into volumetric water content by the calibrated equation from Kaleita et al. (2005) that used field data collected in Des Moines Lobe soils. The observed volumetric water content data were multiplied by the representative depth intervals to compute the soil water storage (SWS) for each depth and then summed to obtain total SWS information. Because the soil water content at 100 cm would be largely influenced by the high water table, SWS was calculated in the soil layers from 0 through 60 cm below the ground surface. Details on SWS measurement and calculation can be found in Qi et al. (2011a).

Biomass and Yield Sampling

Aboveground biomass of rye and main crops was sampled in 2006 through 2009. Rye shoots were sampled weekly from early spring until chemically desiccated by glyphosate. From July, corn and soybean biomass were sampled once every three weeks until early October. Rye, corn, and soybean were sampled along a 30 cm section at four randomly selected locations in the plot. Samples were dried at 60°C for a week at the Agricultural Engineering Farm of Iowa State University. Total nitrogen (TN) content was analyzed for all sets of rye samples and two sets of corn and soybean samples. TN analysis of the crop tissue was conducted in the Soil Plant Analysis Laboratory at Iowa State University using the combustion method. To determine the crop yield, twelve rows of corn and soybean out of 20 rows were harvested with a combine. Grain seed was weighed and sampled to determine moisture for each pass.

Table 3. Measured soil hydraulic properties.[a]

Depth (cm)	BD ($g\ cm^{-3}$)	Sand (%)	Silt (%)	SOM (%)	P_b (cm)	λ	K_{sat} ($cm\ h^{-1}$)	LK_{sat} ($cm\ h^{-1}$)	Water Content ($cm^3\ cm^{-3}$)[b]				
									θ_r	θ_s	θ_{33}	θ_{10}	θ_{1500}
0-10	1.37	0.32	0.36	4.3	-2.89	0.17	4.8	9.7	0.071	0.482	0.376	0.383	0.189
10-20	1.38	0.32	0.36	3.8	-3.89	0.12	3.3	6.6	0.072	0.476	0.376	0.384	0.230
20-30	1.39	0.33	0.53	3.3	-3.89	0.12	5.1	10.1	0.079	0.473	0.376	0.384	0.201
30-40	1.39	0.4	0.30	1.3	-4.67	0.11	4.1	8.2	0.072	0.474	0.399	0.384	0.212
40-60	1.39	0.46	0.30	1.3	-4.31	0.11	4.1	8.2	0.065	0.474	0.368	0.408	0.218
60-90	1.45	0.44	0.34	0.6	-4.99	0.14	2.6	5.3	0.034	0.450	0.368	0.380	0.204
90-120	1.46	0.44	0.34	0.5	-2.99	0.11	2.6	5.3	0.033	0.450	0.299	0.312	0.184
120-200	1.46	0.44	0.34	0.5	-2.99	0.11	2.6	5.3	0.033	0.450	0.299	0.310	0.168
200-300	1.50	0.44	0.34	0.5	-2.99	0.11	2.6	5.3	0.033	0.450	0.299	0.310	0.168
300-390	1.50	0.44	0.34	0.5	-2.99	0.11	0.01	5.3	0.033	0.450	0.299	0.310	0.168

[a] BD = bulk density, SOM = soil organic matter, P_b = bubbling pressure, λ = pore size distribution, K_{sat} = saturated conductivity, and LK_{sat} = lateral saturated conductivity.

[b] θ_r = residual water content, θ_s = saturated water content, θ_{33} = soil water content at pressure of 33 kPa, θ_{10} = soil water content at pressure of 10 kPa, and θ_{1500} = soil water content at pressure of 1500 kPa.

MODEL INITIALIZATION

Measured bulk density, particle size distribution, and saturated hydraulic conductivity tests were used as input parameters in the RZWQM2 model (table 3). Preliminary study indicated that simulated drainage, soil moisture, and crop growth varied little over the range of the observed values for bulk density, particle size distribution, and saturated hydraulic conductivity at this site. Soil depth above the impermeable layer was selected to be 390 cm according to a similar modeling study by Singh et al. (2006) for this site. Lateral hydraulic conductivity (LK_{sat}), which is a key parameter to calculate subsurface drainage flow in Hooghoudt's equation, was adjusted to $2K_{sat}$ to match the peak of daily drain flow. Soil properties from 0 to 120 cm depth were measured using soil cores, while hydraulic properties of soil below 120 cm were not measured and as such were assumed to be the same as the 90 to 120 cm layer. To maintain a water table in the soil profile, K_{sat} of the bottom soil layer (300 to 390 cm) was assumed to be 0.01 cm h^{-1}. The second exponent of the soil water retention curve (N2) was calculated by $3\lambda + 2$, and the second intercept of the curve (C2) was computed by $K_{sat} \times P_b^{N2}$, where λ is the pore size distribution index, K_{sat} is the saturated hydraulic conductivity (cm h^{-1}), and P_b is the bubbling pressure (cm). Soil dry heat capacity for the soil layers from 0 to 60 cm depth was estimated by the sum of the heat capacity of sand, silt, clay, and organic matter content for the soil in each depth (Jury and Horton, 2004). The calculated dry heat capacities averaged 1.31 MJ m^{-3} $°C^{-1}$ for 0 to 60 cm soils and 1.35 MJ m^{-3} $°C^{-1}$ for 60 to 390 cm soils.

The chemical background of precipitation was set to 0.5 mg N L^{-1} for NH_4-N, 1.3 mg N L^{-1} for NO_3-N, and 5.1 for pH value according to the online information provided by the National Atmospheric Deposition Program. The initial residual N in the soil profile, including the three pools of crop residue, organic matter, and microorganism, and surface residue properties were all from Thorp et al. (2007) except that the death rate of aerobic heterotrophs was adjusted from 9×10^{-37} to 4×10^{-37} to get a better fit of NO_3-N concentration in the drainage. Crop parameters for maize (IB 1068 Dekalb 521) and soybean (990002 M Group 2) were essentially default values with minor calibration, as described below. Attention has been paid to the calibration of crop parameters for the winter rye cover crop. The initial soil pH values were set to 7.1 for soils in 0 to 30 cm and to 7.2 for soils deeper than 30 cm, the same as measured values for soils sampled in November 2006 at this site. Soil moisture data obtained from the first soil sampling in November 2005 were set as initial soil water content.

MODEL CALIBRATION AND VALIDATION

In this study, soil physical and hydraulic properties were mainly obtained by laboratory measurements for site-specific soil cores. Nutrient component parameters, except for aerobic heterotroph death rate, were from recently calibrated values for Iowa soils by Thorp et al. (2007, 2009). The main goal of the model calibration was to find the best values for crop parameters of corn, soybean, and rye. Therefore, the crop parameters were calibrated using the five-year cropping system of TRT1, and data from cropping systems of CTRL1, TRT2, and CTRL2 were used for validation (table 1). According to Li et al. (2008), temperatures below -10°C were increased to -10°C to avoid simulating winter kill of rye shoots by frigid weather due to the lower lethal temperature of rye than wheat.

Field-measured data from 2005 through 2009, including crop yield, biomass, N uptake, drainage flow, soil water storage, and nitrate loss, were compared with the simulated output. To get a stable humus and soil microbial biomass, as required for running RZWQM2, weather data and conventional agronomic management in the years of 1960 through 2004 were loaded into the model and run as a pretreatment for the plot. For the component of crop yield, biomass, and N uptake, the model performance was evaluated by percent error (PE, denoted as %D by Ahuja et al., 2000) and relative root mean square error (RRMSE, denoted as n-RMSE by Liu et al., 2011), which are widely accepted measures utilized by Hanson et al. (1999), Ahuja et al. (2000), Thorp et al. (2007), and Liu et al. (2011). In accordance with Hanson et al. (1999) and Ahuja et al. (2000), the model performance was satisfactory when PE < ±15%, and we also adopted the criteria from Liu et al. (2011) in which the model performance can be considered "satisfactory" when RRMSE < 30%. Three quantitative statistics, Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and root mean square error to the standard deviation (RSR), as detailed in Moriasi et al. (2007), were used to evaluate the performance of the model in simulating hydrology and NO_3-N in drainage. According to Moriasi et al. (2007), model performance was considered to be "satisfactory" when NSE > 0.50 and RSR $\leq$ 0.70, and if

PBIAS is within ±25% for hydrology and ±70% for NO_3-N loss and concentration.

MODEL APPLICATION

The calibrated and validated RZWQM2 model was used to simulate the long-term effects of the winter rye cover crop on hydrologic cycling and nitrogen dynamics for a corn-soybean rotation cropping system in Iowa. The historical weather and agronomic management information from 1960 to 2009 was input into the model. The first 10 years (1960-1969) were considered to be the initialization period for RZWQM2 with a corn-soybean rotation cropping system, while the 40 years from 1970 to 2009 were simulated with two cropping scenarios: corn-soybean rotation with or without winter rye cover crop. For each scenario, the model was run twice with a corn-soybean rotation and a soybean-corn rotation. Results such as subsurface drainage and NO_3-N loss were averaged over these two runs for each scenario. Corn and soybean were planted on May 12 and May 20, respectively, and were harvested on Oct 5. Aqueous ammonia-nitrogen was injected at a rate of 140 kg N ha^{-1} to corn at planting. The field was assumed to be tandem disked and field cultivated in every October between corn or soybean harvest and rye planting. The tillage depth was 10 cm for tandem disk and field cultivator, and the tillage intensities were 0.45 and 0.25, respectively (Rojas and Ahuja, 2000). In reality, corn residue might usually be chisel plowed rather than disked in fall when no cover crop is grown. For the scenario with rye cover crop, rye was planted on October 12 in every year, and rye growth was terminated on April 30 if prior to corn and on May 18 if prior to soybean. The other scenario without rye was considered to be a baseline scenario and was run in the model by removing the rye while holding all other management unchanged. Model output of annual hydrologic and nitrogen components in the 40 years from 1970 through 2009 were compared between the two scenarios to evaluate the effects of the winter rye cover crop.

RESULTS AND DISCUSSION

MODEL CALIBRATION

For calibration of the crop growth component, LFMAX was adjusted to 0.97 for soybean to get a good fit between predicted and observed soybean yields. For corn, the phylochron interval between successive leaf tip appearances (PHINT) was adjusted to obtain harvest indices around 0.50. The PHINT value was modified within the range between 60 (Thorp et al., 2007) and 38.9 (Ma et al., 2006), and a value of 40 was selected to get a good simulation of aboveground biomass accumulation. Kernel number (G2) and grain fill (G3) parameters were adjusted to 750 and 6.75, respectively, to reduce the error between simulated and measured yield. Crop parameters for wheat were adapted from Thorp et al. (2010). Because the critical time for the development stage of the rye was not recorded, calibration of the wheat parameters was based on the observed aboveground biomass. In order to reduce the overestimation of biomass in the early stage before late April in each year, the emergence phase duration (PECM) and the germination phase duration (PEG) were set to 25 and 75 ˚C d, respectively, similar to the values calibrated by Thorp et al. (2010). The values for P1V and P1D were adopted from Thorp et al. (2010). The final cultivar parameters are listed in table 4 for simulating corn, soybean, and rye growth. In the previous version of RZWQM2, soil root growth factors (SRGF) were not allowed to vary independently among crops in a rotation (Thorp et al., 2007). The updated version of the model improved this component, and SRGF was adjusted for individual crops to fit the crop growth and the moisture and measurements. In the soil depths of 5, 15, 30, 40, 60, and 90 cm, the SRGF were 1, 1, 0.3, 0.07, 0.07, and 0.01 for corn; 1, 1, 0.3, 0.1, 0.1, and 0.1 for soybean; and 1, 1, 0.7, 0.54, 0.4, and 0.1 for rye, respectively.

MODEL EVALUATION

Crop Yield and Growth

The crops were damaged by hail in late July 2009, which led to a low observed soybean yield (table 5). However, the corn recovered in a timely manner after the hail, and the yield

Table 4. Calibrated crop parameters for corn, soybean, and winter rye. Values not listed in this table are default numbers.

Crop	Parameter		Value
Corn[a]	G2	Maximum possible number of kernels per plant	750
	G3	Kernel filling rate during linear grain filling stage under optimum conditions (mg d^{-1})	6.75
	PHINT	Phylochron interval between successive leaf tip appearance	40
Soybean[b]	LFMAX	Maximum leaf photosynthesis rate at 30 C, 350 vpm, and high light (μmol CO_2 m^{-2} s^{-1})	0.97
Winter rye[c]	PEG	Germination phase duration (°C d cm cm^{-1})	75
	PECM	Emergence phase duration (°C d cm cm^{-1})	25
	P1V	Relative amount that development is slowed for each day of unfulfilled vernalization, assuming 50 d is sufficient.	5
	P1D	Relative amount that development is slowed when plants are grown in photoperiod 1 h shorter than optimum (d)	12
	PARUV	Conversion rate from photosynthetically active radiation to dry mater before the end of leaf growth (g MJ^{-1})	2.8
	LAVS	Area of standard vegetative phase leaf (cm^2)	15
	LARS	Area of standard reproductive phase leaf (cm^2)	25
	LARWS	Lamina area to weight ratio of standard first leaf (cm^2 g^{-1})	230
	LAWR2	Lamina area to weight ratio, phase 2 (cm^2 g^{-1})	200
	P5	Relative grain filling duration based on thermal time (d)	400
	PHINT	Phylochron interval: time between successive leaf appearance (PD)	80

[a] Cultivar IB1 068 Dekalb 521 was selected.
[b] Cultivar 990002 M Group 2 was selected.
[c] Cultivar 990003 Winter-US was selected.

Table 5. Observed and simulated crop grain yield (Mg ha^{-1}).[a]

	Calibration			Validation								
	TRT1			CTRL1			TRT2			CTRL2		
Year	Main crop	Obs.	Sim.	Main crop	Obs.	Sim.	Main crop	Obs.	Sim.	Main crop	Obs.	Sim.
2005	Corn	9.3	9.5	Corn	10.2	9.5	Soybean	3.4	3.3	Soybean	3.1	3.3
2006	Soybean	3.0	3.1	Soybean	3.3	3.1	Corn	7.8	8.2	Corn	9.0	8.1
2007	Corn	6.8	8.8	Corn	7.3	9.0	Soybean	2.4	3.3	Soybean	3.0	3.4
2008	Soybean	2.8	2.9	Soybean	3.0	2.9	Corn	10.0	10.3	Corn	9.5	10.3
2009	Corn	8.0	6.0	Corn	7.9	6.0	Soybean	1.9	2.4	Soybean	1.9	2.4
Average		6.0	6.1		6.3	6.1		5.1	5.5		5.3	5.5
PE			1%			-4%			8%			4%
RRMSE			21%			19%			10%			12%

[a] Obs. = observed; Sim. = simulated.

loss was not evident. In 2007, which was a dry year, the simulated corn yield was overestimated by RZWQM2 both for the calibration and validation plots. Nevertheless, the simulated main crop yield of corn and soybean responded to the observed yield in a "satisfactory" manner for all the treatments. For the calibration plots, the PE value of simulated and observed average yield of corn and soybean was 1%. For the validation plots, the PE values for corn and soybean yield ranged from 8% to -4%. The RRMSE values ranged from 21% to 10% for the calibration and validation plots.

Corn, soybean, and rye were not sampled for biomass measurement in 2005. In general, simulated total aboveground dry biomass was in "satisfactory" agreement with the observed data except for soybean in the validation plots. Figure 1 illustrates the simulated and observed total aboveground biomass for corn and soybean. In the calibration plots of TRT1, the PE values of the total aboveground biomass on the final measurement dates were 6% for both corn and soybean, and the RRMSE value was 18%. In the validation plots, the biomass accumulation of corn was predicted well, although in 2007 it was overestimated in the late growth stages. The values of PE and RRMSE were 5% and 25% for the time series data of corn biomass in all the validation plots. Soybean biomass was generally overestimated by the model for the validation plots, with values of 41% and 59% for PE and RRMSE in all the validation plots, respectively.

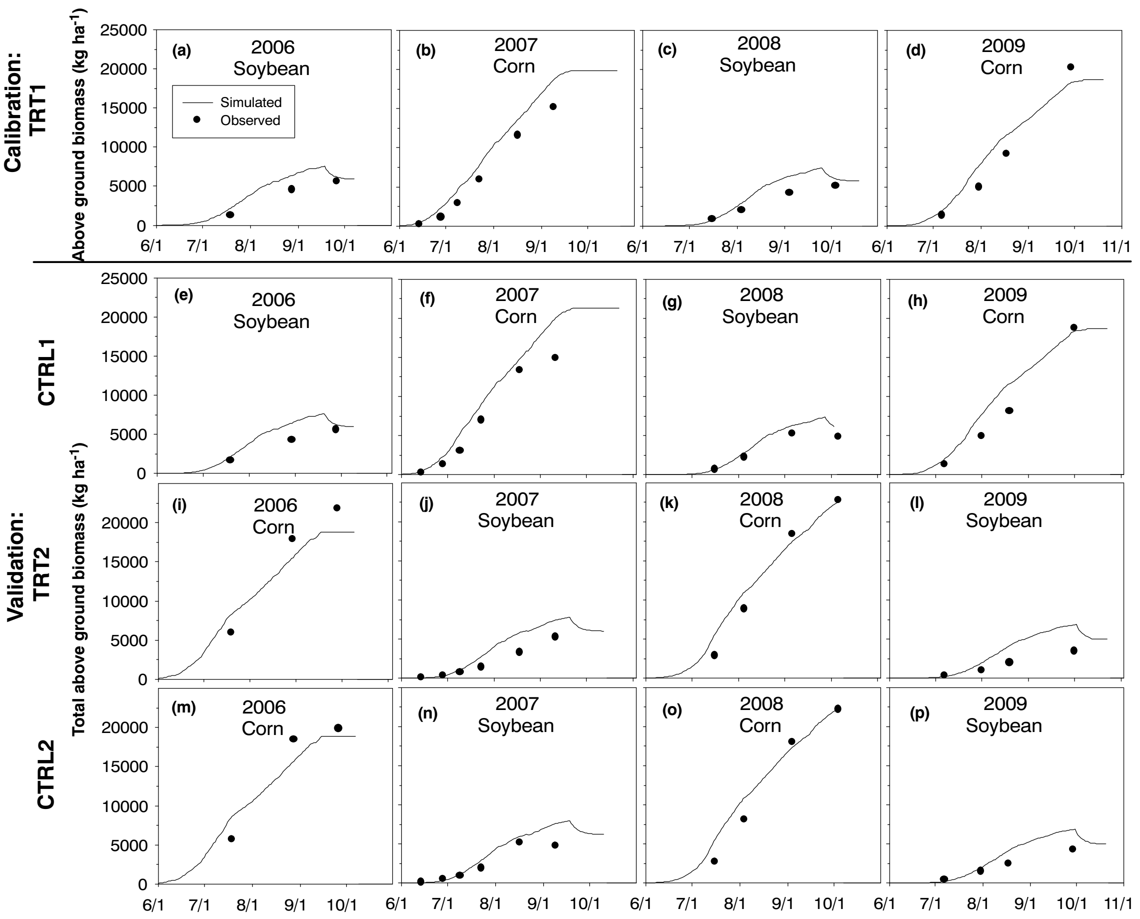

Figure 1. Average measured and simulated total aboveground biomass for corn and soybean in the (a-d) calibration plots of TRT1, validation plots of (e-h) CTRL1, (i-l) TRT2, and (m-p) CTRL2.

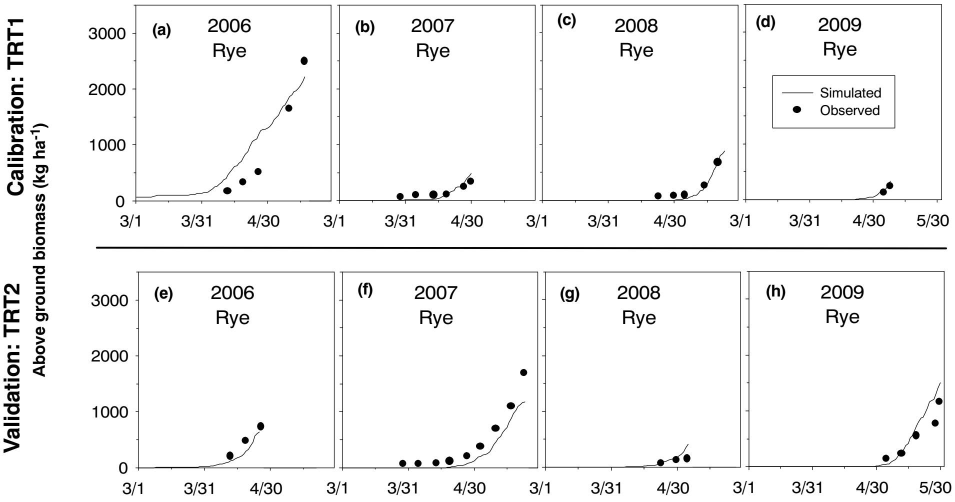

Figure 2. Average observed and simulated rye biomass accumulation in (a-d) calibration plots of TRT1 and (e-h) validation plots of TRT2.

The RZWQM2 model performed "satisfactorily" in predicting rye biomass accumulation according to the statistical criteria (fig. 2). For the calibration plots of TRT1, the simulated average total aboveground biomass on the last observation dates was 0.93 Mg ha^{-1}, the same as the observed value. The RRMSE value for the measured and simulated annual total rye aboveground biomass in the four years was 11% for the calibration plots. For the validation plots of TRT2, the predicted average total aboveground biomass on the last measurement dates was 1.04 Mg ha^{-1} versus the observed average of 0.93 Mg ha^{-1}. The PE and RRMSE values for the observed and simulated rye biomass were 12% and 28%, respectively.

HYDROLOGY

The average annual precipitation in the five study years (2005-2009) was 82.6 cm, close to the long-term annual precipitation of 82.1 cm in this area. The simulated annual subsurface drainage volume in general matched well with the observed drainage for all the treatment and control plots (table 6). In the calibration plots (TRT1), the annual simulated subsurface drainage was 31.6 cm over the five years, within 11% bias of the observed value of 28.3 cm and the NSE and RSR values of 0.88 and 0.34, respectively. For the CTRL2 plots, the simulated drainage was 24% higher than the observed average, with overestimation in four of the five years. We speculate that there might be water loss through lateral seepage from the CTRL2 plots to the ambient area. For the validation plots CTRL1 and TRT2, the PBIAS values were within ±5%, NSE $\geq$ 0.84, and RSR $\leq$ 0.40. Therefore, the performance of RZWQM2 can be considered "satisfactory" in predicting annual subsurface drainage.

The simulated average actual evapotranspiration (ET) of 45.3 cm year^{-1} for the conventional corn-soybean control plots of CTRL1 and CTRL2 was close to the 46.8 cm simulated by Thorp et al. (2007). The simulated average ET in May through September in the five years for the control plots varied from 34.4 to 46.8 cm year^{-1}, comparable to the observed ET values (33.4 to 49.3 cm year^{-1}) from 1992 to 1994 in central Iowa (Bakhsh et al., 2004). For the treatment plots where rye grew prior to soybean, the simulated average daily ET in May was 2.1 mm d^{-1} in the five years, while the ET in the control plots in this month averaged 1.1 mm d^{-1}. This was lower than the ET values of 2.4 and 1.5 mm d^{-1} for rye and bare lysimeters computed by the water balance method in central Iowa (Qi and Helmers, 2010b). However, the difference between simulated daily ET of the rye and control treatment plots in May was 1.0 mm d^{-1}, close to the ET difference of 0.9 mm d^{-1} computed from the lysimeter study.

Detailed information from the simulation results suggested that the increased transpiration by rye in TRT1 and

Table 6. Average observed and simulated annual subsurface drainage in the calibration plots of TRT1, and validation plots of CTRL1, TRT2, and CTRL2 (cm).

	Calibration		Validation					
	TRT1		CTRL1		TRT2		CTRL2	
Year	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
2005	17.7	19.7	25.8	23.4	26.8	22.8	15.1	28.2
2006	11.6	17.5	12.4	19.7	9.8	19.2	11.3	13.4
2007	54.5	51.5	48.8	48.3	57.7	51.8	38.3	52.0
2008	35.2	44.4	49.2	45.2	51.6	41.3	38.7	35.5
2009	22.7	24.7	19.2	24.2	27.4	29.2	22.8	27.0
Average	28.3	31.6	31.1	32.2	34.7	32.9	25.2	31.2
PBIAS		11%		3%		-5%		24%
NSE		0.88		0.91		0.84		0.40
RSR		0.34		0.29		0.40		0.77

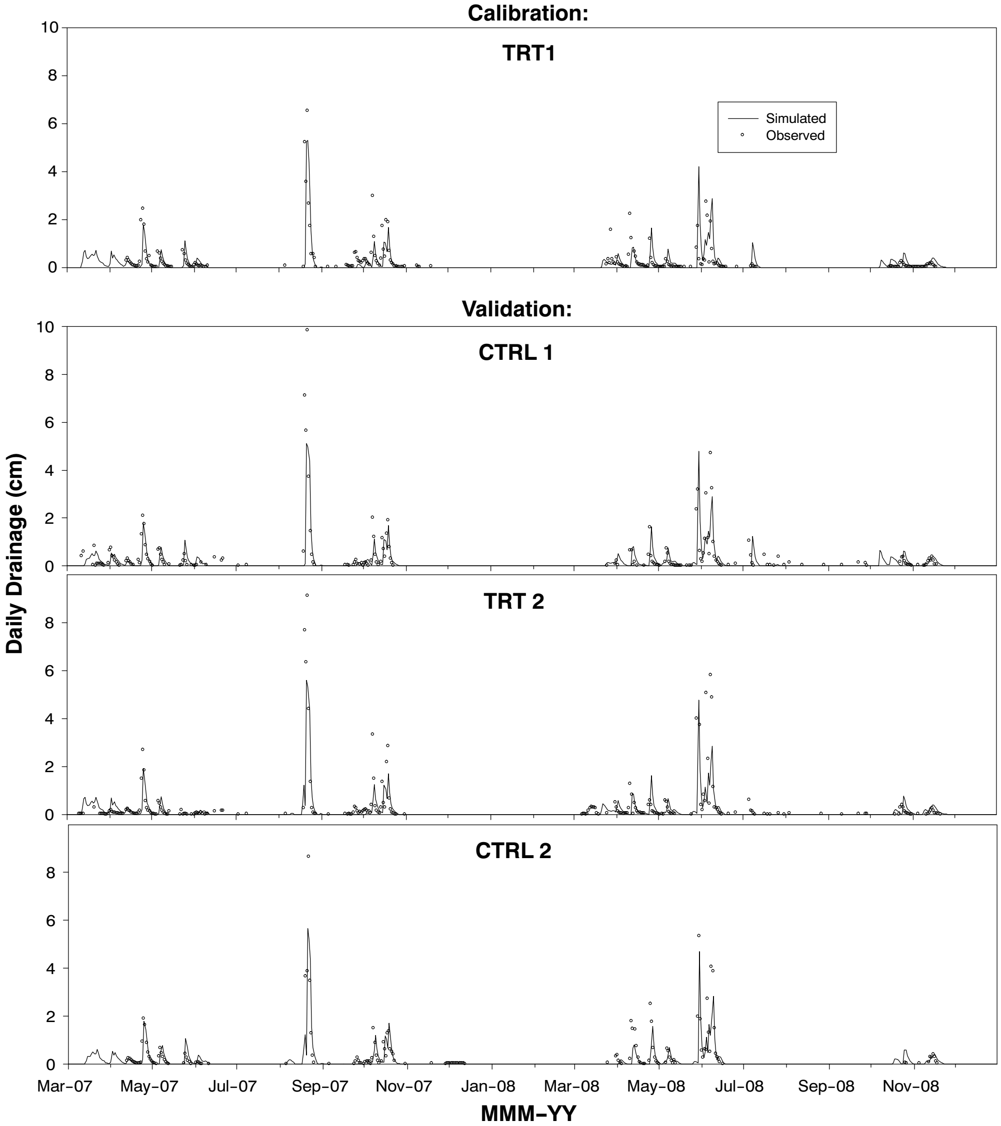

Figure 3. Observed and simulated daily drainage in 2007 and 2008. Daily drainage in 2006 was very little after the daily drainage measurement starting date of April 12, 2006.

TRT2 during spring was offset by the reduced soil evaporation by rye residue cover, especially in wet and cold years such as 2007, 2008, and 2009. The simulated annual average transpiration in 2007-2009 for plots with rye cover crop was 29.8 cm, which was 4.2 cm higher than the 25.6 cm of transpiration in plots without rye. However, the simulated annual average evaporation was 17.2 cm for rye treatments versus 21.4 cm for the no-rye controls. The reduction of soil evaporation was the same amount as the increase of transpiration by rye. This explained the phenomenon that the simulated drainage from rye treatments was close to drainage from controls in the five years from 2005 to 2009.

Daily drainage in 2006 was very little after the daily drainage measurement starting date of April 12, 2006, and the magnetic meter did not work well in fall 2009, so only observed and simulated daily drainage for 2007 and 2008 were compared to evaluate the performance of RZWQM2 in simulating daily drainage (fig. 3). The daily flow prediction was satisfactory with respect to NSE, with values of 0.50, 0.64, 0.59, and 0.70 for the TRT1, CTRL1, TRT2, and CTRL2 plots, respectively. The RSR values were 0.70, 0.60, 0.64, and 0.55, and the PBIAS values were 7%, -5%, -15%, and -3% for the four treatments. The NSE values were greater than 0.50, the RSR values were less than 0.7, and PBIAS was within ±15%. Therefore, according to Moriasi et al (2007), the daily drainage prediction by the RZWQM2 model was satisfactory.

Water stored in the soil profile is mainly a function of both crop water uptake and soil hydraulic properties. The average measured and predicted soil water storage (SWS) in the 0 to 60 cm layer soil for the three observation years are shown in figure 4. Although the PBIAS values were 1%, 5%, 2%, and 5% for TRT1, CTRL1, TRT2, and CTRL2, respectively, the RZWQM2-predicted soil water storage was unsatisfactory under all treatments and controls because the NSE values were 0.46 for the calibration plots and ranged from -0.79 to -0.04 for the validation plots, with RSR > 0.70. However, the soil water storage in this study was predicted similarly to other studies with RZWQM2, CERES, WOFOST, and SWAP (Ma et al., 2003; Eitzinger et al., 2004).

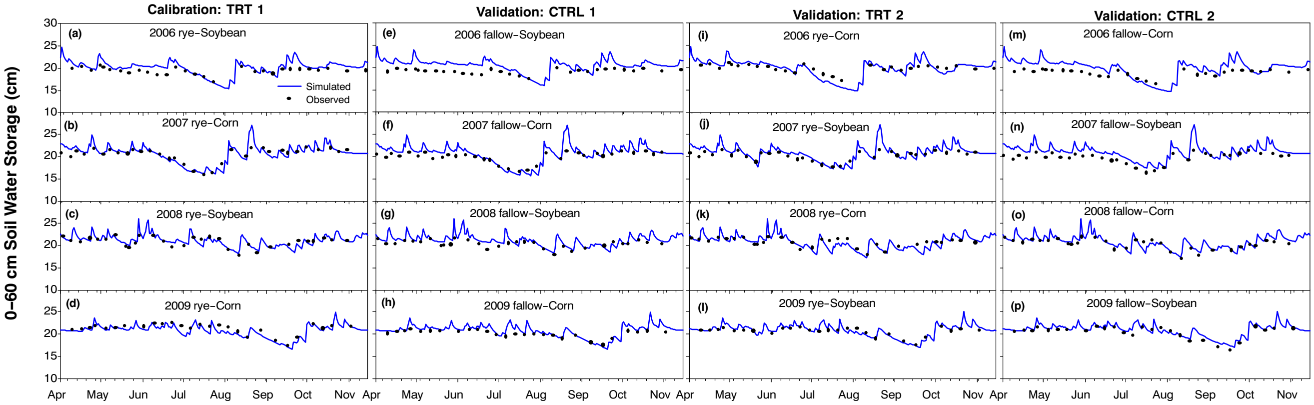

Figure 4. Average measured and simulated soil water storage in the 0 to 60 cm profile in the (a-d) calibration plots of TRT1, and validation plots of (e-h) CTRL1, (i-l) TRT2, and (m-p) CTRL2.

Nitrogen Dynamics

The annual total nitrate-nitrogen loss through subsurface drainage was simulated satisfactory by the RZWQM2 model. The simulated average annual NO_3-N loss was 35.8 kg N ha^{-1} for the calibration plots over five years, within 4% bias when compared with the observed average of 34.4 kg N ha^{-1} with NSE = 0.84 and RSR = 0.40 (table 7). The NO_3-N loss in CTRL2 was not simulated well, with NSE = 0.46 and RSR = 0.73, but the PBIAS was within ±20%. This difference in simulated and observed NO_3-N loss is attributed to the overestimation of subsurface drainage in this treatment. For the validation treatments other than CTRL2, annual NO_3-N loss through subsurface drainage was predicted in a satisfactory manner, with NSE $\geq$ 0.73, RSR $\leq$ 0.52, and PBIAS within ±15%. The prediction of NO_3-N concentration was within ±20% error for the calibration and validation treatments, but the NSE values were all negative and RSR > 0.70 (table 8). Both average observed and simulated NO_3-N concentrations showed a low variability: the observed average NO_3-N concentrations ranged from 9.4 to 17.6 mg N L^{-1}, and the simulated concentrations were within 7.7 to 18.4 mg N L^{-1}. The underestimation of N concentration was evident in 2009 due to simulated low mineralization in that year. The simulated reduction of NO_3-N concentration by rye was 2.2 mg N L^{-1}, higher than the observed reduction of 1.4 mg N L^{-1} when averaged over the five years.

The simulated and average observed total N in the aboveground biomass of corn and soybean are listed in table 9. In general, the average total N in the corn and soybean aboveground biomass was predicted satisfactorily, which was indicated by the PE $\leq$ 11%, and the RRMSE values

Table 7. Average observed and simulated NO_3-N loss in the tile drainage for the calibration and validation plots (kg N ha^{-1}).

	Calibration		Validation					
	TRT1		CTRL1		TRT2		CTRL2	
Year	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
2005	22.5	22.4	38.0	33.5	39.1	29.7	26.6	46.7
2006	14.5	19.3	18.7	36.3	14.5	18.2	15.7	12.6
2007	62.4	61.3	65.8	58.7	54.5	52.7	49.6	57.9
2008	41.7	53.0	55.8	58.3	56.2	46.5	49.5	48.3
2009	31.1	23.1	28.3	24.5	35.4	25.5	27.1	30.4
Average	34.4	35.8	41.3	42.3	39.9	34.5	33.7	39.2
PBIAS		4%		2%		-14%		16%
NSE		0.84		0.73		0.74		0.46
RSR		0.40		0.52		0.51		0.73

Table 8. Average observed and simulated annual flow-weighted average NO_3-N concentration (FWANC) in the subsurface drainage for the validation and calibration plots (mg N L^{-1}).

	Calibration		Validation					
	TRT1		CTRL1		TRT2		CTRL2	
Year	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
2005	12.7	11.4	14.7	14.3	14.6	13.0	17.6	16.5
2006	12.5	11.0	15.1	18.4	14.8	9.5	13.9	9.4
2007	11.4	11.9	13.5	12.1	9.4	10.2	13.0	11.1
2008	11.8	11.9	11.3	12.9	10.9	11.3	12.8	13.6
2009	13.7	9.4	14.7	10.1	12.9	8.7	11.9	11.2
Average	12.4	11.1	13.9	13.6	12.5	10.5	13.8	12.4
PBIAS		-11%		-2%		-16%		-10%
NSE		-6.70		-2.85		-1.25		-0.28
RSR		2.77		1.96		1.50		1.13

Table 9. Average observed and simulated nitrogen (N) uptake for the main crops of corn and soybean (kg N ha^{-1}).

		Calibration			Validation								
		TRT1			CTRL1			TRT2			CTRL2		
Year	Sampling Date	Crop	Obs.	Sim.	Crop	Obs.	Sim.	Crop	Obs.	Sim.	Crop	Obs.	Sim.
2006	26 Sept.	Soybean	200	214	Soybean	201	225	Corn	261	217	Corn	234	225
2007	17 Aug.	Corn	135	172	Corn	145	182	Soybean	119	135	Soybean	185	142
2008	4 Sept.	Soybean	140	178	Soybean	174	157	Corn	207	188	Corn	211	183
2009	29 Sept.	Corn	226	216	Corn	205	215	Soybean	104	168	Soybean	124	170
Average			175	195		181	195		173	177		189	180
PE				11%			7%			2%			-5%
RRMSE				16%			13%			24%			18%

were within ±25% for each treatment. Due to the damage to soybean by hail in 2009, the average N content in the soybean biomass was overestimated by 36% for TRT2.

The nitrogen uptake by rye aboveground biomass was in general overpredicted by the RZWQM2 model (fig. 5). For the calibration plots (TRT1), the simulated annual average N uptake by the aboveground rye biomass was 28.3 kg N ha^{-1}, 17% higher than the observed value of 24.1 kg N ha^{-1}. Time series data of rye N uptake from TRT1 had an NSE value of 0.74, indicating a satisfactory prediction of N assimilation by rye for the calibration treatment, while the RRMSE value was 38%. However, for the validation TRT2 plots, the N content in rye shoot was simulated with a PE value of 22%, and the RRMSE was 50%. However, this overestimation mainly occurred in 2009. When excluding the 2009 data, the PE and NSE values for the time series data from TRT2 were 0% and 0.68, respectively.

The simulated average annual net mineralization of this study in 2005-2009 was 140.4 kg N ha^{-1} for the control plots and 160.5 for the rye treatment plots. The simulated mineralization in the control plots was comparable to the field-measured average of 142 kg N ha^{-1} for soils under a corn-soybean system in Brookings, South Dakota (Carpenter-Boggs et al., 2000). However, the simulated mineralization in the control and rye treatment plots was higher than the simulated 10-year average of 109.6 kg N ha^{-1} in Thorp et al. (2007). The elevated net mineralization in this study was attributed to the differences in soil hydraulic properties. To determine the factor of aerobic condition, which is positively related to the rate of organic matter decay, RZWQM2 makes use of soil moisture expressed as percent of water-filled pore space (% WFP) based on work by Linn and Doran (1984). When the percent of WFP is lower than 60%, mineralization is limited by water availability, but above 60% WFP, aerobic microbial activity decreases with the increase of % WFP due to reduced aeration. The bubbling pressure for soils in this study was much lower than soils in Thorp et al. (2007), which led to lower soil water contents. Based on the modeling using ADWQ-RDS site soils or soils from Thorp et al. (2007), the simulated WFP percentage was lower for the simulation with soils from ADWQ-RDS (fig. 6). This would indicate greater mineralization for ADWQ-RDS soils.

MODEL APPLICATION

Long-Term Impacts on Hydrologic Cycling

The calibrated RZWQM2 performed "satisfactorily" in simulating the response of subsurface drainage and NO_3-N loss to the change of cropping system in this study. Other components, including crop grain yield and biomass accumulation of each treatment, were simulated "satisfactorily" except for an overestimation of soybean biomass. N uptake by rye was simulated "satisfactorily" when excluding the data from 2009.

The annual precipitation during the simulation period (1970-2009) varied from 50.3 cm in 2000 to 125.9 cm in 1993 and averaged 83.0 cm, close to the 30-year (1971-2000) long-term normal of 82.1 cm. The simulation results indicate that rye cover crops reduced annual subsurface drainage by 11% and increased annual evapotranspiration (ET) by 5% (table 10). The simulated percentage of drainage reduction by rye

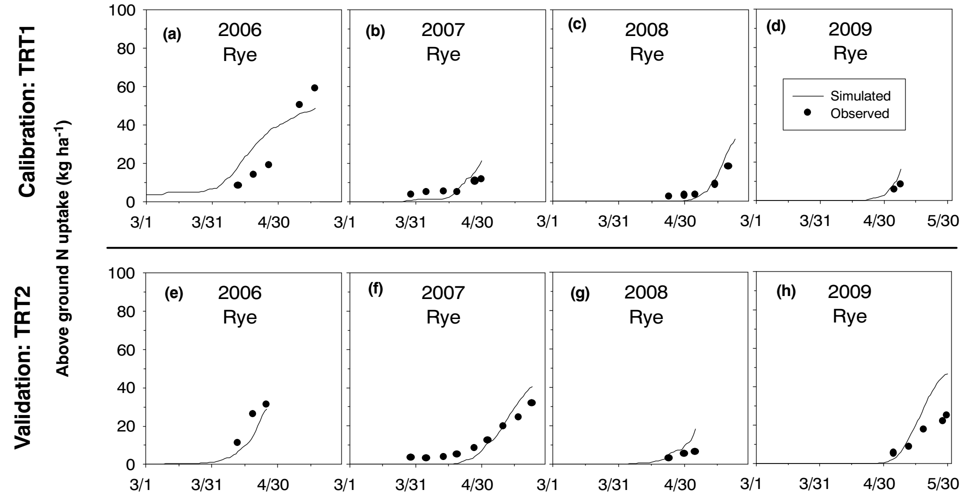

Figure 5. Average observed and simulated nitrogen uptake by rye aboveground biomass for (a-d) calibration plots (TRT1) and (e-f) validation plots (TRT2).

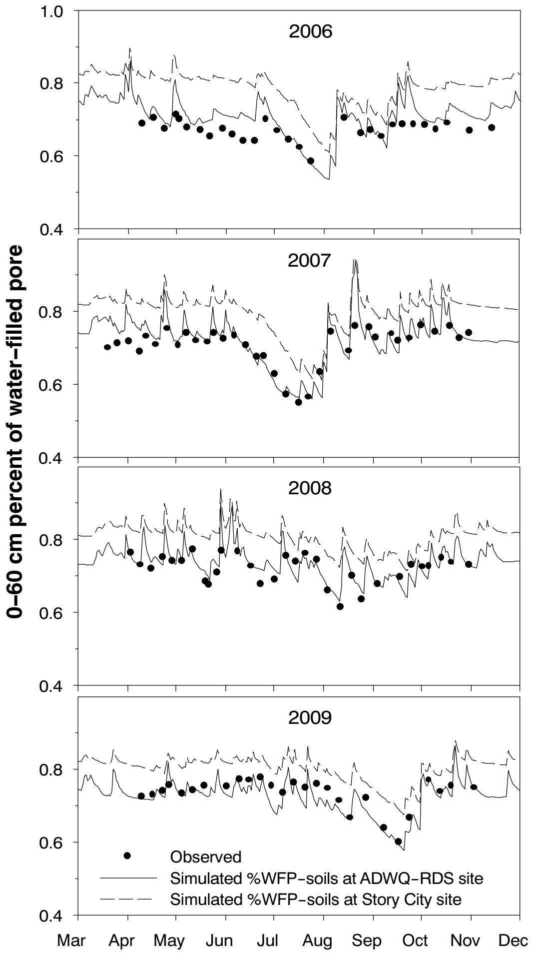

Figure 6. Observed and simulated fraction of water-filled pore under TRT1 using soil information at ADWQ-RDS site in this study and Story City site in Thorp et al. (2007).

was equal to the value of 11% reported by Strock et al. (2004) based on a field study in southern Minnesota. The simulated drainage was 0 in 1981 and was the highest in 1993, with a value around 83.0 cm for both the rye and no-rye scenarios. The simulated impact of rye cover crop on infiltration and runoff was very limited because there is no vegetative interception component in the RZWQM2 model. When ET was partitioned into soil evaporation and crop transpiration, rye cover crop reduced the annual soil evaporation by 16% and increased the annual plant transpiration also by 20%.

The impact of winter rye cover crop on drainage and ET was more evident in April through June, suggesting that planting rye is an effective approach to modifying agricultural hydrology in these three months. Although rye growth was terminated no later than late May, it may have impacted drainage in June through reduced soil moisture. Therefore, an investigation of the effect of rye in spring was extended to June. In April through June, the simulated drainage with rye cover was reduced by 20% when compared to the drainage without a cover crop. The simulated ET in the rye scenario was increased by 29% relative to the simulated ET in the no-rye scenario. During the three months from April through June, the growing days of rye were 30 (April 1 to 30) prior to corn and 49 (April 1 to May 18) prior to soybean in the simulation. For the 40-year simulation, rye had existed for 40 days on average for every year in April through June, and the increase of ET was 4.2 cm during these 40 days. Therefore, the calculated increase in ET by rye was 1.1 mm day^{-1}, close to the increase of 0.9 mm day^{-1} reported in a non-weighing lysimeter study conducted in Iowa (Qi and Helmers, 2010b).

Other than 1981, when no subsurface drainage occurred for both scenarios with and without rye cover, simulated drainage reduction by rye was observed in 36 years, while in three years the simulated drainage was higher with rye than without rye. Drainage was reduced by more than 20% in 14 years. The highest percentage of drainage decrease (50% to 100%) occurred in the years with relative low annual precipitation. The rye impact on subsurface drainage reduction was more effective when growing rye prior to soybean than corn. The simulated average annual subsurface drainage under corn was 23.7 cm for 1970-2009 versus 29.1 cm under soybean for the scenario without rye. When rye was added into the corn-soybean system, the simulated annual drainage reduction was 1.0 cm under rye-corn, while it was 4.9 cm under rye-soybean. This is attributed to the extended 18 days of growth for rye prior to soybean in the simulations.

The hydrologic simulation results indicated that the presence of rye in the corn-soybean system mainly affected soil evaporation, plant transpiration, and subsurface drainage, and its impacts on other hydrology components such as infiltration, seepage, and runoff were not substantial. Plant transpiration was increased by rye in its growing season; however, soil evaporation was reduced by the rye live shoot stand and residue coverage after growth termination.

Table 10. Hydrologic components simulated by RZWQM2 with and without rye cover crop for corn-soybean rotation in 40 years during 1970-2009.

	Annual				April-June			
	No Rye	Rye	Difference		No Rye	Rye	Difference	
Component	(cm)	(cm)	(cm)	(%)	(cm)	(cm)	(cm)	(%)
Precipitation	83.0				30.9			
Infiltration	79.3	79.3	0	0	30.6	30.6	0	0
Actual ET	53.0	55.9	2.9	5	14.4	18.6	4.2	29
Actual evaporation	21.6	18.2	-3.4	-16	9.7	7.7	-2	-21
Actual transpiration	31.4	37.7	6.3	20	4.7	10.9	6.2	132
Potential ET	80.0	80.1	0.1	0	27.9	24.2	-3.7	-13
Potential evaporation	43.5	35.8	-7.7	-18	22.7	11.6	-11.1	-49
Potential transpiration	36.5	44.3	7.8	21	5.2	12.6	7.4	142
Runoff	3.6	3.6	0	0	0.3	0.3	0	0
Tile drainage	26.4	23.5	-2.9	-11	16.5	13.2	-3.3	-20

Table 11. RZWQM2 simulated nitrogen dynamics and main crop yield with and without rye cover crop for corn-soybean rotation in 40 years during 1970-2009.

	Annual				April-June			
	No Rye	Rye	Difference		No Rye	Rye	Difference	
Component	(kg N ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	(%)	(kg N ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	(%)
Fertilization[a]	70.0						70.0	
N in precipitation	13.0						5.5	
N fixation	93.0	90.4	-2.6	-3	4.1	4.2	0.1	2
N in incorporated residue	120.2	186.4	66.2	55	20.6	56.9	36.3	176
Denitrification	6.1	9.1	3.0	49	2.7	4.4	1.7	63
Volatilization	0	0	0	--	0	0	0	--
N in runoff	0.1	0.1	0	0	0	0	0	--
NO_3-N in tile drainage	54.7	42.9	-11.8	-22	35.3	24.9	-10.4	-29
Crop N uptake	280.9	344.9	64.0	23	62.2	122.1	59.9	96
Net mineralization	167.7	224.1	56.4	34	49.4	67.8	18.4	37
	(mg N L^{-1})	(mg N L^{-1})	(mg N L^{-1})	(%)	(mg N L^{-1})	(mg N L^{-1})	(mg N L^{-1})	(%)
Annual FWANC	20.7	18.3	-2.4	-12	21.4	18.9	-2.5	-12

[a] Aqueous ammonia was applied at 140 kg N ha^{-1} to corn (every other year).

When averaged over the 40 simulation years, plant transpiration increased by 6.3 cm in the scenario with rye growth, but the soil evaporation decreased by 2.9 cm. In the three years of 1977, 2008, and 2009, when the simulated drainage was higher with rye than without rye, the decrease in evaporation by the rye stand and residue exceeded the increase of rye transpiration due to the short growing period for rye prior to corn and the long-lasting wet soil surface posed by abundant rainfall.

Long-Term Impacts on Nitrogen Dynamics

Gaining reasonable soil mineralized N values is essential to the simulation of nitrogen dynamics using RZWQM2. In this study, the simulated long-term annual net soil mineralization for a conventional corn-soybean rotation system was 167.7 kg N ha^{-1}, comparable to the 189-day field-measured value of 142 kg N ha^{-1} for soils under a corn-soybean system in Brookings, South Dakota (Carpenter-Boggs et al., 2000). The simulated long-term annual soil mineralization of the scenario with rye was 224.1 kg N ha^{-1}, 34% higher than the conventional corn-soybean scenario without rye cover. The simulated annual NO_3-N load to subsurface drainage was reduced by 11.8 kg N ha^{-1} when a winter rye cover crop was included in the simulation, which was a 22% reduction in NO_3-N loss when compared to the simulation without a cover crop (table 11).

The simulated reduction in this study was higher than the reduction of 5.8 kg N ha^{-1} by a long-term simulation conducted for southwestern Minnesota with similar rye sowing and desiccation dates (Feyereisen et al., 2006), and the reduction percentage was also higher than the field measurement of 13% in that area of Minnesota (Strock et al., 2004). These differences could be attributed to warmer weather conditions in Iowa compared with southern Minnesota. Li et al. (2008) reported a simulated NO_3-N reduction by rye in Iowa of 17.2 kg N ha^{-1} at a fertilization rate of 140 kg N ha^{-1} based on weather data from 2002 to 2005. Our study suggested that the weather conditions in Iowa from 2002 to 2005 were more favorable than average for winter cover crop growth. The long-term simulation showed that, during 2002-2005, the NO_3-N loss reduction through drainage by rye was 13.9 kg N ha^{-1}, 20% higher than the reduction of the 40-year average.

The simulated long-term average NO_3-N reduction by rye in this study was higher than the simulated long-term reduction of 3.9 kg N ha^{-1} by RZWQM2 (Malone et al., 2007a) and the 4.8 kg N ha^{-1} by the APSIM model (Malone et al., 2007b) at a fertilization rate of 150 kg N ha^{-1}. In comparison to those simulations, this study tested the RZWQM2 model with field-measured crop biomass and N assimilation data, which presented a more reliable crop biomass and rye N uptake simulation.

The simulated total N uptake by rye shoot was 49.0 kg N ha^{-1} for rye prior to corn and 71.0 kg N ha^{-1} for rye prior to soybean, with simulated total rye above biomass of 1.5 and 2.8 Mg ha^{-1}, respectively. The high biomass production and N uptake were mainly attributed to warm weather in most of the years. The relatively cold weather during the calibration and validation years of 2006-2009 led to the low simulated and observed rye growth in those years. Except for 1981 when no simulated drainage occurred, the results showed that NO_3-N loss was increased in five years from the rye plots and decreased in 34 years. The increase in NO_3-N loss in the scenario with rye was mainly attributed to the increase in drainage and NO_3-N concentration.

The annual flow-weighted average NO_3-N concentration (FWANC) in the drainage water was reduced by 12% in the scenario with rye over the 40-year simulation. The simulated average surface residue mass for the rye treatment in 40 years was 5.1 Mg ha^{-1}, 20% higher than the surface residue mass of 4.1 Mg ha^{-1} for the no-rye scenario. Rye residue resulted in an increase of 56.4 kg N ha^{-1} in the soil mineralization, accounting for 34% of the mineralized N in the no-rye scenario (table 11). Adding rye into the corn-soybean system increased the N uptake by both aboveground biomass and root by 63.0 kg N ha^{-1}, which compared to the conventional corn-soybean system without rye cover.

Possibly the cover crop in the field may have increased immobilization and reduced net mineralization (Parkin et al., 2006), which was not simulated. In this study, the simulated average annual immobilization was 15.7 kg N ha^{-1} for the scenario with rye growing in corn-soybean and 16.4 kg N ha^{-1} for the conventional corn-soybean crop system without rye cover crop. In the simulation conducted by Li et al. (2008), the RZWQM2-estimated annual immobilization for rye cover crop was equal to no cover crop treatments in a corn-soybean system (10 kg N ha^{-1}). Li et al (2008) also reported that RZWQM2 may overpredict net mineralization under winter cover compared to no cover crop. If the plots with cover crops had more simulated immobilization than the plots without cover crops, then less net mineralization would have been simulated and less NO_3-N would be available for leaching for cover crop plots than was currently simulated.

SUMMARY AND CONCLUSIONS

The calibrated RZWQM2 model in general satisfactorily simulated crop yield and biomass with percent error (PE) < ±15% and relative root mean square error (RRMSE) < 30% except for the overestimation of soybean biomass. Daily and annual drainage were simulated satisfactorily, with Nash-Sutcliffe efficiency (NSE) > 0.50, ratio of RMSE to standard error (RSR) < 0.70, and percent bias (PBIAS) within ±25% except for the overestimation of annual drainage for CTRL2. The simulation in soil water storage was unsatisfactory according to the statistical criteria. Annual NO_3-N loss was simulated in a satisfactory manner ($NSE \geq 0.73$, $RSR \leq 0.52$, and PBIAS within ±15%) except for the CTRL2 plots due to the drainage overestimation. The model did not capture the annual variance of drainage NO_3-N concentration, with negative NSE and RSR > 0.70. The total N uptake by corn and soybean in the aboveground biomass was simulated satisfactorily, with $PE \leq 11\%$ and RRMSE within ±25%. The N uptake by rye shoot was overpredicted by 17%, but the overestimation mainly occurred in 2009. However, for a data set with low variance, such as soil water storage and NO_3-N concentration, it is a formidable task to get a satisfactory NSE value for an agricultural system model. Furthermore, the simulation of soil moisture was comparable to other published studies. In general, RZWQM2 is a reliable agricultural system model in simulating hydrologic cycling and nitrogen dynamics.

Based on the long-term simulation, growing a winter rye cover crop in a conventional corn-soybean rotation in Iowa reduced the annual subsurface drainage and NO_3-N loss by 11% (2.9 cm) and 22% (11.8 kg N ha^{-1}), respectively, and increased annual ET by 5% (2.9 cm). Reduction of simulated annual FWANC over the long term was 12% (2.4 mg N L^{-1}) under rye cover crop. A non-weighing lysimeter study conducted by Riley et al. (2009) in Boone, Iowa, showed that controlled drainage reduced subsurface drainage by approximately 14%. In southern Minnesota, a shallow drainage system resulted in a reduction of drainage and NO_3-N loss by 20% and 18%, respectively (Sands et al., 2008), and NO_3-N loss through the tile drainage was reduced by 14% to 36% for spring N application compared with fall application of N (Randall and Sawyer, 2005). Studies in Iowa have shown that drainage NO_3-N loss was not significantly different between N application in fall and spring (26.0 vs. 25.3 kg N ha^{-1}) at an N rate of 168 kg N ha^{-1} (Lawlor et al., 2004). In comparison to those field management strategies targeting an environmental improvement, this long-term simulation suggests that planting a winter rye cover crop is a promising approach to reducing drainage NO_3-N loss to surface water bodies.

The simulated long-term annual FWANC reduction by rye is much smaller than the result reported by Li et al. (2008), in which a short-term simulation showed 49% reduction in drainage NO_3-N concentration by rye cover crop. From the simulations, the cover crop increased long-term simulated mineralization but not immobilization. Parkin et al (2006), however, reported higher immobilization in cover crop treatments than with no cover crop. More study is needed to determine if a winter cover crop over the long term will increase immobilization and thus largely decrease FWANC along with drainage. According to a highly cited article, one of the primary values of a water quality model is to illuminate which aspects of a system are in most need of further research (Oreskes et al., 1994). Therefore, this study highlights a future study assessment of cover crops on nitrogen immobilization and mineralization.

REFERENCES

Ahuja, L. R., K. W. Rojas, J. D. Hanson, M. J. Shaffer, and L. Ma. 2000. *Root Zone Water Quality Model: Modeling Management Effects on Water Quality and Crop Production*. Highlands Ranch, Colo.: Water Resources Publications.

Baker, J. L., K. L. Campbell, H. P. Johnson, and J. J. Hanway. 1975. NO_3-N, phosphorus, and sulfate in subsurface drainage water. *J. Environ. Qual.* 4(3): 406-412.

Baker, J. L., S. W. Melvin, D. W. Lemke, P. A. Lawlor, W. G. Crumpton, and M. J. Helmers. 2004. Subsurface drainage in Iowa and the water quality benefits and problem. In *Proc. 8th Intl. Symp.: Drainage VIII*. ASAE Paper No. 701P0304. St. Joseph, Mich.: ASAE.

Bakhsh, A., and R. S. Kanwar. 2001. Simulating tillage effects on nonpoint-source pollution from agricultural lands using GLEAMS. *Trans. ASAE* 44(4): 891-898.

Bakhsh, A., J. L. Hatfield, R. S. Kanwar, L. Ma, and L. R. Ahuja. 2004. Simulating nitrate drainage losses from a Walnut Creek watershed field. *J. Environ. Qual.* 33(1): 114-123.

Blackmer, A. M., R. D., Voss, and A. P. Mallarino. 1997. Nitrogen fertilizer recommendations for corn in Iowa. PM-1714. Ames, Iowa: Iowa State University Extension Service.

Cambardella, C. A., T. B. Moorman, D. B. Jaynes, T. B. Parkin, and D. L. Karlen. 1999. Water quality in Walnut Creek watershed: NO_3-N nitrogen in soils, subsurface drainage water, and shallow groundwater. *J. Environ. Qual.* 28(1): 25-34.

Carpenter-Boggs, L., J. L. Pikul Jr., M. F Vigil, and W. E. Riedell. 2000. Soil nitrogen mineralization influenced by crop rotation and nitrogen fertilization. *Soil Sci. Soc. Am. J.* 64(6): 2038-2045.

Dinnes, D. L., D. L. Karlen, D. B. Jaynes, T. C. Kaspar, J. L. Hatfield, T. S. Colvin, and C. A. Cambardella. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. *Agron. J.* 94(1): 153-171.

Eitzinger, J., M. Trnka, J. Hosch, Z. Zalud, and M. Dubrovsky. 2004. Comparison of CERES, WOFOST, and SWAP models in simulating soil water content during growing season under different soil conditions. *Ecol. Model.* 171(3): 223-246.

Feyereisen, G. W., B. N. Wilson, G. R. Sands, J. S. Strock, and P. M. Porter. 2006. Potential for a rye cover crop to reduce nitrate loss in southwestern Minnesota. *Agron. J.* 98(6): 1416-1426.

Garrsion, M. V., W. D. Batchelor, R. S. Kanwar, and J. T. Ritchie. 1999. Evaluation of the CERES-Maize water and nitrogen balances under tile drained conditions. *Agric. Syst.* 62(3): 189-200.

Hanson, J. D., K. W. Rojas, and M. J. Shaffer. 1999. Calibrating the root zone water quality model. *Agron. J.* 91(2): 171-177.

Helmers, M. J., P. A. Lawlor, J. L. Baker, S. Melvin, and D. Lemke. 2005. Temporal subsurface flow patterns from fifteen years in north central Iowa. ASABE Paper No. 052234. St. Joseph, Mich.: ASABE.

Jones, J. W., G. Hoogenboom, C. H. Porter, K. J. Boote, W. D. Batchelor, L. A. Hunt, P. W. Wilkens, U. Singh, A. J. Gijisman, and J. T. Ritchie. 2003. The DSSAT cropping system model. *European J. Agron*. 18(3): 235-265.

Jury, W. A., and R. Horton. 2004. *Soil Physics.* 6th ed. Hoboken, N. J.: John Wiley and Sons.

Kaleita, A. L., J. L. Heitman, and S. D. Logsdon. 2005. Field calibration of the Theta probe for Des Moines lobe soils. *Applied Eng. in Agric*. 21(5): 865-870.

Kaspar, T. C., D. B. Jaynes, T. B. Parkin, and T. B. Moorman. 2007. Rye cover crop and gamagrass strip effects on NO_3 concentration and load in tile drainage. *J. Environ. Qual*. 36(5): 1503-1511.

Lawlor, P. A., J. L. Baker, S. W. Melvin, and M. J. Helmers 2004. Nitrification inhibitor and nitrogen application timing effects on yields and nitrate-N concentrations in subsurface drainage from a corn-soybean rotation. ASAE Paper No. 042273. St. Joseph, Mich.: ASAE.

Lawlor, P. A., M. J. Helmers, J. L. Baker, S. W. Melvin, and D. W. Lemke. 2008. Nitrogen application rate effect on NO_3-N-nitrogen concentration and loss in subsurface drainage for a corn-soybean rotation. *Trans. ASABE* 51(1): 83-94.

Li, C., N. Farahbakhshazad, D. B. Jaynes, D. L. Dinnes, W. Salas, and D. McLaughlin. 2006. Modeling nitrate leaching with a biogeochemical model modified based on observations in a row-crop field in Iowa. *Ecol. Model*. 196(1-2): 116-130.

Li, L., R. W. Malone, L. Ma, T. C. Kaspar, D. B. Jaynes, S. A. Saseendran, K. R. Thorp, Q. Yu, and L. R. Ahuja. 2008. Winter cover crop effects on nitrate leaching in subsurface drainage as simulated by RZWQM-DSSAT. *Trans. ASABE* 51(5): 1575-1583.

Linn, D. M., and J. W. Doran. 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. *Soil Sci. Soc. Am. J.* 48(6): 1267-1272.

Liu, H. L., J. Y. Yang, C. S. Tan, C. F. Drury, W. D. Reynolds, T. Q. Zhang, Y. L. Bai, J. Jin, P. He, and G. Hoogenboom. 2011. Simulating water content, crop yield, and nitrate-N loss under free and controlled tile drainage with subsurface irrigation using the DSSAT model. *Agric. Water Mgmt.* 98(6): 1105-1111.

Logsdon, S. D., T. C. Kaspar, D. W. Meek, and J. H. Prueger. 2002. Nitrate leaching as influenced by cover crops in large soil monoliths. *Agron. J*. 94(4): 807-814.

Ma, L., D. C. Nielsen, L. R. Ahuja, R. W. Malone, S. A. Saseendran, K. W. Rojas, J. D. Hanson, and J. G. Benjamin. 2003. Evaluation of RZWQM under varying irrigation levels in eastern Colorado. *Trans. ASAE* 46(1): 39-49.

Ma, L., G. Hoogenboom, L. R. Ahuja, D. C. Nielsen, and J. C. Ascough II. 2005. Development and evaluation of the RZWQM-CROPGRO hybrid model for soybean production. *Agron. J*. 97(4): 1172-1182.

Ma, L., G. Hoogenboom, L. R. Ahuja, and J. C. Ascough II, and S. A. Saseendran. 2006. Evaluation of the RZWQM-CERES-Maize hybrid model for maize production. *Agric. Syst*. 87(3): 274-295.

Malone, R. W., J. Weatherington-Rice, M. J. Shipitalo, N. R. Fausey, L. Ma, L. R. Ahuja, R. D. Wauchope, and Q. Ma. 2004. Herbicide leaching as affected by macropore flow and within-storm rainfall intensity variation: A RZWQM simulation. *Pest Mgmt. Sci*. 60(3): 277-285.

Malone, R. W., L. Ma, P. Heilman, D. L. Karlen, R. S. Kanwar, and J. L. Hatfield. 2007a. Simulated N management effects on corn yield and tile-drainage nitrate loss. *Geoderma* 140(3): 272-283.

Malone, R. W., N. Huth, P. S. Carberry, L. Ma, T. C. Kaspar, D. L. Karlen, T. Meade, R. S. Kanwar, and P. Heilman. 2007b. Evaluating and predicting agricultural management effects under tile drainage using modified APSIM. *Geoderma* 140(3): 310-322.

Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Binger, R. D. Harmel, and T. L. Veith. 2007. Model evaluation guidelines for systematic qualification of accuracy in watershed simulations. *Trans. ASABE* 50(3): 885-900.

Oreskes, N., K. Shrader-Frechette, and K. Belitz. 1994. Verification, validation, and confirmation of numerical models in the earth sciences. *Science* 263(5147): 641-646.

Parkin, T. B., T. C. Kaspar, and J. W. Singer. 2006. Cover crop effect on the fate of N following soil application of swine manure. *Plant Soil* 289(1-2): 141-152.

Paz, J. O., W. D. Batchelor, B. A. Babcock. T. S. Colvin, S. D. Logsdon, T. C. Kaspar, and D. L. Karlen. 1999. Model-based technique to determine variable rate nitrogen for corn. *Agric. Syst*. 61(1): 69-75.

Qi, Z., and M. J. Helmers. 2010a. The conversion of permittivity as measured by a PR2 capacitance probe into soil moisture values or Des Moines lobe soils in Iowa. *Soil Use Mgmt* . 26(1): 82-92.

Qi, Z., and M. J. Helmers. 2010b. Soil water dynamics under winter rye cover crop in central Iowa. *Vadose Zone J*. 9(1): 53-60.

Qi, Z., M. J. Helmers, and P. A. Lawlor. 2008. Effect of different land covers on nitrate-nitrogen leaching and nitrogen uptake in Iowa. ASABE Paper No. 084806. St. Joseph, Mich.: ASABE.

Qi, Z., M. J. Helmers, and A. L. Kaleita. 2011a. Soil water dynamics under various agricultural land covers on a subsurface drained field in north-central Iowa, USA. *Agric. Water Mgmt.* 98(4): 655-674.

Qi, Z., M. J. Helmers, R. D. Christianson, and C. H. Pederson. 2011b. Nitrate-nitrogen losses through subsurface drainage under various agricultural land covers. *J. Environ. Qual.* 40(5): 1578-1585.

Rabalais, N. N., R. E. Turner, and W. J. Wiseman, Jr. 2001. Hypoxia in the Gulf of Mexico. *J. Environ. Qual.* 30(2): 320-329.

Randall, G. W., and J. E. Sawyer. 2005. Nitrogen application timing, forms, and additives. In *Final Report: Gulf Hypoxia and Local Water Quality Concerns Workshop*, 73-85. St. Joseph, Mich.: ASABE.

Riley, K. D. M. J. Helmers, P A. Lawlor, and R. Singh. 2009. Water balance investigation of controlled drainage in non-weighing lysimeters. *Applied Eng. in Agric.* 25(4): 507-514.

Rojas, K. W., and L. R. Ahuja. 2000. Chapter 8: Management practices. In *Root Zone Water Quality Model: Modeling Management Effects on Water Quality and Crop Production*, 245-280. L. R. Ahuja, K. W. Rojas, J. D. Hanson, M. J. Shaffer, and L. Ma, eds. Highlands Ranch, Colo.: Water Resources Publications.

Sands, G. R., I. Song, L. M. Busman, and B. Hansen. 2008. The effects of subsurface drainage depth and intensity on nitrate loads in the northern corn belt. *Trans. ASABE* 51(3): 937-946.

Shaffer, M. J., K. W. Rojas, D. G. Decoursey, and C. S. Hebson. 2000. Chapter 5: Nutrient chemistry processes - OMNI. In *Root Zone Water Quality Model: Modeling Management Effects on Water Quality and Crop Production*, 119-144. L. R. Ahuja, K. W. Rojas, J. D. Hanson, M. J. Shaffer, and L. Ma, eds. Highlands Ranch, Colo.: Water Resources Publications.

Singh, R., M. J. Helmers, and Z. Qi. 2006. Calibration and validation of DRAINMOD to design subsurface drainage systems for Iowa's tile landscapes. *Agric. Water Mgmt*. 85(3): 221-232.

Strock, J. S., P. M. Porter, and M. P. Russelle. 2004. Cover cropping to reduce nitrate loss through subsurface drainage in the northern U.S. Corn Belt. *J. Environ. Qual.* 33(3): 1010-1016.

Thorp, K. R., R. W. Malone, and D. B. Jaynes. 2007. Simulating long-term effects of nitrogen fertilizer application rates on corn yield and nitrogen dynamics. *Trans. ASABE* 50(4): 1287-1303.

Thorp, K. R., M. A. Youssef, D. B. Jaynes, R. W. Malone, and L. Ma. 2009. DRAINMOD-N II: Evaluated for an agricultural system in Iowa and compared to RZWQM-DSSAT. *Trans. ASABE* 52(5): 1557-1573.

Thorp, K. R., D J Hunsaker, A. N. French, J. W. White, T. R. Clarke, and P. J. Pinter Jr. 2010. Evaluation of the CSM-CROPSIM-CERES-Wheat model as a tool for crop water management. *Trans. ASABE* 53(1): 87-102.

USDA. 1985. Soil survey of Pocahontas County, Iowa. Washington, D.C.: USDA Soil Conservation Service.