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Cover crops in the upper midwestern United States: Simulated effect on nitrate leaching with artificial drainage

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Abstract: A fall-planted winter cover crop is an agricultural management practice with multiple benefits that may include reducing nitrate (NO_3) losses from artificial drained agricultural fields. While the practice is commonly used in the southern and eastern United States, little is known about its efficacy in midwestern states where winters are longer and colder, and artificial subsurface drainage is widely used in corn–soybean systems (*Zea mays* L.–*Glycine max* L.). We used a field-tested version of the Root Zone Water Quality Model (RZWQM) to simulate the adoption of cereal rye (*Secale cereale* L.) as a winter cover crop and estimate its impact on NO_3 losses from drained fields at 41 sites across the Midwest from 1961 to 2005. The average annual nitrogen (N) loss reduction from adding winter rye ranged from 11.7 to 31.8 kg N ha^{-1} (10.4 to 28.4 lb N ac^{-1}) among four simulated systems. One of the simulated treatments was winter rye overseeded (aerial seeded) into a no-till corn–soybean rotation at simulated main crop maturity (CC2). On average, this treatment reduced simulated N loss in drainage by 20.1 kg N ha^{-1} (17.9 lb N ac^{-1}) over the sites compared to systems without winter rye (NCC2), from 47.3 to 27.2 kg N ha^{-1} (42.2 to 24.3 lb N ac^{-1}). Adding spring tillage to this treatment and killing the rye earlier (CC3) reduced simulated N loss from 57.3 (NCC3) to 34.4 kg N ha^{-1} (30.7 lb N ac^{-1}). Replacing the corn–soybean rotation with continuous corn and spring tillage reduced simulated N loss from 106 (NCC4) to 74.2 kg N ha^{-1} (CC4) (94.6 to 66.2 lb N ac^{-1}). Adding a winter rye cover crop reduced N loss more in the continuous corn system despite earlier spring termination of the winter rye and slightly less N uptake by the rye possibly because of more denitrification. Regression analysis of the RZWQM variables from these sites showed that temperature and precipitation during winter rye growth, N fertilizer application rates to corn, and simulated corn yield account for greater than 95% of the simulated site-to-site variability in NO_3 loss reductions in tile flow due to winter rye. Our results suggest that on average winter rye can reduce N loss in drainage 42.5% across the Midwest. Greater N loss reductions were estimated from adding winter rye at sites with warmer temperatures and less precipitation because of more cover crop growth and more soil N available for cover crop uptake.

Key words: best management practices—hypoxia—nitrate—Root Zone Water Quality Model—subsurface drainage—water quality

A fall-planted "winter" cover crop is an agricultural management practice with multiple benefits that may include reducing nitrate (NO_3) losses from artificially drained agricultural fields, which could help reduce the hypoxic zone in the Gulf of Mexico if implemented on a large scale in the midwestern United States. Anthropogenic perturbation of the global nitrogen (N) cycle is of increasing concern, and contributes to hypoxia, loss of biodiversity, and habitat degradation in coastal ecosystems (Galloway et al. 2003; Gruber and Galloway 2008; Canfield et al. 2010). Excessive NO_3 in the Mississippi River has been identified as a leading cause of hypoxia in the northern Gulf of Mexico (Rabalais et al. 1996; EPA SAB 2007). Numerous studies at the field and watershed scale (David et al. 1997; Jaynes et al. 1999; Goolsby et al. 2001; Royer et al. 2006) have shown that much of the NO_3 in surface waters of the Midwest comes from land used for corn (*Zea mays* L.) and soybean (*Glycine max* L.) production. These same studies indicate that one of the primary pathways for NO_3 to enter surface waters is through subsurface drains (tiles) that are common across the midwestern Corn Belt (Zucker and Brown 1998). Thus, it is not surprising that the area within the Mississippi River Watershed, identified by Goolsby et al. (2001) as the primary source of NO_3 to the Gulf, is the same area where corn production on artificially drained lands is prevalent.

A dual challenge associated with reducing NO_3 in the environment is the increasing demand for corn and soybean required to feed an increasing world population that is more prosperous with higher per capita meat consumption (Godfray et al. 2010). Thus, improved agricultural management systems must increase food production without degrading the environment (Chen et al. 2011). The following issues complicate this challenge, and cover crops may be part of the solution:

- improved N fertilizer management alone, such as improving synchrony between fertilizer application and spatial and temporal variability in crop demand, will not reduce NO_3 losses from drained fields sufficiently to meet water quality goals (Dinnes et al. 2002; Shanahan et al. 2008);
- increased use of N-fertilizer will be required under nearly all possible scenarios to meet increasing world-wide cereal demand (Cassman et al. 2003); and
- soil N depletion has recently been reported in the Midwest partly due to

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soil N loss through tile drainage, which may be exacerbated with trends of higher grain yields and flat fertilizer N rates (Jaynes and Karlen 2008; Gentry et al. 2009; Liu et al. 2010).

Fall-planted cover crop is a promising method for substantially reducing NO_3 contamination from artificially drained agricultural fields in the Midwest (Kaspar et al. 2007; 2008; 2012). Nitrate leaching is reduced by cover crops because N-uptake occurs in the fall and early spring, which reduces soil NO_3 susceptibility to leaching. The N sequestered by the cover crop is then released during residue decomposition and becomes available to subsequent crops (Wagger et al. 1998; Kessavalou and Walters 1999; Logsdon et al. 2002; Li et al. 2008).

Other benefits of winter cover crops include erosion control, tile flow reduction, improved infiltration, and increased soil organic matter (Kaspar and Singer 2011). Cover crops may improve the hydrology of watersheds by reducing peak stream flow/runoff and erosion through decreased surface sealing, increased infiltration, increased surface roughness, increased evapotranspiration, and increased available water storage capacity of soil (Dabney 1998; Unger and Vigil 1998; Mitchell et al. 1999; Kaspar and Singer 2011). Increased stream flow during storms contributes to increased nonpoint source pollution, increased flooding, and reduced ecological health (Yeo et al. 2004; Roy et al. 2005; Walsh et al. 2005). Surface runoff may be considered the leading cause of increased streamflow, but tile drainage can approach or exceed surface runoff amounts (Chung et al. 1992; Drury et al. 1993).

Li et al. (2008) tested the Root Zone Water Quality Model (RZWQM) using field data from one central Iowa site and concluded that RZWQM was a promising tool to estimate the relative effects of winter cover crops on NO_3 loss in tile drains. More research, however, is needed to determine the potential water quality improvement resulting from large-scale winter cover crop adoption across the artificially drained Midwest. Related to this research need, RZWQM has been used to quantify the long-term performance of drainage water management across the midwestern United States (Thorp et al. 2008). Thorp et al. (2008) used one soil in their analysis across the region. Models other than RZWQM have been used to evaluate opportunities for winter cover crops in corn–soybean systems across the Midwest using one soil, such as the biofuel potential of winter rye (*Secale cereal* L.) (Baker and Griffis 2009; Feyereisen et al. 2013).

Here, we (1) use a field tested version of RZWQM to simulate both a control treatment with no cover crop (NCC) and a cover crop treatment (CC) using fall-planted winter rye for 45 years (1961 to 2005) at 41 sites across the midwestern United States and (2) use regression analysis to quantify the most important meteorological and management factors contributing to the simulated CC effect on N loss in drainage. We simulate both NCC and CC under four field management combinations of spring tillage or no tillage, winter rye overseeded early in the fall or planted after the main crop harvest later in the fall, and continuous corn or corn–soybean rotations. We use a geographic information system (GIS) to interpolate the N reduction potential from using cover crops across the Midwest based on the results from the 41 sites. The NO_3 load reduction estimates of CC from this research are used in a companion paper by Kladivko et al. (2014 [this issue]) to determine the potential to reduce NO_3 loading to the Mississippi River.

Materials and Methods

Modeling. Li et al. (2008) successfully tested the RZWQM-Decision Support System for Agrotechnology Transfer (DSSAT) hybrid for response to a cereal rye cover crop treatment using field data from an experiment in central Iowa. This test used the winter wheat component of RZWQM-DSSAT with modified parameters as a surrogate for a cereal rye winter cover crop. Because the winter wheat component of RZWQM-DSSAT was subsequently modified, we briefly reevaluate the current model using the same field data described by Li et al. (2008). We used the recently calibrated and tested model parameterization described by Fang et al. (2012) as the base RZWQM parameterization, where RZWQM was applied to a field in an adjacent county.

Field Used to Test Model. The Boone County, Iowa, field experiment used to test RZWQM for response to winter rye was described in detail in Li et al. (2008) and Kaspar et al. (2007), and we briefly summarize it here. Predominant soils are Canisteo (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) and Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludolls). Eight 30.5 × 42.7 m (100 × 140 ft) plots were included in the experiment. Four plots included rye as the winter cover crop, and four were a control treatment without winter rye. Corn was planted in late April to mid-May of even years, and soybean planted in early to mid-May of odd years from 2000 to 2005. Split applications of fertilizer were spring applied in corn years at 235 to 247 kg N ha^{-1} (210 to 220 lb N ac^{-1}). A 7.6 cm (3 in) diameter corrugated drainage pipe was installed 1.2 m (4 ft) below the soil surface in the center of each plot. Flow rates in the drainage pipes were measured and composite samples from each plot collected for analysis of flow-weighted NO_3 concentration on a weekly or shorter basis. Soybean and corn yield were determined and grain samples were collected at harvest for protein and total N content. Above ground winter rye shoot dry matter was collected before spring termination and analyzed for N content.

Model Testing and Initialization. Model input includes meteorological data (rainfall, temperature, wind speed, solar radiation, and humidity) collected from a weather station located 5.4 km (3.4 mi) southwest of the study area. The majority of soil and carbon (C)/N cycling parameters were input from a central Iowa experiment near Story City (Fang et al. 2012). Field management, drain spacing and depth, weather, lateral hydraulic gradient, the lateral saturated conductivity (LKs), and vertical saturated conductivity by depth (Ks), were input similar to Li et al. (2008). The pore size distribution index (PSD) is a parameter required to describe the soil water retention curve. The PSD was adjusted so that total 2002 to 2005 drainage from the control treatment RZWQM simulations was similar to field measurements. For simplicity, the same PSD was used for the entire soil profile. Two parameters discussed below that affect denitrification and mineralization were adjusted to match measured N loss in tile flow from the control treatment. The winter rye treatment was not used for model calibration of soil parameters. Soil parameters are described in more detail in Fang et al. (2012).

The calibrated PSD used for all soil layers was 0.075. In comparison, Fang et al. (2012) used 0.09 (0 to 15 cm [0 to 6 in] soil depth) and 0.06 (15 to 150 cm [6 to 59 in] soil depth) for PSD input into RZWQM and Ma et al. (2007c) measured PSD of 0.06 to

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0.09 for 0 to 100 cm (0 to 39 in) for tile drained soils in northeastern Iowa.

The rate coefficient for decay of the slow organic matter pool was adjusted from the default value of 4.4×10^{-10} (unitless) to a calibrated value of 2.2×10^{-9}. The denitrification reaction rate coefficient was adjusted from the default of 1×10^{-13} to 3×10^{-14}. In comparison, Thorp et al. (2007) calibrated these same organic matter and denitrification coefficients to be 2.4×10^{-9} and 1×10^{-14} for the same Story City site of Fang et al. (2012). Therefore, our calibrated coefficients are between the default values and the calibrated values of Thorp et al. (2007).

The initial corn and soybean parameters were taken from Fang et al. (2012), which were calibrated using the Story City experiment. The default US winter wheat parameters from DSSAT were input to simulate rye growth with several parameters adjusted to match observed and assumed growth patterns and cold temperature tolerance (table 1). Winter wheat was used because RZWQM-DSSAT does not include rye as an option. The actual field seeding rates were input most years, but the fall of 2002 seeding rate was reduced to reflect poor field establishment. Simulated main crop harvest was in late September to early October, and winter rye was planted within five days of simulated harvest.

Table 1

Winter wheat cover crop parameters that were adjusted from default.

Parameter (Decision Support System for Agrotechnology Transfer acronym and units in parentheses)	Default	Input
Days at optimum vernalizing temperature required to complete vernalization (P1V)	40	50
Percentage reduction in development rate in a photoperiod 10 hour shorter than the threshold relative to that at the threshold (P1D)	50	20
Temperature response for development, leaf growth, and photosysnthesis (TRDV1, TRDV2, TRLFG, TRPHS, °C)	0	1.5
Lethal temp, 50% kill, unhardened seedling (LT50S, °C)	−6	−16
Duration of phase end juvenile to double ridges (P1, °C d)	350	300
Cold tolerance when fully hardened (LT50H, °C)	−20	−40

Indicators used for model evaluation include the relative root mean square error (RRMSE) and Nash-Sutcliffe model efficiency (NSE) using annual values, which Li et al. (2008) also used. We include a simple coefficient of determination (r^2) of the annual values to show the strength of the linear relationship because the CC flow weighted annual NO_3 concentration (FWANC) is overpredicted by RZWQM as discussed below and by Li et al. (2008):

$$NSE = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2}, \quad (1)$$

$$\text{RRMSE} = \frac{1}{\overline{O}}\sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2}, \text{ and} \quad (2)$$

$$R^2 = \left[\frac{\sum_{i=1}^{n}(P_i - \overline{P})(O_i - \overline{O})}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O})^2 \sum_{i=1}^{n}(P_i - \overline{P})^2}}\right]^2, \quad (3)$$

where O_bar and P_bar 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. The values of RRMSE and NSE when model estimates perfectly match observed data are 0 and 1, respectively. An NSE value less than zero indicate that the average of observed measurements was a better estimator than the model.

Winter Rye Simulations Across the Midwest. Our simulation study focused only on the variations of the reduction of NO_3 losses in tile drainage with a cereal rye winter cover crop compared to no cover crop. This variation in N loss reduction resulted from regional differences across the Midwest in N fertilizer application rates, weather, and main crop differences (cultivar and planting/harvest dates). Other factors that may contribute to variability in the winter rye effect, such as soils and cover crop type, were not considered (e.g., soil parameters and cover crop parameters remained constant across the region). Although assuming uniform soil properties across the region is a simplification, a mechanistic agricultural systems model is not available that has been calibrated for the range of soils on subsurface drained cropland across the region (Thorp et al. 2008). Other modeling research on cover crops also used one soil across the region (Feyereisen et al. 2013; Baker and Griffis 2009).

Historical weather data from 1961 to 1990 was obtained from the National Solar Radiation Data Base (NREL 1995) and updated through 2005 (NREL 2007). We used 41 of the 48 sites in Thorp et al. (2008). Seven sites were omitted mostly because of missing weather records after 1990: Akron, Ohio; Eau Claire, Wisconsin; Erie, Pennsylvania, Kansas City, Missouri; Lacrosse, Wisconsin; Lansing, Michigan; and Mason City, Iowa. Although RZWQM was run for each site from 1961 to 2005, the 1961 to 1969 simulation results were omitted from analysis to allow an initialization period for stabilization of the nutrient pools (Thorp et al. 2008). We then use the 1970 to 2005 model results for analysis.

Using the calibrated RZWQM for Boone County, Iowa, described above, simulations were conducted across the Midwest with both winter rye as a cover crop (CC) planted every fall and no winter rye (NCC) at each of the 41 sites. Corn was planted in even years and soybean in odd years. Subsurface drainage was included at 120 cm (47 in). Using the method described in Thorp et al. (2008), corn cultivar parameters were adjusted for each of the 41 sites so that 2001 to 2005 observed and simulated silking and maturity dates were within four days, and the maximum possible number of kernels per plant (G2) was adjusted so that yield was simulated within 3% of observed. Soybean cultivar parameters were chosen from a list of DSSAT default parameters for specific soybean maturity groups. Parameters were chosen at each of the 41 sites so that 2001 to 2005 observed and simulated maturity dates were within four days, and the maximum leaf photosynthesis rate (LFMAX) was adjusted so that soybean yield was simulated within 3% of observed. Site-specific fertilizer application rate, yield, and silking and maturity dates were from state-level National

Table 2

Median nitrogen (N) fertilizer application rates and dates for field activities for the 41 sites for the 4 winter rye treatments. Fertilizer application rate and planting date for each of the 41 sites were the same as Thorp et al. (2008) state-wide 2001 to 2006 averages (USDA 2008; USDA 2010). The values in parentheses are the 90th percentile, which are used in the regression analysis and provide a measure of the data range. For treatments 2 to 4, the rye is seeded three days after main crop RZWQM-simulated maturity to represent overseeding of rye into standing corn-soybean.

Treatment	N rate (kg N ha^{-1})	Crop	Crop planting	Harvest	Rye planting	Rye kill	Disking date	Brief description of treatment
1	165 (181)	Corn	May 3	Oct. 19	Oct. 22	Apr. 24	No til	No-till with rye seeded after
		Soy	May 22	Oct. 12	Oct. 15	May 18		corn-soybean harvest
2	165 (181)	Corn	May 3	Sept. 21	Sept. 24	Apr. 24	No till	No-till with rye overseeded after
		Soy	May 22	Sept. 20	Sept. 23	May 18		corn-soybean maturity
3	165 (181)	Corn	May 3	Sept. 21	Sept. 24	Apr. 19	Apr. 23	Spring-till with rye overseeded after
		Soy	May 22	Sept. 20	Sept. 23	May 8	May 14	corn-soybean maturity
4	202 (218)	Corn	May 3	Sept. 22	Sept. 25	Apr. 19	Apr. 23	Spring-till with rye overseeded after continuous corn maturity

Agricultural Statistics Service (NASS) data for crop development and management across the region (USDA 2010), or district-level data were used where available. The fertilizer N rate to continuous corn was assumed to be 37 kg N ha^{-1} (33 lb N ac^{-1}) greater than for corn in a corn–soybean rotation (Sawyer et al. 2006). Information on the progress of planting, crop development, and harvesting operations was obtained for growing seasons 2001 through 2005. This information was presented by NASS as the five-year average, state-level percent completion of these operations/events on a weekly basis throughout the growing season. For the 41 sites in our study, planting and harvest operations were simulated on the five-year average date at which the operations were 50% complete in each reporting area. When necessary, linear interpolation was used to find the true 50% completion date between weekly NASS estimates.

RZWQM was run for both CC and NCC at each site under 4 field managements with winter rye planted 3 days after simulated crop harvest and fertilizer applied 10 days after simulated corn emergence (table 2). Three of the treatments were a corn–soybean rotation and the fourth was continuous corn. Treatment 1 had corn and soybean harvested 28 and 22 days after simulated maturity to represent a normal harvest date. Because RZWQM can only simulate one crop at a time, treatments 2, 3, and 4 had the main crop harvested at simulated maturity and the winter rye planted 3 days later to simulate overseeding or aerial seeding. This resulted in additional growth of the winter rye, additional N uptake, and reduced N loss in drainage compared to treatment 1. Overseeding can be less reliable than planting after harvest (Fisher et al. 2011), but this effect was not simulated with RZWQM. Treatments 3 and 4 included simulated spring tillage that required an earlier winter rye termination in the spring, while treatments 1 and 2 were simulated using no tillage that allowed a later winter rye termination in the spring. The spring tillage consisted of tandem disk 8 days before soybean planting and 10 days before corn planting, and field cultivator 2 days after disking. For spring-till, winter rye was killed 15 days before corn planting and 13 days before soybean planting. For no-till, winter rye was killed 10 days before corn planting (Clark 2007; Duiker and Curran 2005) and 3 days before soybean planting. The simulated management treatments can be summarized as follows:

1. no-till, winter rye seeded at normal harvest, late winter rye spring-kill, corn–soybean;
2. no-till, winter rye overseeded at crop maturity, late winter rye spring-kill, corn–soybean;
3. spring-till, winter rye overseeded at crop maturity, early winter rye spring-kill, corn–soybean; and
4. spring-till, winter rye overseeded at crop maturity, early winter rye spring-kill, corn–corn.

These four treatments were required by Kladivko et al. (2014 [this issue]) to estimate the reduction in NO_3 loss to the Mississippi River by adding winter rye to different corn and soybean management scenarios. The RZWQM has been shown to accurately simulate N loss under different tillage and crop rotation such as continuous corn and corn–soybean (Ma et al. 2007a). Furthermore, several sources report that the model accurately responds to different fertilizer rates and long-term, year-to-year weather differences (Bakhsh et al. 2001; Thorp et al. 2007; Qi et al. 2012; Ma et al. 2007b).

Regression Analysis. To summarize the simulation results and determine the most important variables involved with the simulated CC effect on N loss in drainage, multivariate regression analysis was performed. Weather variables, N application rate, and corn yield were examined as predictors. The difference of NO_3 loss in tile flow between CC and NCC simulated by RZWQM from 1970 through 2005 was the dependent variable. The average annual value for each site/treatment combination was used for a total of 160 observations. Memphis, Tennessee, simulation results were required for the spatial analysis described below, but were not included in the regression analysis because it was an outlier and outside the five-state region of interest (Minnesota, Iowa, Illinois, Indiana, and Ohio). Weather variables included in the analysis were the sums of (1) the daily minimum and maximum temperatures from winter rye planting through December 31, when the daily average temperature ([Tmax + Tmin]^2) was greater than zero (flmint and flmaxt [°C]); (2) daily precipitation from January 1 through winter rye termination date (sprecip [cm]); (3) the fall and spring solar radiation during winter rye growth on days when average temperature was above 0°C (32°F) (flrad and sprad [MJ m^{-2}]); and (4) the fall precipitation and spring temperature variables determined similar to sprecip, flmint, and flmaxt (flprecip, spmint, and spmaxt [cm and °C]). Stepwise regression, k-fold cross-validation, and leave-one-out cross-validation were used for selection of variables. For simplicity, interactions (e.g., flmaxt × spmaxt) and variables contributing less than 0.001 to the r^2 were not included. The interactions and exponen-

Table 3

Observed (Obs) and Root Zone Water Quality Model (RZWQM) simulated results for the Boone County, Iowa, field experiment with winter rye used as the cover crop treatment. Observed flow weighted annual nitrate concentration (FWANC) is calculated by dividing average annual nitrate loss by average tile flow amount from four plots. This is slightly different from Li et al. (2008) where the average FWANC was calculated from the annual FWANC from the four plots.

	Crop constituents											
	Main crop yield (Mg ha^{-1})				Cover crop shoot dry mass (Mg ha^{-1})				Cover crop shoot N (kg N ha^{-1})			
	No cover crop		Cover crop		No cover crop		Cover crop		No cover crop		Cover crop	
Year	Obs	RZWQM	Obs	RZWQM	Obs	RZWQM	Obs	RZWQM	Obs	RZWQM	Obs	RZWQM
2002	10.5	9.9	9.5	9.8	—	—	2.4	2.4	—	—	56	58
2003	2.4	2.1	2.4	2.1	—	—	0.3	1.5	—	—	9	38
2004	11.2	11.4	11.3	11.3	—	—	1.5	2.2	—	—	49	61
2005	3.9	3.9	3.6	3.8	—	—	2.7	2.6	—	—	77	64
Average	7.0	6.8	6.7	6.8	—	—	1.7	2.2	—	—	48	55

	Water constituents											
	Tile flow amount (cm)				Flow-weighted annual nitrate concentration (mg N L^{-1})				Nitrate loss in tile flow (kg N ha^{-1})			
	No cover crops		Cover crops		No cover crops		Cover crops		No cover crops		Cover crops	
Year/statistic	Obs	RZWQM	Obs	RZWQM	Obs	RZWQM	Obs	RZWQM	Obs	RZWQM	Obs	RZWQM
2002	22.7	19.1	20.9	14.0	17.8	9.9	5.4	3.8	40.4	19.0	11.2	5.3
2003	34.6	34.7	30.2	33.1	23.4	24.1	11.2	14.4	81.1	83.6	33.9	47.7
2004	24.8	29.9	25.4	26.8	19.0	19.6	9.1	13.4	47.2	58.5	23.0	36.0
2005	17.5	20.0	14	15.3	19.7	21.3	7.9	10.8	34.4	42.5	11.1	16.5
Average	24.9	25.9	22.6	22.3	20.4	19.6	8.8	11.8	50.8	50.9	19.8	26.4
NSE	0.71	—	0.58	—	−2.76	—	−1.26	—	0.50	—	−0.18	—
r^2	0.77	—	0.79	—	0.65	—	0.90	—	0.71	—	0.92	—
RRMSE (%)	14.0	—	17.0	—	20.0	—	38.0	—	25.0	—	52.0	—

	Summary of Li et al. (2008) water constituent simulations											
	Tile flow amount (cm)				Flow-weighted annual nitrate concentration (mg N L^{-1})				Nitrate loss in tile flow (kg N ha^{-1})			
	No cover crops		Cover crops		No cover crops		Cover crops		No cover crops		Cover crops	
Statistic	Obs	RZWQM	Obs	RZWQM	Obs	RZWQM	Obs	RZWQM	Obs	RZWQM	Obs	RZWQM
Average	24.9	23.8	22.6	18.5	21.3	18.2	8.7	9.3	50.8	44.8	19.8	19.3
NSE	0.53	—	−0.01	—	−2.05	—	0.64	—	0.48	—	0.82	—
r^2	—	—	—	—	0.62	—	0.86	—	—	—	—	—
RRMSE (%)	17.0	—	27.0	—	18.0	—	15.0	—	26.0	—	20.0	—

Notes: RRMSE = relative root mean square error. NSE = Nash Sutcliffe model efficiency. NCC = no cover crop. CC = cover crop.

tial and squared functions of these variables were considered during the analysis, but an acceptable model was developed using only the linear variables.

The k-fold cross-validation was used in the event of serial correlation of variables used in the regression, where the data were split into 2 blocks of 80 observations for model calibration and 80 omitted values for model validation (GLMSELECT procedure) (SAS 2010). The data used for cross-validation were average annual 1970 to 2005 RZWQM predicted cover crop effect on N loss in tile flow (CC-NCC) and the predictands for the regression equation (predictand is the predicted value for the observations omitted from the calibration blocks of data). The equation with the final set of included variables produced the lowest predictand residual sum of squares (cross-validation PRESS statistic) and lowest mean square error (MSE) for all the steps in the regression procedure. The two validation blocks for k-fold were split alphabetically by city. This cross-validation technique is similar to Malone et al. (2009; 2010). Moran's I test for residual spatial autocorrelation was used in the final equation for each of the four treatments (see Thorp et al. 2008 for more discussion concerning Moran's I test). To test for multicollinearity among predictors, the variance inflation factor and condition index were determined.

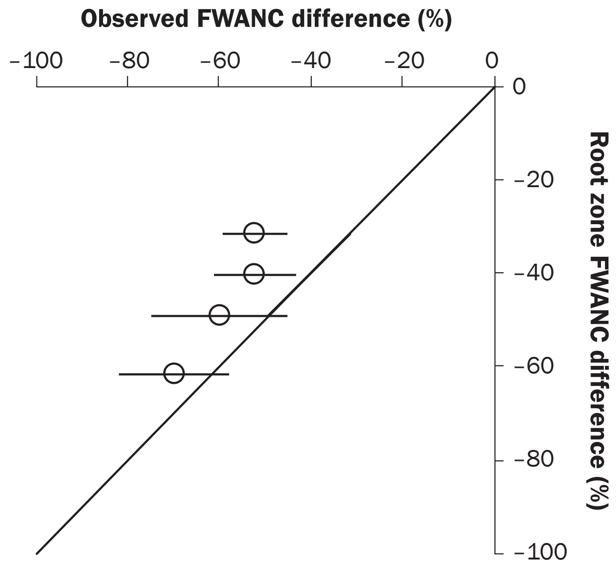
Spatial Analysis. Finally, the RZWQM simulated NO_3 reductions from using a cover crop at the 41 locations were input into a ArcMap 10.1 (Esri, Inc, Redlands, California) to graphically portray the regional results. Reductions in N losses to tile drainage were also interpolated between the 41 sites across the Midwest using an ordinary kriging routine contained with ArcMap 10.1 to estimate cover crop benefits at all locations across the Midwest.

Results and Discussion

Model Calibration and Testing. The average annual simulated tile flow and N loss in the no cover crop treatment (NCC) were 4% and

Figure 1

Flow weighted annual nitrate concentration (FWANC) (mg N L^{-1}) difference between cover crop (CC) and no cover crop (NCC). Flow weighted annual nitrate concentration difference = (CC - NCC) × 100 × NCC^{-1}. The line is $x = y$, and the error bars are the standard deviation of the observed data.



0.2% greater, respectively, than measured for the Boone County, Iowa, field site (table 3). The calibrated model estimated NCC annual tile flow and N loss in tile flow with NSE ≥ 0.50, r^2 ≥ 0.70, and RRMSE ≤ 25%. Annual corn and soybean yield was simulated within 0.3 Mg ha^{-1} of observed yield (dry basis; corn, 5.7 bu ac^{-1}; soybean, 5.1 bu ac^{-1}) every year except RZWQM underpredicted the control treatment corn yield by 0.6 Mg ha^{-1} (11.3 bu ac^{-1}) in 2002. These model performance indicators suggest that the estimated NCC annual tile flow, N loss in tile flow, and corn and soybean yield were similar to or more accurate than Li et al. (2008) (table 3).

The average annual N uptake by the winter rye cover crop treatment (CC) was overpredicted by 15%, mostly because spring of 2003 N uptake was overpredicted by 29 kg N ha^{-1} (26 lb N ac^{-1}) when field establishment was poor. Li et al. (2008) reported that RZWQM overpredicted winter rye N uptake by 21 kg N ha^{-1} (19 lb N ac^{-1}) in 2003. Excluding the 2003 results, both the observed and simulated average annual N uptake by the winter rye were 61 kg N ha^{-1} (54.4 lb N ac^{-1}), and the simulations were within 13 kg N ha^{-1} (11.6 lb N ac^{-1} or 25%) of observations each year (table 3). As discussed below, greater simulated N uptake by winter rye generally reduces N loss in drainage.

Using the calibrated soil parameters from NCC and the calibrated parameters for winter rye growth resulted in simulated tile flow to be underpredicted by 1% for CC with a NSE of 0.58 and RRMSE of 17%. Li et al. (2008) underpredicted CC tile flow by 18% with a NSE of –0.01 and RRMSE of 27%, suggesting the current calibration more accurately simulates CC tile flow.

Simulated flow weighted annual NO_3 concentration (FWANC) in tile flow was overpredicted by 26% for CC with a NSE of –1.26 and RRMSE of 38%. Simulated FWANC in tile flow was underpredicted by 6.5% for NCC with a NSE of –2.76 and RRMSE of 20%. Although both the CC and NCC NSE values suggest that the FWANC simulations were poor, the model matched the observed trend of the greatest and smallest FWANC in 2003 and 2002, respectively (table 3). Li et al. (2008) overpredicted FWANC in tile flow by 7% for CC with a NSE of 0.64 and RRMSE of 15% and overpredicted FWANC by 14.6% for NCC with a NSE of –2.05 and RRMSE is 18%. This suggests that the current calibration simulates FWANC for CC less accurately. However, Li et al. (2008) stated that the observed and RZWQM differences between CC and NCC are the most important comparisons, and the current calibration accurately responded to year-to-year FWANC treatment differences between CC and NCC (figure 1). Similar to Li et al. (2008), the current simulations did not accurately describe year-to-year FWANC variations compared to observed for both NCC and CC (table 3; NSE <0) and underpredicted the FWANC percent difference between CC and NCC each year by a fairly consistent 13% (figure 1 and table 3). Both the NCC and CC treatments for the most part simulated greater FWANC for years when the observed FWANC was greater (table 3; r^2 ≥ 0.65).

Simulated N loss in tile flow was overpredicted by 33% for CC with a NSE of –0.18 and RRMSE of 52%. As with the simulated FWANC, the simulated CC N loss in tile flow was greater for years when the observed N loss was greater (r^2 is 0.92). Li et al. (2008) underpredicted CC N loss in tile flow by 2.5% with a NSE of 0.82 and RRMSE of 20%. The current calibration is less accurate for CC N loss partly because Li et al. (2008) underpredicted tile flow amount by 18% while the current calibration only underestimated tile flow by 1%. The simulated winter rye treatment reduced N loss in tile flow by 48% compared to field observations of 61%. The annual winter rye effect was underpredicted each year except for 2002 (table 3).

Li et al. (2008) discussed that the effect of winter rye may be underpredicted because winter rye may increase immobilization of N (Parkin et al. 2006), which is poorly understood and not fully simulated by RZWQM. Another possible reason that the model overpredicts N loss in tile drainage from CC is that the high N content of the winter rye residue results in faster simulated rates of decomposition and N release from the composite surface residue pool (i.e., corn, soybean, and rye) compared to the simulated control treatment. Therefore, the simulated winter rye effect in this study is underpredicted and conservative compared to field observations.

These model-testing results from Boone County, Iowa, briefly suggest that the calibrated model performed adequately to use for our objectives. Li et al. (2008) more thoroughly discussed RZWQM performance with their main objective "to compare the simulated and observed effects of a winter cover crop on nitrate leaching in a tile-drained corn–soybean rotation." They used accepted model-testing techniques and the Boone County field experiment to conclude that "RZWQM is a promising tool to estimate the relative effects of a winter crop under different conditions on NO_3 loss in tile drains."

Table 4

Root Zone Water Quality Model (RZWQM) simulated results summary for each treatment (Trt, averaged over all 41 sites except for Memphis for years from 1970 to 2005; 1961 to 1969 results omitted to allow initialization of RZWQM simulated nutrient pools). Flmint, Spmaxt, and Sprecip are the sums of fall and spring temperature and precipitation. NCC is no cover crop and CC is cover crop. The value in parentheses is the 90 percentile, which are used in the regression analysis and provide a measure of the data range. Memphis was excluded because it was a regression analysis outlier and had little effect on the overall results due to its far southern location. Nitrogen (N) tile (% diff) is 100 × (N tile CC — N tile NCC) × (N tile NCC)$^{-1}$. Brief descriptions of treatments are (1) no-till, winter rye seeded at normal harvest, late winter rye spring-kill, corn–soybean; (2) no-till, winter rye overseeded at crop maturity, late winter rye spring-kill, corn–soybean; (3) spring-till, winter rye overseeded at crop maturity, early winter rye spring-kill, corn–soybean; and (4) spring-till, winter rye overseeded at crop maturity, early winter rye spring-kill, corn–corn.

Trt	Flmint (C°)	Spmaxt (C°)	Sprecip (cm)	Corn yield NCC (kg ha^{-1})	Corn yield CC (kg ha^{-1})	CC N uptake	N tile NCC (kg N ha^{-1})	N tile CC (kg N ha^{-1})	N tile diff. (CC-NCC)	N tile (% diff)
1	133 (284)	959 (1,382)	25 (33)	6,521 (8,114)	6,531 (8,068)	42.1	49.0	37.3	–11.7	–23.9
2	318 (582)	971 (1,382)	25 (33)	6,620 (8,127)	6,515 (8,097)	65.5	47.3	27.2	–20.1	–42.5
3	318 (582)	825 (1,236)	23 (30)	6,706 (8,246)	6,629 (8,263)	62.4	57.3	34.4	–22.9	–40.0
4	320 (694)	642 (877)	20 (28)	6,492 (8,013)	6,456 (7,985)	61.9	106	74.2	–31.8	–30.0

Root Zone Water Quality Model Simulated Winter Rye Effect on Nitrogen Loss. The model estimated average annual N loss reduction from adopting winter rye as a cover crop (CC) compared with NCC across 40 midwestern sites ranging from 23.9% to 42.5% or 11.7 to 31.8 kg N ha^{-1} (0.4 to 28.4 lb N ac^{-1}) depending on the treatment (table 4). Winter rye planted after harvest of the main crop in a corn–soybean rotation with no till (treatment 1) reduced simulated N loss in tile flow by 23.9%. By overseeding the winter rye at main crop maturity in a corn–soybean rotation with no-till (treatment 2), the winter rye reduced N loss by 42.5% relative to NCC (20.1 kg N ha^{-1} [17.9 lb N ac^{-1}]; table 4). Treatment 2 reduced N loss more than treatment 1 because winter rye was planted earlier and thus had greater simulated growth and more N uptake from the soil. Feyereisen et al. (2006b) also reported that as the planting date for rye cover crop in the fall was delayed, it was less effective at reducing N loss in subsurface drainage. Overseeding the winter rye at main crop maturity with spring tillage reduced N loss by 40% in corn–soybean and 30% in continuous corn (treatments 3 and 4). The N loss reduction amount from CC was greater under treatments 3 and 4 (22.9 and 31.8 kg N ha^{-1} [20.4 and 28.4 lb N ac^{-1}]; table 4) despite earlier winter rye termination in the spring and slightly less CC N uptake on average than treatment 2.

In general, greater simulated N uptake by winter rye reduces N loss in drainage from site to site (figure 2). Nitrogen uptake by the winter rye, however, is not the reason for tile flow N loss reduction (NLR) differences between treatments 2, 3, and 4 (table 4; columns 7 and 10, "N tile diff" and "CC N uptake"). Winter rye reduced tile flow N loss more for treatments 3 and 4 than treatment 2 but both treatments 3 and 4 had less N uptake by winter rye than treatment 2. One potential factor reducing NLR in drainage between treatments 3 and 4 is greater simulated denitrification with the combination of winter rye and continuous corn. For example, the average annual simulated denitrification in Springfield, Illinois, for CC3, NCC3, CC4, and NCC4 were 21.6, 12.8, 43.3, and 21.9 kg N ha^{-1} (19.3, 11.4, 38.6, and 19.5 lb N ac^{-1}; table 5). Therefore, denitrification was 8.8 kg N ha^{-1} (7.9 lb N ac^{-1}) greater with the winter rye (CC) compared with NCC in treatment 3 and 21.4 kg N ha^{-1} (19.1 lb N ac^{-1}) greater with CC compared to NCC in treatment 4. In contrast, Jarecki et al. (2009) observed no significant effect of a winter rye cover crop on cumulative nitrous oxide emissions in the field. Perhaps the increase in RZWQM simulated denitrification under winter rye should be increasing immobilization instead (Parkin et al. 2006), but more research is needed in this area.

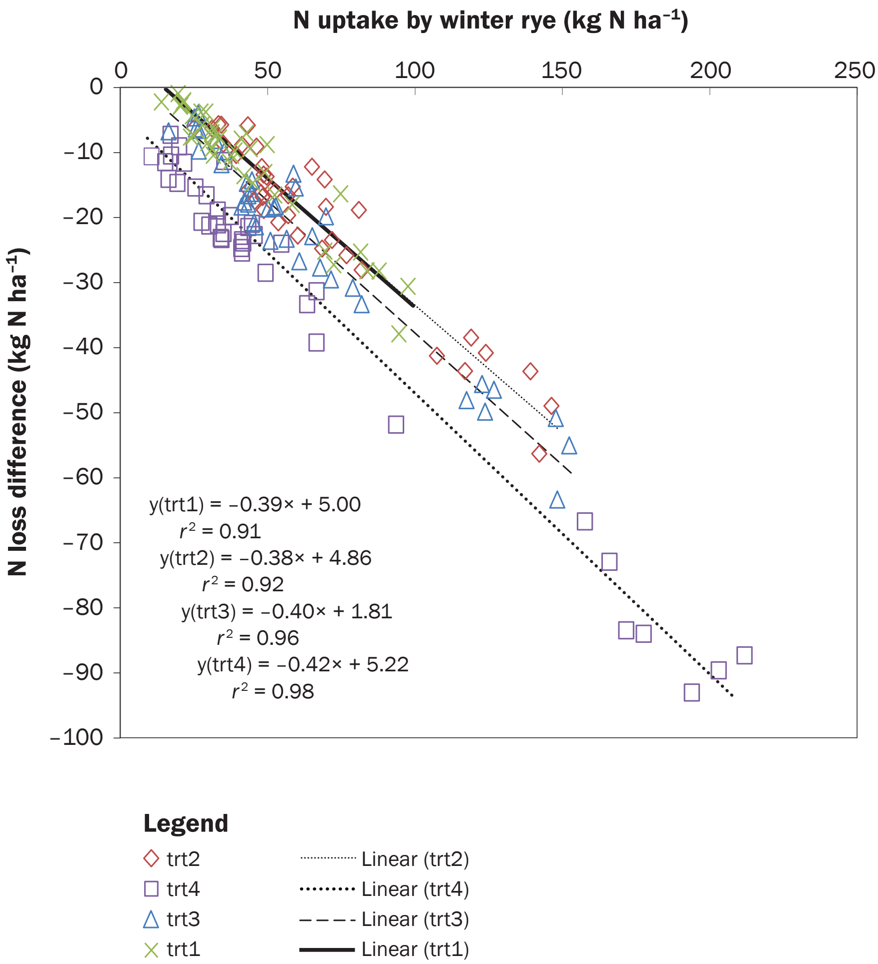
The simulated NLR difference between treatments 2 and 3 may appear small (table 4; 2.8 kg N ha^{-1} [2.5 lb N ac^{-1}]), but the regression analysis below suggests it is significant. The NLR difference between treatments 2 and 3 was not because of denitrification. Again using Springfield, Illinois, as an example, the denitrification is greater in no-till (treatment 2) and the denitrification difference between CC and NCC is nearly 4 kg N ha^{-1} (3.6 lb N ac^{-1}) greater in treatment 2 compared to 3 (table 5). Instead the Springfield NLR difference between treatments 2 and 3 is mainly because of total N uptake by the corn–soybean–rye system despite similar rye uptake and slightly less corn yield under CC (table 5). The average annual total N uptakes for CC2, NCC2, CC3, and NCC3 were 348, 270.1, 360.8, and 276.3 kg N ha^{-1} (310.5, 241, 321.9, and 246.5 lb N ac^{-1}; table 5). Therefore, total N uptakes were 84.4 and 77.9 kg N ha^{-1} (75.3 and 69.5 lb N ac^{-1}) greater with winter rye (CC) compared with NCC in treatments 3 and 2, respectively. The Springfield N uptake from rye was equal for both treatments 2 and 3 at 82 kg N ha^{-1} (73.2 lb N ac^{-1}), suggesting that the treatment 2 and 3 NLR differences are not due to different winter rye uptake. This all suggests that more RZWQM simulated N is retained in the soil from year to year in CC than NCC as reported by Li et al. (2008), which allowed more corn and soybean N uptake. The N fixation also supports greater N uptake from the soil by the soybean in the tilled and rye treatments: 97.2, 107.5, 91.2, and 102.5 kg N ha^{-1} (86.7, 95.9, 81.4, and 91.5 lb N ac^{-1}) for CC2, NCC2, CC3, and NCC3 (table 5). The tilled system had more net mineralization than no-till, thus more N fixation was required by the no-till system. RZWQM simulates greater fixation to meet soybean N demand when soil available N is insufficient (Malone and Ma 2009; Li et al. 2008).

The overall simulated N loss differences with and without winter rye are less than the Boone County, Iowa, field results (tables 3 and 4), which suggests that the N reductions modeled in this study are again on the conservative side for the Midwest. The Des Moines, Iowa, average N loss difference (e.g., 18.4 kg N ha^{-1} [16.4 lb N ac^{-1}] for treatment 2; figure 4a) is also less than the Boone County field results.

Our central Indiana model simulations appear comparable to field results in southeast Indiana reported by Kladivko et al. (2004). In that study a combination of introducing winter wheat as a cover crop, reducing the

Figure 2

Simulated average annual nitrate (NO_3) loss reduction (NLR) for the four treatments described in table 4 across 40 midwestern sites as a function of nitrogen (N) uptake by the winter rye. Nitrate loss reduction is the difference in tile flow nitrate between winter rye (CC) and no winter rye (NCC) (NLR = nitrate loss in CC — NCC).



fertilizer N rate, and changing to a corn–soybean rotation reduced NO_3 concentrations in drain flow to 8 mg N L^{-1} (8 ppm; 1997 to 1999) compared to 28 mg N L^{-1} (28 ppm; 1986 to 1988) with no winter wheat, higher N rate, and continuous corn. We simulated drain flow NO_3 concentrations of 4.9 mg N L^{-1} (4.9 ppm) with winter rye in treatment 1 (1997 to 1999) and 22.3 mg N L^{-1} (22.3 ppm) without winter rye in treatment 4 (1986 to 1988) for Indianapolis, Indiana. The concentration values of Kladivko et al. (2004) were compared rather than N loss because our simulated drain flow was much more than the field results partially due to the shallower tile depth used in the Indiana study (0.75 m [2.5 ft] compared to 1.2 m [3.9 ft] simulated here). The simulated N concentration percent difference between the two treatments and periods may be slightly greater than the field results partially because Nitrapyrin was used as a nitrification inhibitor in the early period but not in the later period when winter wheat was planted after harvest (Kladivko et al. 2004). A nitrification inhibitor was not used in our simulations.

Root Zone Water Quality Model Simulated Winter Rye Effect on Corn Yield. One concern over winter rye use is potential corn yield loss. The winter rye reduced RZWQM simulated corn yield by less than 2% compared to NCC based on N and water stress effects.

The average simulated corn yield over all 40 sites and years (1970 to 2005) is low compared to recent USDA National Agricultural Statistic Service (NASS) records (table

Table 5

Simulated annual nitrate (NO_3) budget and corn yield for cover crop (CC) and no cover crop (NCC) at Springfield, Illinois.

Treatment	Fertilizer (kg N ha−1)	Fixation (kg N ha−1)	Denitrification (kg N ha−1)	Net mineralization (kg N ha−1)	Tile drainage (kg N ha−1)	Total uptake (kg N ha−1)	Rye uptake (kg N ha−1)	Corn yield (kg ha−1)
NCC								
2	87	107.5	24.6	151.8	62.1	270.1	—	6,758
3	87	102.5	12.8	163.5	74.3	276.5	—	6,812
4	211	0	21.9	138.5	131.2	203.7	—	6,441
CC								
2	87	97.2	37	223.9	34	348	81.9	6,563
3	87	91.2	21.6	234.2	41	360.8	82	6,685
4	211	0	43.3	203	79.4	299.9	93.6	6,378

Note: Partial NO_3 budgets nearly balance for both CC and NCC. For example, ±1 kg N/ha > fertilizer + fix. – denit + net min. + rain – tile drain – uptake – runoff – volatilization. For all treatments except NCC4 which was 2.3 kg N ha−1. Average annual nitrate was 12.2 in rain, between 1 and 2 in runoff, and between 0.2 and 0.8 kg N ha−1 in volatilization. The small unaccounted for NO_3 is due to average annual soil N storage change (Li et al. 2008).

4). However, the simulated corn yield for each site was calibrated to be within 3% of observed values for 2001 to 2005. For example, the average Springfield, Illinois, simulated corn yield for CC2 (6,563 kg ha^{-1} [dry basis; 123.7 bu ac^{-1}]) is representative of the overall average of all 40 sites (table 4), where the average simulated and observed corn yield in the calibration years (2000, 2002, and 2004) are 9,456 and 9,158 kg ha^{-1} (dry basis [178.3 and 172.7 bu ac^{-1}]).

The observed Springfield, Illinois, corn yield for the even years from 1970 to 2005 is 7,375 kg ha^{-1} (USDA 2010) (Sangamon County, Illinois [139.1 bu ac^{-1}]). This suggests the model responds to the lower observed Springfield, Illinois, corn yield early in the simulation (1970 to 1999) compared to later in the simulation (2000 to 2005). The model simulates lower corn yield in the early years due to greater water stress, which could be partially due to large relative humidity increases in the central United States from 1976 to 2004 (Aiguo 2006). The annual average even year July relative humidity input for Springfield, Illinois, is 68% from 1972 to 1980 and 77% from 1996 to 2004. The average temperatures for these respective periods are 25°C and 23°C (77°F and 73°F), and the average June precipitation is 6 and 11 cm (2.4 and 4.3 in). While the increase in July relative humidity over the period is fairly clear graphically ($r^2 = 0.42$; results not shown), more scatter is associated with the July temperature and June precipitation ($r^2 = 0.17$ and 0.02). Therefore, the simulated corn yield is reasonable compared to USDA NASS records, which is important for our analysis because simulated N uptake and corn yield substantially affect N loss in drain flow (Malone and Ma 2009).

Regression and Spatial Analysis. Root Zone Water Quality Model is a complex process-based model. To explore the relationship between the simulated effect of winter rye on N loss in tile drainage and the RZWQM driving variables we developed a cross-validated regression equation. The following equation accounts for >95% (figure 3) of the site-to-site variation in average annual RZWQM simulated NLR in tile flow between CC and NCC (NLR = N loss in CC minus N loss in NCC):

$$NLR = 11.26 - 0.1107 \times NrateA - flmint \times (0.04986 + 0.01676 \times till + 0.04311 \times ccorn) + spprecip \times (0.4533 + 0.27955 \times ccorn) - 0.02489 \times spmaxt + cyield \times (7.85e-4 + 0.00146 \times ccorn), \quad (4)$$

where NrateA is the annual N application rate (kg N ha^{-1}; note that NrateA = the biennial N rate applied for the 2-year, corn–soybean rotation divided by 2 [see table 2]); till is 1 for treatments 3 and 4 and 0 for the other treatments (see table 2); ccorn is 1 for treatment 4 and 0 for the other treatments; cyield is corn yield; and flmint, spmaxt, and spprecip are the sums of fall and spring temperature and precipitation described in detail above. All variables are the average across years from 1970 to 2005 for each site/treatment combination, which are illustrated in figure 4 for treatment 2. The average and 90 percentile of all predictors except NrateA under the four treatments are listed in table 4 (flmint, spprecip, spmaxt, and cyield).

Regression diagnostics did not reveal significant multicollinearity among predictors or spatial autocorrelation among the residuals, the lack of which are assumptions associated with regression. For example, the variance inflation factor (VIF) for each of the predictors was less than 4 and the overall condition index was 4.1 when combining the type variables as a single variable in the regression development (i.e., $-0.01676 \times till \times flmint - 0.04311 \times ccorn \times flmint + 0.27955 \times ccorn \times spprecip + 0.00146 ccorn \times cyield$). Also, Moran's I test for residual spatial autocorrelation in equation 1 was insignificant for each of the four treatments ($p > 0.4$).

On a very basic level, equation 1 shows that winter rye in the rotation (CC) reduces simulated N loss more compared to NCC with greater N rates, greater cumulative temperature during winter rye growth, less precipitation during winter rye growth, less corn yield, spring tilled corn–soybean versus spring tilled continuous corn, and spring tillage versus no-till. No-till continuous corn was not a simulated treatment. The most sensitive variable involved with the RZWQM simulated winter rye effect was the sum of daily spring maximum temperature (spmaxt, figure 5). As the fall and spring temperature increase (flmint and spmaxt), NLR decreases (becomes more negative) because winter rye growth and N uptake increases (equation 1 and figure 5; note that NLR is N loss in CC minus N loss in NCC). Nitrogen loss reduction is correlated with CC N uptake from site to site (figure 2; $r^2 > 0.90$). The simple rye growth model of Feyereisen et al. (2006a) is also very sensitive to spring and fall temperature according to G. Feyereisen (personal communication, September 30, 2011).

As simulated corn yield increases, NLR increases slightly because more N uptake occurs with the corn and less N is available for uptake by the winter rye (equation 1 and figure 5) (Li et al. 2008; Malone and Ma 2009). Nitrogen loss reduction decreased with the tilled treatments because more N was available for leaching or total crop uptake in these systems as discussed above (equation 1; "N tile" from table 4; and the "RZWQM simulated winter rye effect on N loss" section). Tillage increases RZWQM simulated average annual net mineralization (e.g., by 11.7 kg N ha^{-1} [10.4 lb N ac^{-1}] for Springfield, Illinois, NCC; table 5). As NrateA increases, NLR becomes more negative because simulated N uptake by winter rye increases with more available N in the system (Li et al. 2008).

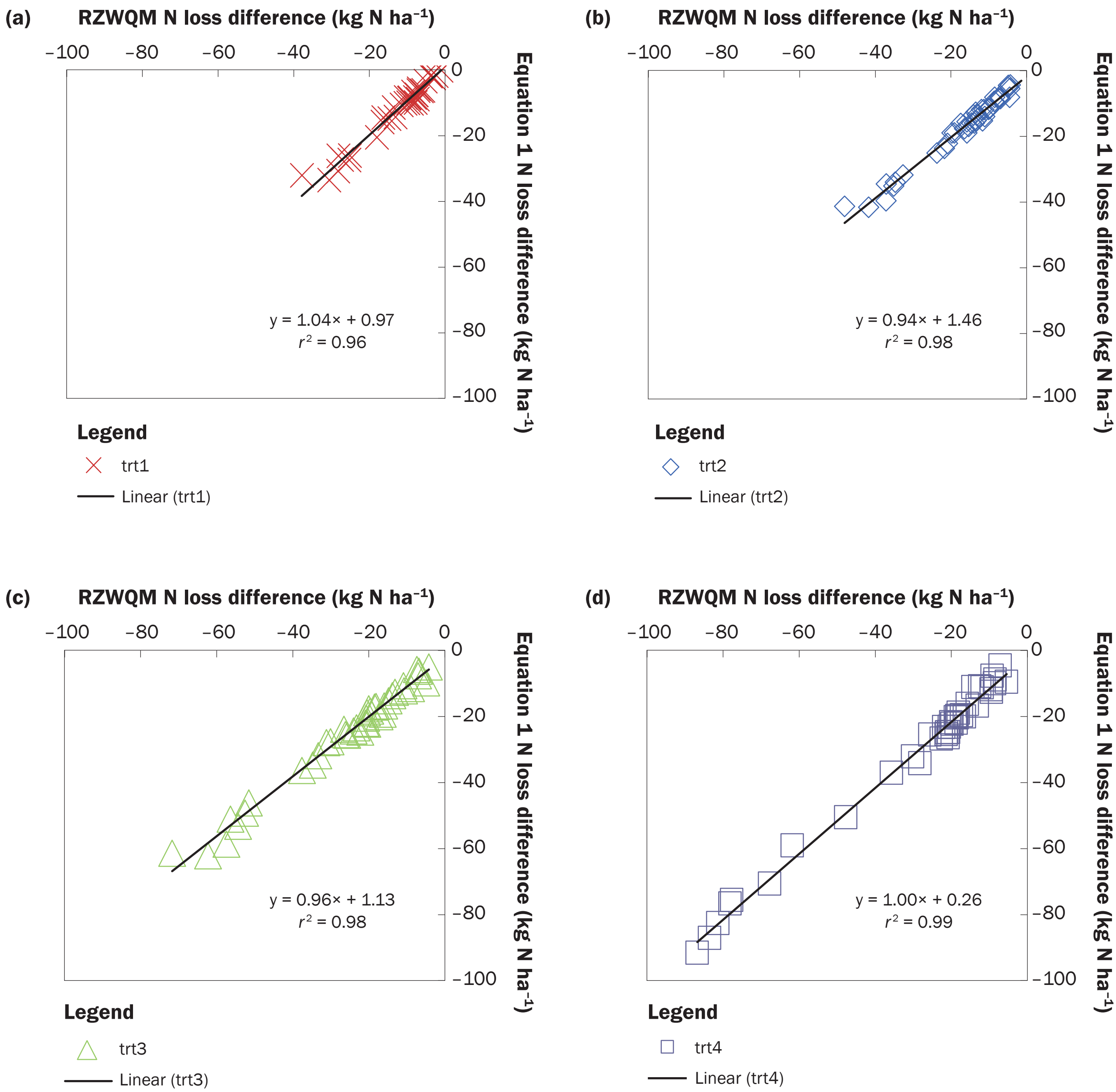
In summary, when the weather conditions favor winter rye growth and N uptake, the simulated reductions in N loss due to winter rye become larger (NLR becomes more negative). Also, when the soil NO_3 is greater because of greater N mineralization, greater N fertilizer rates (NrateA), lower corn yield, or less spring precipitation, then the winter rye has greater N uptake and the simulated reductions in N loss due to winter rye becomes larger (NLR becomes more negative).

These conditions resulted in a spatial trend across the Midwest. As an example, figure 4 shows the RZWQM simulated reduction in NO_3 loss in tile drainage for a no till corn–soybean rotation due to winter rye overseeded into the cash crop at maturity for the 40 sites (treatment 2). The interpolation of the results (that include Memphis, Tennessee) from the 41 sites across the Midwest using ArcGIS suggests that, in general, winter rye produced more biomass and was more effective in removing NO_3 from tile drainage when moving from the colder northern portion of the Midwest to the warmer southern portion. Feyereisen et al. (2013) showed a similar rye biomass trend across the Midwest.

A few perceived anomalies were noticed. For example, the simulated NLR is −18.4 vs −10.6 kg N ha^{-1} (16.4 vs 9.5 lb N ac^{-1}) in Des Moines, and Waterloo, Iowa, (figure 4). Also, the NLR is −25.8 vs −16.9 kg N ha^{-1} (23 vs 15.1 lb N ac^{-1}) in Indianapolis,

Figure 3

Comparison of Root Zone Water Quality Model (RZWQM) simulated and equation 1 predicted values of nitrate loss reduction (NLR) for (a) treatment 1, (b) treatment 2, (c) treatment 3, and (d) treatment 4 described in table 4 across 40 midwestern sites. Nitrate loss reduction is the difference in tile flow nitrate between winter rye (CC) and no winter rye (NCC) (NLR = nitrate loss in CC — NCC).



and Fort Wayne, Indiana. The NLR differences between these nearby cities are mostly because of fall and spring temperature differences with little difference in other sensitive variables such as spring precipitation (figure 4 and equation 1). The fall temperature variables (flmint) for Des Moines, Waterloo, Indianapolis, and Fort Wayne are 345.2°C, 217.2°C, 418.7°C, and 237.3°C (653°F, 423°F, 786°F, and 459°F). These trends can be confirmed using the average November minimum temperatures obtained from Climate-Zone: −1.2°C, −3.2°C, 1.2°C and 0.8°C (29.8°F, 26.2°F, 34.2°F, and 33.4°F) (http://www.climate-zone.com/). Another factor causing the large flmint difference between Indianapolis and Fort Wayne is that the planting date of the rye is 12 days later for Fort Wayne while Des Moines and Waterloo were planted within 2 days of each other. The NASS corn maturity dates used to calibrate RZWQM for Indianapolis and Fort Wayne were September 15 and 23 (from 2001 to 2005). Another perceived anomaly is

Figure 4

The 40 locations used in regression analysis: (a) average Root Zone Water Quality Model (RZWQM) simulated annual nitrate loss reduction (NLR) from planting rye in the fall under treatment 2, (b) average annual nitrogen fertilizer rate (NrateA), (c) sum of daily fall minimum temperature after rye planting (flmint), (d) sum of daily spring precipitation before rye termination (sprecip), (e) sum of daily spring maximum temperature before rye termination (spmaxt), and (f) corn yield (cyield). The interpolated NLR across the region is also presented (graduated color).

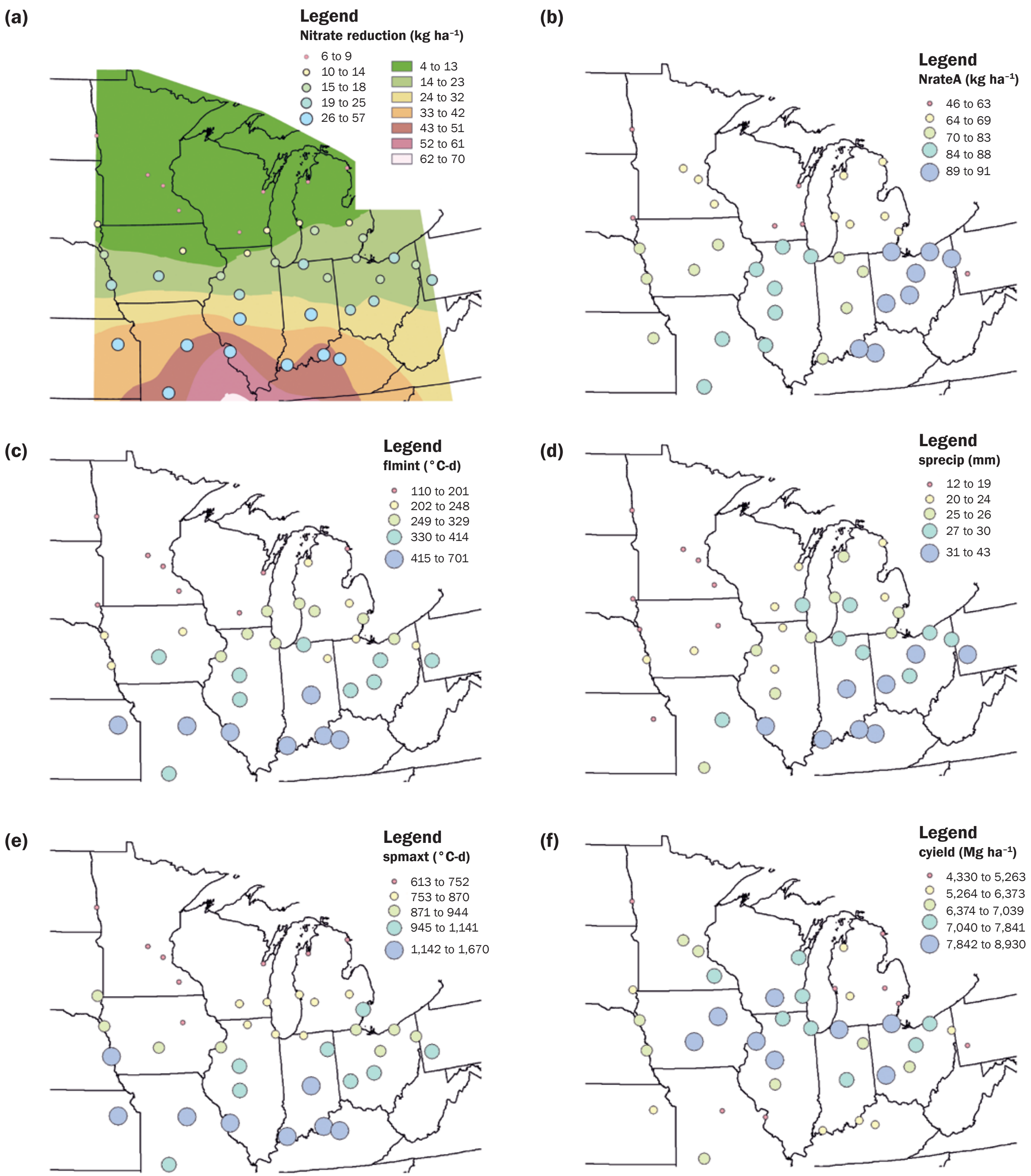
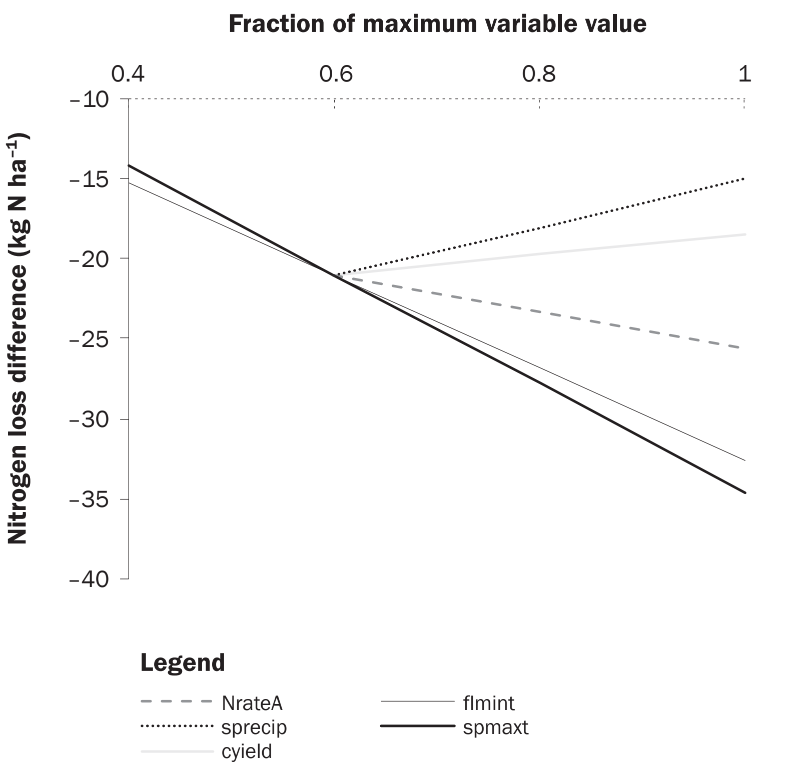


Figure 5

Winter rye effect on nitrate (NO_3) loss reduction (NLR) in subsurface drainage as a function of site to site variability as described by equation 1. Nitrate loss reduction is the Root Zone Water Quality Model (RZWQM) simulated difference in tile flow NO_3 between winter rye (CC) and no winter rye (NCC) (N loss = NO_3 loss in CC minus NCC). The management is corn–soybean with no-till. The variables are fertilizer N application rate (NrateA described in text), corn yield (cyield), and the sum of spring and fall temperature and precipitation (spmaxt, flmint, and sprecip described in detail in text). The maximum variable values for NrateA, spmaxt, flmint, sprecip, and cyield were the overall 90 percentile of the data used to develop equation 1 (105 kg N ha^{-1}, 1,382 C, 582 C, 33 cm, and 8,127 kg ha^{-1}; table 4). A portion of the curve is not shown if the fraction of the maximum variable value was not in the dataset used to develop equation 1 (e.g., NrateA of 0.4*105). The variables in equation 1 remained constant at 0.6 times the maximum variable value except for the single variable indicated. The effects of spring tillage and continuous corn are included in equation 1 but not presented here.



that Columbia, Missouri, simulated corn yield was 4,793 kg ha^{-1} (90 bu ac^{-1}; figure 4), but the NASS value for the simulated period was also low at 4,821 kg ha^{-1} (91 bu ac^{-1}).

Summary and Conclusions

Simulations of fall planted winter rye as a CC and NCC for climate conditions and common management practices across the Midwest demonstrate that CC has potential to reduce annual NO_3 loss in agricultural drain flow 42.5% or 20.1 kg N ha^{-1} (17.9 lb N ac^{-1}). This estimated reduction is for winter rye grown on tile drained lands in corn–soybean production with no-till and cover crop seeding at main crop maturity (treatment 2). The effect of CC on NO_3 loss was less under rye planted later in the fall because of lower temperatures during winter rye growth. Despite earlier spring termination of winter rye, CC reduced NO_3 loss more under continuous corn than in corn–soybean systems possibly because of more denitrification.

The modeling results were reasonable compared to observed field data and were on the conservative side. Observed NO_3 leaching losses in subsurface drainage water showed a more than twofold difference between CC and NCC in central Iowa and the calibrated model described most of the observed difference, but under predicted the effect on N loss by 33%. The model also reasonably simulated the winter cover crop effect on the N concentration in drain flow compared to field results in southeast Indiana. Although several features of the model results were probably conservative and underpredicted the NO_3 loss reduction, we assume that overseeding leads to full establishment of the winter rye, which may over predict NO_3 loss reductions. Modeling germination and establishment of winter rye cover crop has not been tested in RZWQM and needs further research.

Our simulations suggest that CC is more effective in reducing NO_3 losses in subsurface drainage in the southern part of the region. Regression analysis of the simulated results suggests that air temperature during winter rye growth is the most important variable affecting the performance of CC across the region. Precipitation, N application rate, and corn yield were also significant but less sensitive. Our simulations, however, did not account for regional variation in soil and cover crop type. The analysis of Thorp et al. (2008), Baker and Griffis (2009), and Feyereisen et al. (2013) also only considered one soil across the region. Our study also did not consider the effects of cover crop on land that is not under subsurface drainage or in rotation with crops other than corn and soybean; nor did it consider the CC effect on factors such as erosion, P losses, soil organic matter, and soil quality. Further analysis of CC considering these important factors is the next step to more fully assess the potential regional impacts of CC on the environment.

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