

WINTER COVER CROP EFFECTS ON NITRATE LEACHING IN SUBSURFACE DRAINAGE AS SIMULATED BY RZWQM-DSSAT

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ABSTRACT. *Planting winter cover crops such as winter rye (*Secale cereale L.*) after corn and soybean harvest is one of the more promising practices to reduce nitrate loss to streams from tile drainage systems without negatively affecting production. Because availability of replicated tile-drained field data is limited and because use of cover crops to reduce nitrate loss has only been tested over a few years with limited environmental and management conditions, estimating the impacts of cover crops under the range of expected conditions is difficult. If properly tested against observed data, models can objectively estimate the relative effects of different weather conditions and agronomic practices (e.g., various N fertilizer application rates in conjunction with winter cover crops). In this study, an optimized winter wheat cover crop growth component was integrated into the calibrated RZWQM-DSSAT hybrid model, and then we compared the observed and simulated effects of a winter cover crop on nitrate leaching losses in subsurface drainage water for a corn-soybean rotation with N fertilizer application rates over 225 kg N ha⁻¹ in corn years. Annual observed and simulated flow-weighted average nitrate concentration (FWANC) in drainage from 2002 to 2005 for the cover crop treatments (CC) were 8.7 and 9.3 mg L⁻¹ compared to 21.3 and 18.2 mg L⁻¹ for no cover crop (CON). The resulting observed and simulated FWANC reductions due to CC were 59% and 49%. Simulations with the optimized model at various N fertilizer rates resulted in average annual drainage N loss differences between CC and CON increasing exponentially from 12 to 34 kg N ha⁻¹ for rates of 11 to 261 kg N ha⁻¹, but the percent difference remained relatively constant (65% to 70%). The results suggest that RZWQM-DSSAT is a promising tool to estimate the relative effects of a winter crop under different conditions on nitrate loss in tile drains, and that a winter cover crop can effectively reduce nitrate losses over a range of N fertilizer levels.*

Keywords. *Agroecosystem model, Corn-soybean rotation, Cover crop, Nitrate-nitrogen leaching, Subsurface drainage.*

Application of nitrogen (N) fertilizer to soil is usually necessary to achieve optimum corn yield. Nitrate-N (NO₃-N) leaching from cultivated soil within the Mississippi basin, however, is transported to surface waters, contributing to their degradation and to hypoxia in the Gulf of Mexico (Rabalais et al., 1996). This effect has been linked directly to NO₃-N transport down the Mississippi River from regions associated with Midwest-

ern corn and soybean production (Burkart and James, 1999; Goolsby et al., 2001). Nitrate-N concentration of surface waters and rivers has been an increasing concern in the past few decades. The U.S. Environmental Protection Agency (USEPA) has established an upper level for NO₃-N in drinking water of 10 mg L⁻¹ (USEPA, 1999). To reduce the NO₃-N losses to surface waters from agricultural fields, alternative management practices for N fertilizer have been investigated (Baker and Johnson, 1981; Ressler et al., 1998; Jaynes et al., 2001; Randall et al., 2003). But, improving N fertilizer management alone will not adequately reduce nitrate-N loss (Baker et al., 1975; Gast et al., 1978; Kladvik et al., 1999; Cambardella et al., 1999; Dinnes et al., 2002).

Winter cover crops show promise as a management strategy to help reduce NO₃-N losses in tile drainage (Kaspar et al., 2007; Stroock et al., 2004; Kladvik et al., 2004). However, examining the effect of different N application rates in conjunction with winter cover crops were beyond the scope of these studies. If properly tested against short-term data, simulation models can be used to objectively estimate the potential effects of conservation practices under different management and climate conditions.

Several simulation models have the potential to estimate NO₃-N dynamics in agricultural fields (e.g., DRAINMOD, EPIC, NLEAP, LEACHM, GRASIM, RZWQM, and DSSAT). Numerous researchers have made use of one or more of these models to estimate the nitrate leaching in soil-

Submitted for review in August 2007 as manuscript number SW 7138; approved for publication by the Soil & Water Division of ASABE in September 2008.

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plant systems in various regions (Chung et al., 2001; Helwig et al., 2002; Jabro et al., 2006). Comparing RZWQM and DSSAT, the plant growth processes simulated by DSSAT (which uses the CROPGRO and CERES crop growth models) are considered superior, while the hydrologic, nutrient, and pesticide processes in soils simulated by RZWQM are considered superior. To combine the best aspects of each model, Ma et al. (2005, 2006) coupled the CERES-Maize and -CROPGRO crop growth models from DSSAT version 3.5 with RZWQM to develop the RZWQM-DSSAT hybrid model. The RZWQM-DSSAT hybrid has been validated successfully for corn, soybean, and winter wheat cropping systems (Ma et al., 2005; Ma et al., 2006; Yu et al., 2006). Thorp et al. (2007) used ten years of experimental data to calibrate and validate the RZWQM-DSSAT hybrid model for simulating subsurface drainage, flow-weighted average nitrate concentration, and crop yield under various N application rates in a corn-soybean system in central Iowa.

Several models have been used to examine the effects of cover crops on nitrate leaching to subsurface water (Delgado, 1998; Feyereisen et al., 2006a, 2006b; Malone et al., 2007a), including RZWQM (Malone et al., 2007b). Few studies, however, have attempted to integrate a cover crop growth component into a comprehensive agricultural system model and test the model-estimated water quality effects of winter cover crops against observed data. Abrahamson et al. (2006) evaluated RZWQM with a cover crop and two tillage practices and cotton production as part of the agricultural system, but investigating the effects of cover crop on nitrate leaching in a corn-soybean rotation in the U.S. Midwest was not an objective of their study. Therefore, we integrated a calibrated winter cover crop component into the RZWQM-DSSAT hybrid model with a corn-soybean rotation. The research objectives were to compare the simulated and observed effects of a winter cover crop on nitrate leaching in a tile-drained corn-soybean rotation, and then to use the optimized model to investigate the winter cover crop effects on nitrate loss in response to different N fertilizer application rates from 12 to 262 kg N ha⁻¹ in corn growing seasons.

MATERIALS AND METHODS

FIELD EXPERIMENT

A field experiment (Kaspar et al., 2007) was conducted from 2000 to 2005 in Boone County, in central Iowa (42° 1' N, 93° 46' E, 335 m above mean sea level). Predominate soils in this area are Canisteo (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) and Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludolls). There were 24 plots of 30.5 × 42.7 m each at the research site, but only eight plots were used to address the objectives of the current research. Experimental treatments were winter cover cropping (CC) and a control treatment without cover crops (CON). Each treatment had four replications. Corn following soybean was the main cropping system for this experiment. Soybean was planted at 4.45 × 10⁵ seeds ha⁻¹ in early to mid-May in 2001, 2003, and 2005. Corn was planted at 7.9 × 10⁴ seeds ha⁻¹ in late April in 2002 and 2004. Winter rye was used for the cover crop treatment with a simulated planting date shortly after main crop harvest and a seeding density of 3.7 × 10⁶ seeds ha⁻¹ (2001 and 2002) and 2.5 × 10⁶ seeds ha⁻¹ (2003 and

Table 1. Management operations and fertilization.

Year	Crop	Planting Date	Harvest/Killing Date ^[a]	Fertilizer Date	N Amount (kg ha ⁻¹)
2000 ^[b]	Corn	2 May	2 Oct.	14 Apr.	235
	Rye	5 Oct.	16 Apr.		
2001	Soybean	10 May	28 Sept.		
	Rye	20 Aug. (29 Sept.) ^[c]	17 Apr.		
2002	Corn	25 Apr	30 Sept.	30 May	235
	Rye	10 Sept. (2 Oct.) ^[c]	6 May		
2003	Soybean	12 May.	30 Sept.		
	Rye	2 Oct.	16 May		
2004	Corn	28 Apr.	4 Oct.	21 May	247
	Rye	6 Oct.	25 Apr.		
2005	Soybean	6 May	30 Sept.		

^[a] Killing date for cover crop is the date in the next year of main crop planting.

^[b] The data for 2000 are estimated.

^[c] Dates in parentheses were used for the simulations because the model does not currently simulate intercropping.

2004). Management and fertilization records are summarized in table 1.

The plots were laid out in a randomized complete block design with four replications. The 24 plots were arranged in groups or rows (four plots per group) with field access space between groups. A 25.4 cm diameter drain tile was installed around the perimeter of the site to reduce subsurface flow into the plots, and a plastic sheet was installed to a depth of 1.8 m to act as a flow barrier between groups of plots. In each plot, a 7.62 cm diameter corrugated drainage pipe was installed 1.2 m below the soil surface lengthwise down the center of each plot. Drainage from each plot was conducted by solid plastic pipe to one of three large pits. Within each pit, drainage from eight plots was collected into dedicated sumps that a pump emptied whenever the water level exceeded a preset level. Flow from each pump went through a combination digital and mechanical totalizing flowmeter, with flow volume versus time recorded hourly by a data logger. The mechanical water meters were read periodically and used as a supplement to the digital flow records. Missing flow data caused by system failures were interpolated based on similar flow events. Flow at higher flow rates was more uncertain, as the district drainage pipe servicing the site would occasionally be at over capacity during high flow, preventing adequate pumping of plot sumps. In such cases, the flow amount was estimated.

Flow-weighted water samples were collected in plastic sample jars connected by a small-diameter tube to each sump pump outlet such that a proportional sample was collected each time water was pumped. Collected water samples were transported to the laboratory, and the NO₃-N concentration was determined using a Lachat auto-analyzer (Zellweger Analytics, Lachat Instrument Division, Milwaukee, Wisc.) on a weekly or shorter basis, depending on tile flow rate. Samples were kept refrigerated at 4 °C before analysis.

The yields of soybean in 2001, 2003, and 2005 and corn in 2002 were determined by harvesting the entire plot area. In 2004, because a wind storm had knocked down corn in some areas of the plots, undamaged corn in four strips, each 2.29 m wide × 42.67 m long, from each plot was harvested with a modified combine with a weigh tank. The remaining

area was bulk harvested. Grain samples were used to determine the protein and total N content. Two cover crop shoot dry matter samples per plot were collected just before killing by clipping the rye plant at the soil surface within an area 0.76×0.50 m. Aboveground rye samples were also analyzed for N content using the dry combustion-GC method (Schepers et al., 1989) with an EA1112 Flash NC elemental analyzer (Thermo Electron Corp., Waltham, Mass.).

MODEL INPUT DATA AND PARAMETERS

Required meteorological data were used in the model input files, including daily minimum and maximum temperatures, wind speed, solar radiation, and relative humidity. The model requires breakpoint precipitation data. The precipitation data recorded by a nearby weather station were converted into breakpoint format by plotting the recorded data against time and determining the breakpoint, usually 3 to 6 points in each precipitation day. Nitrate and NH_4 ions were added to precipitation at concentrations of 1.0 and 0.5 mg L^{-1} (0.23 and 0.39 mg N L^{-1}), which are the approximate average annual concentrations for Iowa (NADP, 2007).

The three main components of the RZWQM-DSSAT model (hydrology, nutrient dynamics, and plant growth) are generally calibrated to improve model simulations of measured data. Calibration for this study mainly consisted of soil hydrology and cover crop growth. Nutrient parameters were not calibrated because these were site specific (e.g., measured soil carbon), determined from previous RZWQM applications to Iowa field studies (Thorp et al., 2007; Ma et al., 2007), or default. Corn parameters were also not calibrated but determined from Thorp et al. (2007). Soybean parameters were similar to those of Thorp et al. (2007) with minor differences. When we replaced the final set of soybean parameters of the current research with those of Thorp et al. (2007), the RZWQM-simulated differences between the two scenarios for annual soybean yield and N loss were less than 2%.

For optimizing the subsurface drainage flow, the key parameters were drainable porosity (the difference between porosity and field capacity) and hydraulic conductivity (Shirmohammadi et al., 1998; Bakhsh et al., 2001). For the RZWQM-DSSAT hybrid model, the plant growth module in the original RZWQM model was replaced by the corresponding DSSAT module. The RZWQM and RZWQM-DSSAT hybrid has been calibrated in previous research (e.g., Bakhsh et al., 2004; Saseendran et al., 2005; Abrahamson et al., 2005; Ma et al., 2005, 2006; Yu et al., 2006). The RZWQM-DSSAT hybrid model (including maize and soybean) was successfully calibrated and validated in Story County, Iowa (Thorp et al., 2007). In the current research, the calibrated hybrid model was used directly from Thorp et al. (2007) with a few minor adjustments. Site-specific parameters different from those of Thorp et al. (2007) included soil depth layer design, porosity, field capacity, hydraulic conductivity, and lateral hydraulic conductivity to the drains (table 2).

The current RZWQM-DSSAT version does not include winter rye as an option; therefore, winter wheat was used. All the parameters were obtained from model default values for winter wheat, except the phylochron interval parameter (PHINT) was adjusted to optimize winter cover crop biomass production at the kill date (table 3). The physiological and ecological properties for winter rye and wheat are almost identical. However, the lethal low temperature is generally -10°C for winter wheat, while for winter rye it is -25°C or

Table 2. Soil hydraulic parameters used in the hybrid model.^[a]

Soil Depth (cm)	Porosity ($\text{cm}^3 \text{ cm}^{-3}$)	θ_s ($\text{cm}^3 \text{ cm}^{-3}$)	K_s (cm h^{-1})	LK_s (cm h^{-1})
20	0.491	0.415	1.50	10
41	0.463	0.395	3.50	10
51	0.453	0.365	3.50	10
69	0.434	0.345	3.50	10
89	0.396	0.345	3.50	10
101	0.396	0.340	1.80	10
130	0.396	0.340	1.80	10
150	0.358	0.330	0.01	0.001
200	0.358	0.330	0.01	0.001
248	0.358	0.330	0.01	0.001

^[a] θ_s = field capacity; K_s = hydraulic conductivity; LK_s = lateral hydraulic conductivity to the drains.

Table 3. Wheat cover crop growth parameters used in the hybrid model.

Parameter	Definition	Value
P1V	Relative amount that development is slowed for each day of unfulfilled vernalization (d)	6.0
P1D	Relative amount that development is slowed when plants are grown in a photoperiod 1 h shorter than the optimum (d)	2.5
P5	Relative grain filling duration based on thermal time (d)	-5.0
G1	Kernel number per unit weight of stem (g^{-1})	5.0
G2	Kernel filling rate under optimum conditions (mg d^{-1})	1.2
G3	Non-stressed dry weight of a single stem (g)	1.4
PHINT	Phylochron interval ($^\circ\text{C days}$)	80 ^[a]

^[a] Parameter is modified from default value (60). Other values are defaults.

lower. To avoid simulating winter kill of the cover crop by cold temperatures, the measured temperatures below -10°C were increased to -10°C before model runs. That is, this research did not consider a population reduction for the winter cover crop induced by low temperatures. In addition, the simulated planting density was input as recorded in field notes (2.5 to 3.7×10^6 seeds ha^{-1}), except 3.0×10^5 seeds ha^{-1} were input in 2002 to represent low cover crop shoot biomass due to poor stand establishment (Kaspar et al., 2007).

MODEL TESTING

One of the objectives of this research is to determine if the water quality effects of winter cover crops can be reasonably simulated when hydrology and crop growth are optimized. The cover crop plots were not completely established until fall 2002 (Kaspar et al., 2007); therefore, the data used for model testing and evaluation are from 2002 through 2005. Our objectives do not include thoroughly testing the RZWQM-simulated processes for hydrology and corn, soybean, and cover crop growth. RZWQM has been evaluated numerous times for corn-soybean production and the associated hydrology. In addition, the cover crop growth data contained only four years of record, and the 2002 planting (spring 2003 rye kill) had poor establishment, which limits the value of this dataset for thorough model testing of cover crop growth. Therefore, all of the available data were used for optimization of cover crop growth and hydrology, rather than choosing part of the observed data for model calibration and part for model testing. This is a similar model testing strategy as that performed by Malone et al. (2001, 2004), in which a

process was isolated for testing by optimizing other influential processes using all the available data. Although not formally tested, results of hydrology and crop growth simulations are briefly discussed because of their influence on simulated water quality. In summary, RZWQM-DSSAT is optimized for hydrology and cover crop growth; the optimized model is then tested for its estimate of the water quality effects of cover crop treatments (CC) compared to control treatments with no cover crop (CON) with the same soil, nutrient, and crop growth parameters for both scenarios.

Indicators used for model evaluation include percent difference (PD), root mean square error (RMSE), and model efficiency (EF):

$$PD = \frac{P_i - O_i}{O_i} \times 100\% \quad (1)$$

$$RMSE = \frac{1}{O} * \sqrt{\frac{1}{n} \sum_{i=1}^n (P_i - O_i)^2} \quad (2)$$

$$EF = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (3)$$

where \bar{O} are the mean observed values, P_i are the model estimated values, O_i are the observed values, and n are the number of data pairs. One criterion for crop yield model acceptance is that if the PD value is within 15%, then simulation results can be considered satisfactory (Hanson, 1999). The values of RMSE and EF when model estimates perfectly match observed data are 0 and 1.0, respectively. An EF value less than zero indicates that the average of observed measurements at the site were a better estimator than the model. More discussion concerning use of these performance indicators to evaluate RZWQM is provided by Thorp et al. (2007) and Bakhsh et al. (2004).

For the most part, we used the calibrated RZWQM of Thorp et al. (2007) and only briefly discuss current hydrology and crop simulations; we consider discussion of these simulations especially important if they are not “satisfactory.” Our main purpose in the model testing component of this research is to determine if a previously calibrated and tested RZWQM-DSSAT responds to CC compared to CON treat-

ments. Therefore, we briefly report and discuss model comparisons to observed data such as the individual treatment tile drainage, crop growth, and nitrate loss, but the observed and RZWQM differences between CC and CON are the most important comparisons.

RZWQM SIMULATIONS AT DIFFERENT RATES

The field experiments for this research were conducted with a single high N application rate. In addition, Thorp et al. (2007) concluded that RZWQM-DSSAT can be used to quantify the long-term effects of different N application rates on corn production and subsurface drainage nitrate concentration in Iowa. Therefore, to test the effectiveness of cover crops under different N rates, we used the model to simulate the performance of cover crop N uptake under six different corn-year N rates: 11, 61, 111, 161, 211, and 261 kg N ha⁻¹. The lower N application rates result in reduced simulated corn growth and reduced cover crop growth. Simulated plant N stress occurs when plant N uptake is less than plant N demand. In RZWQM-DSSAT-simulated plant growth, a daily value of 1 indicates no simulated plant N stress, and a value of 0 indicates maximum stress. Nitrogen stress simulated by RZWQM-DSSAT is a function of critical, minimum, and actual plant N concentrations, and plant growth stage (Ma et al., 2006). Simulated N stress is reported in results to explain greater simulated cover crop N uptake at higher N application rates.

RESULTS AND DISCUSSION

MAIN CROP YIELDS, GRAIN N, COVER CROP SHOOT BIOMASS, AND NITROGEN

The RZWQM-DSSAT hybrid model simulated annual main crop yield with a maximum annual difference of 0.6 Mg ha⁻¹ for both corn and soybean (table 4). The model estimated the main crop yield with PD ≤ 5% for corn. Annual soybean yield PD values were higher than those for corn, especially in 2003. High PD values of both CC and CON treatments in 2003 for simulated soybean yield might be due to the same variety being used for simulations while different varieties were planted in the experimental plots.

Corn grain N was overestimated by more than 20% each year (>30 kg N ha⁻¹ year⁻¹), and soybean grain N was overestimated by ≥9% each year (table 4). Grain N is removed from the system; therefore, overestimated grain N may significantly affect N loss, as discussed below. Thorp et al.

Table 4. Observed and simulated main crop yield, grain N, cover crop shoot biomass, and cover crop shoot N uptake in Boone County, Iowa.^[a]

Year	Crop	Main Crop Yield (Mg ha ⁻¹)						Main Crop Grain N (Mg N ha ⁻¹)						Cover Crop Shoot Dry Weight (Mg ha ⁻¹)			Cover Crop Total Shoot N (Mg N ha ⁻¹)		
		CC			CON			CC			CON			CC			CC		
		Obs	Sim	PD	Obs	Sim	PD	Obs	Sim	PD	Obs	Sim	PD	Obs	Sim	PD	Obs	Sim	PD
2002	Corn	9.5	10.0	5	10.5	10.0	-5	120	170	41	132	170	29	2.4	2.6	7	56	61	9
2003	Soybean	2.4	2.9	25	2.4	2.9	23	158	182	15	160	182	14	0.3	0.7	180	9	30	224
2004	Corn	11.3	11.5	2	11.2	11.5	2	155	189	22	155	195	26	1.5	2.1	44	49	51	5
2005	Soybean	3.6	4.2	15	3.9	4.1	6	212	250	18	227	247	9	2.7	2.3	-15	77	44	-43
	Corn average	10.4	10.7		10.9	10.7		138	179		143	182							
	Soybean average	3.0	3.6		3.1	3.5		185	216		194	214							
	CC average													1.7	1.9		47.5	46.3	

^[a] CC = cover crop treatment, CON = no cover crop treatment, Obs = observed value, Sim = simulated values with RZWQM, and PD = percent difference (%).

Table 5. Observed and simulated annual subsurface tile flow, flow-weighted average nitrate concentration (FWANC), and nitrate leaching loss for cover crop (CC) and no cover crop (CON) treatments.^[a]

Year	Crop	Tile Flow Amount (mm)						Flow-Weighted Annual Nitrate Concentration (mg N L ⁻¹)						Nitrate Loss in Tile Flow (kg N ha ⁻¹)					
		CC			CON			CC			CON			CC			CON		
		Obs	Sim	PD	Obs	Sim	PD	Obs	Sim	PD	Obs	Sim	PD	Obs	Sim	PD	Obs	Sim	PD
2002	Corn	209	93	-56	227	176	-22	5.8	5.0	-15	19.1	12.7	-33	11.2	4.6	-59	40.4	22.4	-44
2003	Soybean	302	289	-4	346	296	-15	11.8	12.0	1	24.7	21.9	-11	33.9	34.5	2	81.1	64.6	-20
2004	Corn	254	236	-7	248	292	18	9.3	11.7	25	19.8	19.4	-2	23.0	27.6	20	47.2	56.6	20
2005	Soybean	140	122	-12	175	189	8	8.0	8.6	8	21.6	18.7	-13	11.1	10.5	-5	34.4	35.4	3
Average		226	185		249	238		8.7	9.3		21.3	18.2		19.8	19.3		50.8	44.8	
EF		-0.01			0.53			0.64			-2.05			0.82			0.48		
RMSE (%)		27			17			15			18			20			26		
EF (2003-2005)		0.94			0.69			0.42			-0.19			0.92			0.70		
RMSE (2003-2005)		6			13			13			9			10			17		

^[a] Obs = observed value, Sim = RZWQM simulated values, and PD = percent difference (%).

(2007) also reported overestimated grain N by RZWQM-DSSAT.

Observed cover crop shoot biomass varied from 0.3 to 2.7 Mg ha⁻¹, which the model described within 0.7 Mg ha⁻¹ (table 4). The least accurate cover crop shoot N estimate, excluding 2003 when seed density input was adjusted to more accurately estimate cover crop population, was in 2005 when shoot N was underestimated 43%. The underestimate in 2005 is partly due to cover crop shoot biomass underestimation of 15%. Also in 2005, the N concentration of the cover crop was underestimated (N concentration of 2.8% for observed; 1.8% for RZWQM). Malone et al. (2007a) reported that the APSIM model also underestimated winter wheat N concentration when used as a cover crop. Possibly winter wheat models such as APSIM and RZWQM-DSSAT produce acceptable simulations for mature wheat, but more testing and development are needed to accurately estimate N uptake for early stages of development. When winter wheat or rye cover crops are part of corn-soybean rotations, the cover crop is generally killed early in the spring prior to reaching maturity.

TILE DRAINAGE

The RZWQM model defines water table depth as the depth at which the pressure head first becomes non-negative and all heads below that depth are non-negative (Ahuja et al., 2000). Once the water table depth in the soil profile is above the drain installation depth, flux out of the drain will occur, and consequently nitrate will be transported from the soil profile out of the plot.

The calibrated model estimated CC and CON annual tile flow in 2003-2005 with PD values less than 20%, EF \geq 0.69, and RMSE \leq 13% (table 5). For the most part, the model also responded to daily tile flows in 2003-2005 (fig. 1). In 2003-2005, the model occasionally underestimated the peak tile flows, which might be a common weakness of agricultural models such as EPIC (Chung et al., 2001) and RZWQM (Bakhsh et al., 2004; Thorp et al., 2007). In addition, in a few cases at high flow rates, the measured values are less certain because of system failures such as inadequate pumping of plot sumps, as explained earlier in the Field Experiment section.

The two least accurate annual tile flow simulations are in 2002, when tile flow was underestimated by 22% for CON and 56% for CC (table 5). Adding 2002 to the performance indicators reduces the CC EF to less than zero. An EF value

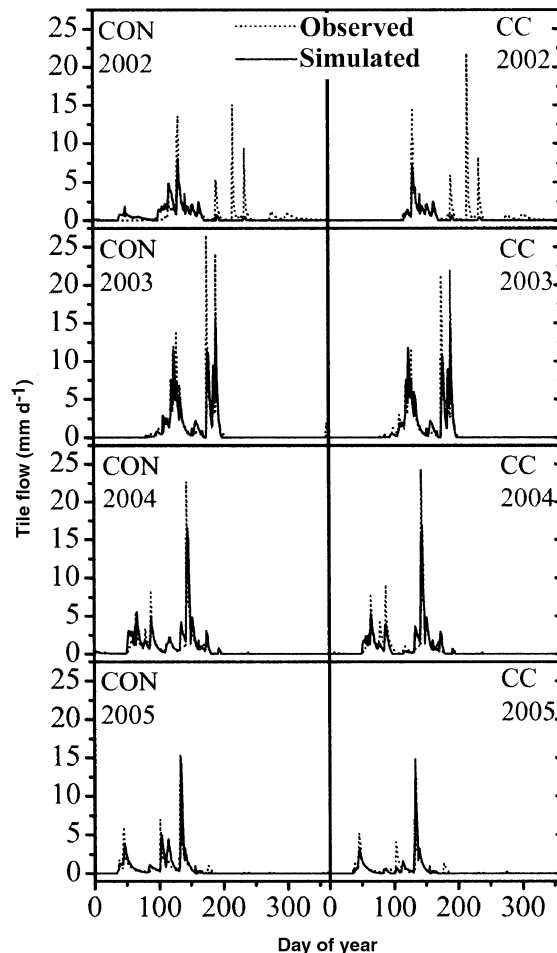


Figure 1. Observed and simulated tile flow amount for control (CON) and cover crop (CC) treatments.

less than zero indicates that the average of tile flow measurements at the site was a better estimator of tile flow than the model. Most of the inaccuracy in 2002 occurs between DOY 191 and 240 (fig. 1), when the three peak flow values had to be estimated rather than directly measured because of system failure due to inadequate pumping of plot sumps, as described earlier. Therefore, measurement error may contribute to the RZWQM underestimated tile flow in 2002.

The average annual observed and RZWQM-simulated tile flow differences between CC and CON were -23 and -53 mm (table 5). The model may overestimate this difference partly because the average observed CC minus CON differences for corn yield, soybean yield, and cover crop shoot dry weight were -0.5, -0.1, and 1.7 Mg ha⁻¹, while the simulated differences were 0, +0.1, and 1.9 Mg ha⁻¹ (table 4), suggesting that the simulated transpiration for CC may be overestimated relative to CON. Measurements were not taken for winter cover crop evapotranspiration at this site to compare with model simulations. The average annual RZWQM-simulated ET difference between CC and CON for 2002 through 2004 was 53 mm.

FLOW-WEIGHTED AVERAGE NO₃-N CONCENTRATION

Average observed and RZWQM-simulated flow-weighted average nitrate concentration (FWANC) in the CC treatment for 2002 to 2005 were 8.7 and 9.3 mg N L⁻¹, compared to 21.3 and 18.2 mg N L⁻¹ for CON, resulting in observed and simulated reductions of 59% and 49% (table 5). Each year, the model underestimated the CON FWANC between -0.4 and -6.4 mg N L⁻¹ (between 2% and 33%), partly because of overestimated grain N removal (table 4). The CC FWANC, however, was estimated with less bias: annual simulated differences from observed ranged from -0.8 to +2.6 mg L⁻¹ (-15% to +25%; table 5). Because the model underestimated FWANC for CON but not for CC, it underestimated the percent difference between CC and CON each year by a fairly consistent 10% (fig. 2). The simulated difference between CC and CON FWANC was underestimated, and thus conservative, possibly because the cover crop in the field may have increased immobilization and reduced net mineralization (Parkin et al., 2006), which was not simulated. The RZWQM-estimated annual immobilization was equal for cover crop and no cover crop treatments (10 kg ha⁻¹ for both CC and CON). Estimated average annual net mineralization was 134 kg N ha⁻¹ for CC and 120 kg N ha⁻¹ for CON (table 6). If the CC plots had more simulated immobilization than the CON, then less net mineralization would have been simulated and less nitrate-N would be available for leaching for CC than is currently simulated.

The least accurate FWANC estimate was for CON in 2002, where FWANC was underestimated by 6.4 mg N L⁻¹ (-33%; table 5). Part of the reason for the underestimated FWANC in 2002 is that the CON corn grain N was overestimated by 39 kg N ha⁻¹ (34%) in 2000, which is more than in 2002 and 2004 (table 4), and this contributes to underestimated nitrate-N in soil profile because of overestimated grain N removal. Another contributing factor may be that some early

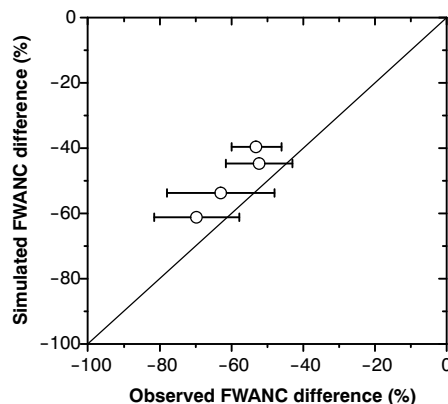


Figure 2. FWANC difference between CC and CON. FWANC difference = (CC-CON)*100*CON⁻¹. CC is cover crop treatment; CON is control treatment (no cover crop); FWANC is flow-weighted annual nitrate concentration. The line is $x = y$; the error bars are the standard deviation of the observed data.

N fertilizer applications and other management practices entered into RZWQM could be wrong because prior to 2000 the management history of the site was uncertain, which could have a lingering effect on the model simulations.

Although the model accurately responded to year-to-year FWANC treatment differences between CC and CON (fig. 2), the annual CON simulations did not describe year-to-year variations (table 5). The EF was negative, indicating that the average of FWANC measurements at the site was a better estimator of FWANC than the model. Bakhsh et al. (2004) and Thorp et al. (2007) also reported low EF values for annual FWANC. However, another measure of model performance (relative RMSE) was 18%. Because the annual observed concentrations only varied from 19 to 25 mg N L⁻¹ and because only four years of data are available (table 5), the poor 2002 estimate dramatically affected the EF value.

NITRATE LOSSES

The average values of observed nitrate leaching losses were 19.8 and 50.8 kg ha⁻¹ for CC and CON, while the simulated values were 19.3 and 44.8 kg ha⁻¹, with RMSE less than 30% and EF ≥ 0.48 for both treatments (table 5). The nitrate leaching losses were underestimated in CC because drainage was generally underestimated and in CON because nitrate concentration in drainage was underestimated (table 5). In 2003 through 2005 for both cover crop and no cover crop treatments, PD values for N loss were ≤ 20%. Excluding 2002 data results in model performance indicators RMSE ≤ 17% and EF ≥ 0.7 for both CC and CON (table 5).

Table 6 Simulated annual nitrate-N budget for cover crop (CC) and control (CON) treatments (all values in kg-N ha⁻¹).

Year	Crop	Fixation		Denitrification		Tile Drainage		Total N Uptake		Net Mineralization		Annual Soil Nitrate-N Change ^[a]	
		CC	CON	CC	CON	CC	CON	CC	CON	CC	CON	CC	CON
2002	Corn	0	0	10.7	14.4	4.6	22.4	311.2	276.8	119.2	103.7	40.3	37.9
2003	Soybean	231.9	226.9	3.2	6	34.5	64.6	372.2	323.1	134.9	126	-14.2	-11.6
2004	Corn	0	0	12.8	7.2	27.6	56.6	338.3	307.8	129.1	121.6	-8.2	-8.2
2005	Soybean	305.1	280.6	5	7.4	10.5	35.4	463.4	408.3	151.9	128.6	-10.8	-28.9
Average		134.3	126.9	7.9	8.8	19.3	44.8	371.3	329.0	133.8	120.0	1.8	-2.7

[a] Annual soil nitrate-N change is the December 31 difference between consecutive years. For example, the CC soil nitrate-N values on December 31, 2001, and December 31, 2002, were 54.1 and 94.4 kg N ha⁻¹, respectively.

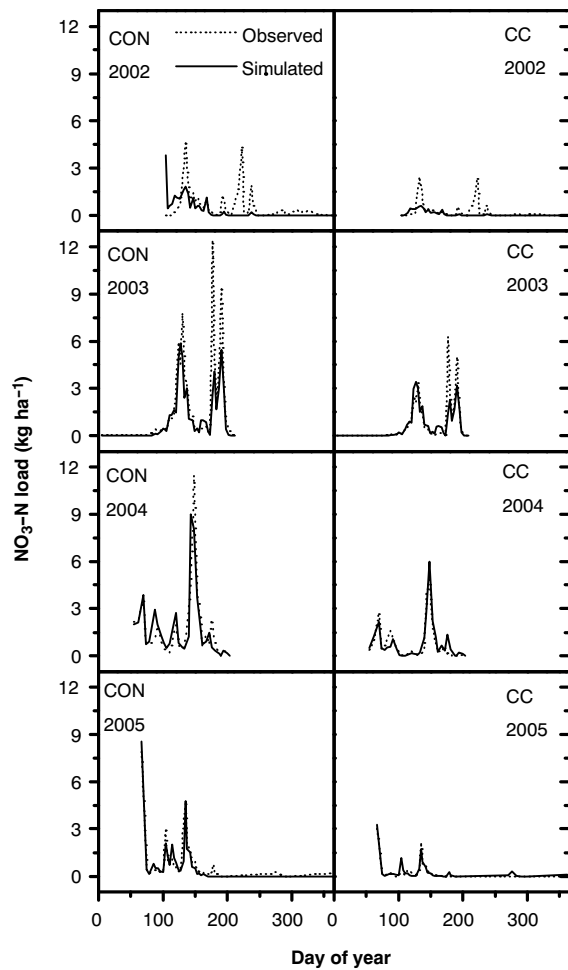


Figure 3. Observed and simulated NO₃-N losses for control (CON) and cover crop (CC) treatments.

Nitrate loss in drainage is a function of nitrate concentration of shallow groundwater and tile flow amount. Therefore, the simulated nitrate leaching losses in subsurface drainage water were underestimated by more than 50% for CC in 2002, mostly because tile flow was underestimated by more than 50%. Simulated nitrate loss for CON was low in 2002, mostly because FWANC was underestimated by 33%, as discussed earlier. For both treatments, much of the 2002 error in nitrate loss simulations occurred because the tile flow amount was underestimated after DOY 190 (fig. 3), possibly because of measurement error in tile flow.

The RZWQM-simulated annual nitrogen budget components in the system indicate that on average CC simulated 25.5 kg ha⁻¹ less N loss in drainage from 2002 through 2005 than CON (tables 5 and 6). The main reason for this prediction is that while CC produced 13.8 kg N ha⁻¹ more annual net mineralization and 14.8 kg ha⁻¹ more fixation during soybean years (7.4 kg ha⁻¹ year⁻¹), CC also simulated 42.3 kg ha⁻¹ more total N uptake (table 6). An average annual partial N mass balance difference between CC and CON can be calculated as 13.8 (net mineralization) + 7.4 (fixation) - 42.3 (N uptake) = -21.1 less N available for leaching, or nearly the -25.5 kg ha⁻¹ N loss difference in drainage. The remaining difference is mostly from +4.5 kg N ha⁻¹ more N retained in the soil from year to year, on average, from CC (table 6) because simulated denitrification, volatilization, runoff, deep

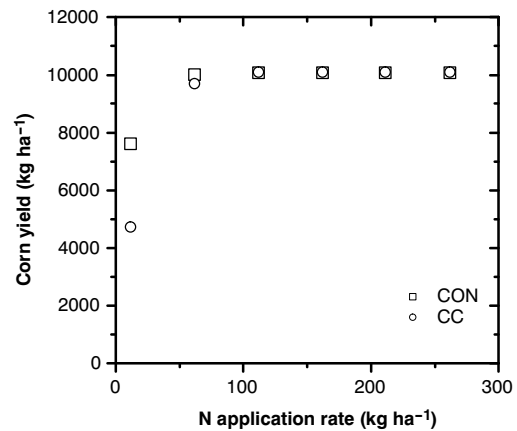


Figure 4. Average annual simulated corn yield at different N rates for cover crop (CC) and control (CON) treatments in 2002 and 2004 in a corn-soybean rotation.

seepage, and application of N are nearly equal between CC and CON. Fixation was higher in CC because with the lower simulated available soil N (e.g., systems that include additional N uptake by cover crops), RZWQM simulates higher fixation to meet soybean N demand (Malone and Ma, 2009). The yearly total plant N uptake (main crop shoot and root N uptake plus cover crop shoot and root N uptake) of CC was greater than that of CON mainly due to the effects of cover crop planting. Therefore, on average, CC temporarily removes more N from the soil profile and retains more nitrate-N in the soil from year to year than CON, which reduces the simulated annual N loss in subsurface drainage water from a minimal value of 18 kg ha⁻¹ in 2002 to a maximum of 30 kg ha⁻¹ in 2003 (table 6). Note that the average annual partial nitrate-N budgets nearly balance for both CC and CON:

$$\pm 1 \text{ kg N ha}^{-1} > \text{appli.} + \text{rain} + \text{fix.} + \text{net min.}$$

$$- \text{denitri.} - \text{uptake} - \text{tile drain} - \text{soil N change}$$

where the average annual nitrate-N from application and rain are equal to 121.7 and 10.9 kg N ha⁻¹ for both CC and CON.

RZWQM-DSSAT-ESTIMATED COVER CROP EFFECTS IN RESPONSE TO N RATES

The corn-year N fertilizer application rate was increased from 12 to 62 kg ha⁻¹, which resulted in a corn yield increase of 5354 and 2471 kg ha⁻¹ for CC and CON, respectively (fig. 4). Increasing N application from 62 to 112, however, resulted in a corn yield increase of only 388 kg ha⁻¹ for CC and nearly no increase for CON. Increasing N application rates beyond 112 kg ha⁻¹ had little effect on simulated corn yield. The response of simulated corn yield to N fertilizer application agreed with the results of Thorp et al. (2007), who found that rates above 100 kg N ha⁻¹ did not result in significant increase in corn yield. The simulations also suggest that CC reduced corn yield compared to CON at low rates (fig. 4). At rates of 12 and 61 kg N ha⁻¹, CC reduced corn yield by 3335 and 311 kg ha⁻¹ compared to CON. Therefore, at low N application rates CC may add additional N stress to corn and reduce yield.

Simulated N loss in subsurface drainage water increased exponentially with increasing N rates (fig. 5). The acceleration of N loss was less for CC than CON because N uptake by

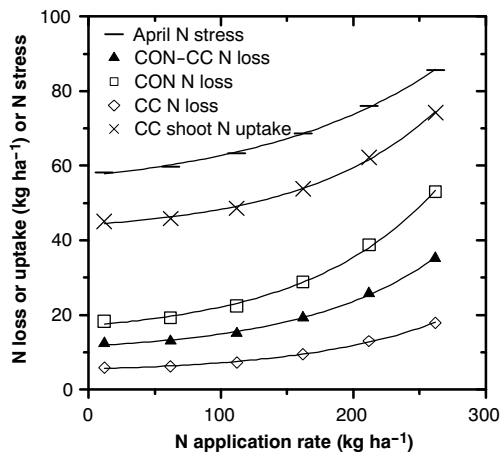


Figure 5. Average annual simulated N dynamics at different N rates for winter cover crop (CC) and control (CON) treatments from 2002 through 2005. The solid lines through the variables are the best fit line ($R^2 > 0.99$): CC shoot N uptake = $45.1 + 2.63E-5 \times (Nrate^{2.5})$; CC N loss = $5.86 + 1.08E-5 \times (Nrate^{2.5})$; CON N loss = $18.3 + 3.14E-5 \times (Nrate^{2.5})$; CON - CC N loss = $12.4 + 2.05E-5 \times (Nrate^{2.5})$; and April N stress = $58.28 + 3.97E-4 \times (Nrate^{2.0})$. April N stress is the sum of the simulated winter cover crop N stress in April from 2002 through 2005, where a daily value of 1 indicates no stress and 0 indicates severe stress. Therefore, greater simulated April N stress actually indicates less N stress and more shoot N uptake by winter cover crops.

winter cover crops increased exponentially with increasing rates and, in turn, CC N stress decreased exponentially with increasing N application (fig. 5). The N loss percent difference ($[(CON - CC) \times 100 \times CON^{-1}]$) with increasing N rates remained relatively constant between 65% and 69% because the N loss difference between CON and CC was an exponential function of N rate (fig. 5). The N loss difference between CON and CC was 12 and 34 $kg\ ha^{-1}$ at the lowest and highest application rates, respectively. The simulated N loss difference between CON and CC shown in figure 5 (65% to 69%) is greater than that shown in figure 2 and table 5 because the planted winter wheat population is 2.5×10^6 seed ha^{-1} for 2001-2005 and was not reduced for fall 2002 planting. This suggests that winter cover crops have great potential to reduce nitrate transport to surface water in drained agricultural regions in central Iowa throughout a large range of N application rates.

SUMMARY AND CONCLUSIONS

We used a calibrated RZWQM-DSSAT hybrid model to investigate the effects of winter cover crop on nitrate leaching losses in subsurface drainage water in Boone County, Iowa. The model results were compared to field experimental data collected from cover crop and no cover crop treatments over several years. Observed nitrate leaching losses in subsurface drainage water (or FWANC) presented a twofold difference between cover crop and no cover crop treatments, and the calibrated model described most of the cover crop effect. Because the RZWQM-DSSAT hybrid model overestimated grain N removal, the simulated annual FWANC for both cover crop and no cover crop treatments should be less than the observed. However, the simulated annual FWANC was not lower than observed for cover crop treatment. A cover crop may increase N immobilization in the soil profile, as reported by Parkin et al. (2006), which is

not simulated by the model, and this may compensate for the overestimated grain N removal.

The model results suggest that cover cropping did not reduce main crop yield with application rates over $61\ kg\ N\ ha^{-1}$, and thus corn N stress is not estimated to increase with cover crop with the vast majority of N management options. On the other hand, the model simulations suggest that cover cropping can reduce nitrate leaching more than 60% at application rates from 11 to $261\ kg\ N\ ha^{-1}$. It has been reported that planting and harvest dates of cover crop greatly affect the cover crop's effectiveness (Feyereisen et al., 2006b). Our results suggest that the cover crop impact on the N balance was related to cover crop growth and N uptake. Therefore, reductions in nitrate losses in tile drainage might be maximized by increasing the cover crop growth period.

The current RZWQM-DSSAT hybrid model shows promise for estimating the hydraulic, nitrogen, and crop growth processes in a complicated agricultural system after calibration; however, future versions should improve the grain-N uptake process, as pointed out by Thorp et al. (2007). In addition, development of a winter rye cover crop growth module integrated into the RZWQM-DSSAT model may more accurately simulate the effects of cover crop on the nitrogen dynamics in this complicated agricultural system. More research is necessary to identify whether increased immobilization in winter cover crop systems is responsible for the increased observed effect of cover crop on N loss compared to RZWQM simulations.

ACKNOWLEDGEMENTS

This project was funded by the Chinese Academy of Sciences International Partnership Project Human Activities and Ecosystem Changes (CXTD-Z2005-1) and the State Key Fundamental Science Funds of China (Grant No. 2005CB121106).

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