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Simulated N management effects on corn yield and tile-drainage nitrate loss

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Abstract

Thoroughly tested simulation models are needed to help quantify the long-term effects of agriculture. We evaluated the Root Zone Water Quality Model (RZWQM) response to different N management strategies and then used the tested model with observed weather data from 1961–2003 to quantify long-term effects on corn (*Zea mays* L.) yield and flow weighted nitrate-N concentration in subsurface "tile" drainage water (Nconc). Fourteen years (1990–2003) of field data from 30, 0.4 ha plots in northeast Iowa were available for model testing. Annual crop yield, nitrate-N loss to subsurface "tile" drainage water (Nloss), Nconc, and subsurface "tile" drainage amount (drain) for various management scenarios were averaged over plots and years to create five chemical fertilizer and five swine manure treatments. Predicted corn yield and Nconc for the 10 treatments were significantly correlated with observed data ($R^2 > 0.83$). The Root Mean Square Errors (RMSE) were 15% and 18% of its observed average Nconc for chemical fertilizer and manure treatments, respectively. Corresponding RMSEs for corn yields were 8% and 10% of its observed average corn yields for chemical fertilizer and manure treatments. The long-term simulations indicate that average corn yield plateaus and Nloss accelerates as quadratic functions of increasing spring UAN-N rates from 100 to 200 kg N/ha. Winter wheat (*Triticum aestivum* L.) sowed after corn and soybean [*Glycine max* (L.) Merr.] harvest was predicted to reduce long-term Nloss by 5 to 6 kg N/ha, which appears consistent with published field studies and may be a treatment to ameliorate agricultural management with potential for elevated Nloss such as swine manure application to soybean. The results suggest that after calibration and thorough testing, RZWQM can be used to quantify the relative effects of corn production and Nconc under several alternative management practices.

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Keywords: RZWQM; Crop rotation; Manure management; Late spring N test; Split application

1. Introduction

Quantifying conservation effects is one of the most important challenges confronting the agricultural community (Cox, 2002). Quantifying the effect of N management on subsurface drained agricultural basins is especially important because of its contribution to increased nitrate loading in the Mississippi river and subsequent effects on Gulf hypoxia (Dinnes et al., 2002). Short-term experiments allow analysis of treatments under limited conditions but are inadequate to quantify temporal variability due to climate (Keating et al., 2002). Agricultural models may be useful for filling knowledge gaps. If properly validated against short-term data, models can be helpful to objectively quantify the potential effects of conservation practices under site-specific climate and soil conditions.

Application or testing of the Root Zone Water Quality Model (RZWQM), a process-based computer simulation model, has resulted in more than 170 research publications (RZWQM publications, 2006). Some of the most thorough testing has occurred using data from Nashua, Iowa where field evaluations have included nitrate and pesticide transport under applications of swine manure, pesticide, and several tillage practices (e.g., Singh and Kanwar, 1995a, 1995b; Singh et al., 1996; Azevedo et al., 1997a; Kumar et al., 1998a, 1998b, 1999; Bakhsh et al., 1999). RZWQM has also been used to simulate long-term nitrate losses and corn yield at this site for different tillage, N rates, and N application timing (Azevedo et al., 1997b). For the most part, Azevedo et al. (1997b) used the RZWQM input parameters of Singh and Kanwar (1995b), where the model was calibrated and tested for response to observed tillage effects with 3 years of field

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data, but testing RZWQM response to N application rate and timing (e.g., split vs. single) was not an objective.

Only a few studies have attempted to thoroughly test an agricultural systems model for response to N management using field data for a specific location and then use the tested model to quantify N loss in tile flow and corn yield under different N management scenarios. Two examples are those by Malone et al. (2007a-this issue) who used the Australian Agricultural Production Systems Simulator (APSIM) to predict long-term N loss and corn yield at the Nashua site and Bakhsh et al. (2001) who quantified the short-term (1996–1999) effect of various N-application rates using RZWQM with four years of N rate data from Story City, Iowa. However, evaluation of RZWQM using long-term field data was not available in the literature. In this study, we evaluated RZWQM using the Nashua experimental site where the experiments were initiated in 1978 and had gone through three phases of treatments (1978–1992, 1993–1998, 1999–2003) (Ma et al., 2007a-this issue). Since detailed "tile" flow data were available starting in 1990, our objectives were to evaluate RZWQM for quantifying N management effects using 14 years (1990–2003) of field data from 30, 0.4 ha plots, and then to predict the even longer-term effects on corn yield and nitrate-N loss under various N management treatments using measured weather data from 1961 to 2003. Soybean yield did not respond to N treatment and thus is excluded from this study (Ma et al., 2007a-this issue).

2. Materials and methods

2.1. Site description and management

A dataset collected from 36, 0.4 ha plots located at the Iowa State University Northeast Research Station near Nashua, IA (43.0°N, 92.5°W) that included fourteen years (1990 to 2003) of weather records, crop yield, "tile" drainage volume, and nitrate-N concentration in drainage water was used for model testing.

Table 1
Treatments used to test RZWQM for response to N management[a]

Plot numbers[b]	Years[c]	Rotation[c]	Tillage[d]	N type[e]	N timing[f]	Symbol[g] (treatment number)
3 24 28	1993–98	SC	NT	UAN	Spring Split (LSNT)	UAN;LSNT;93–99 (1)
9 19	1994–99	CS	CP	UAN	Spring Split (LSNT)	UAN;LSNT;93–99 (1)
10 15 29	1994–99	CS	NT	UAN	Spring Split (LSNT)	UAN;LSNT;93–99 (1)
12 34	1993–98	SC	CP	UAN	Spring Split (LSNT)	UAN;LSNT;93–99 (1)
14 25	1993–98	SC	NT	UAN	Spring Single	UAN;single;93–99 (2)
4 18 33	1994–99	CS	CP	UAN	Spring Single	UAN; single; 93–99 (2)
2 16	1994–99	CS	NT	UAN	Spring Single	UAN; single; 93–99 (2)
6 32 36	1993–98	SC	CP	UAN	Spring Single	UAN; single;93–99 (2)
10 15 29	2000–03	CS	CP	UAN	Spring Single	UAN; single;00–03 (3)
3 24 28	2001–03	SC	CP	UAN	Spring Single	UAN; single;00–03 (3)
10 15 29	1990–93	CS	NT	AA	Spring Single	AA; single;90–93 (4)
3 24 28	1990–92	SC	NT	AA	Spring Single	AA; single;90–93 (4)
1 7	1990–93	CS	CP	AA	Spring Single	AA; single;90–93 (4)
4 18 33	1990–92	SC	CP	AA	Spring Single	AA; single;90–93 (4)
12 34	2001–03	SC	CP	UAN	Spring Split	UAN;split;00–03 (5)
9 19	2000–03	CS	CP	UAN	Spring Split	UAN;split;00–03 (5)
1 7	1994–97	CS	CP	SM	Fall Single	SMF;single;93–97[h] (6)
11 23	1993–96	SC	CP	SM	Fall Single	SMF;single;93–97[h] (6)
11 23	2001–03	SC	CP	SM	Fall Single	SMF;single;00–03 (7)
1 7	2000–03	CS	CP	SM	Fall Single	SMF;single;00–03 (7)
2 16	2000–03	CS	NT	SM	Spring Single	SMS;single;00–03 (8)
14 25	2001–03	SC	NT	SM	Spring Single	SMS;single;00–03 (8)
5 21 26	2000–03	SC	CP	SM	Fall (both corn and soy)	SMF;corn+soy;00–03 (9)
13 22 35	2002–03	CS	CP	SM	Fall (both corn and soy)	SMF;corn+soy;00–03 (9)
4 18 33	2000–03	CS	CP	SM+UAN	Fall SM; spring UAN	SMF+UANS;00–03 (10)
6 32 36	2001–03	SC	CP	SM+UAN	Fall SM; spring UAN	SMF+UANS;00–03 (10)

[a] All treatments performed on the Nashua plots were included in analysis except treatments that included continuous corn, moldboard plow, and ridge-till.

[b] All treatments had 3 replicates but some plots were omitted from analysis for reasons described by Ma et al. (2007a-this issue). Plots omitted from analysis were 8, 17, 20, 27, 30, and 31.

[c] SC is soybean in even years and corn in odd years; CS is corn in even years and soybean in odd years.

[d] NT is no-till; CP is chisel plow.

[e] UAN is urea ammonia nitrate; AA is anhydrous ammonia; SM is injected liquid swine manure; SM+UAN is swine manure and UAN.

[f] LSNT is late spring nitrate test (Blackmer et al., 1997); "Single" N application indicates spring preplant; "Split" application includes about 30 kg/ha spring preplant and larger application in late spring (around 40 days after corn planting); all N application was to corn except where indicated (plots 5, 21, 26, 13, 22, 35); swine manure treatments included application in the fall prior to both corn and soybean, application in the fall prior to corn only, and fall manure and spring UAN applied prior to corn.

[g] Ten unique symbols identify each treatment group (5 for UAN or AA and 5 for SM). Treatment were grouped by pooling the different plot replications, rotations (CS, SC), and tillage (CP, NT) with similar N type, N timing, and years (e.g., 00–03 separated from 93–99 UAN;single) (see Table 4).

[h] Plots 11 and 23 had swine manure applied in spring of 1997 rather than in fall of 1996, therefore, 1997 and 1998 data were not included in analysis for these plots. Analysis for plots 1 and 7 were terminated in 1997 to keep same time frame as plots 11 and 23.

The field research site was initiated in 1978 with tillage and cropping system (*i.e.* continuous corn and both phases of a corn/soybean rotation) treatments. From 1978–1992, moldboard plow, chisel plow, ridge-tillage, and no-tillage were compared using anhydrous ammonia (AA) as the N source for corn. From 1993 through 2003, chisel plow and no-till practices were evaluated using different N sources (swine manure, UAN, or both), times of N application (single in fall, single in spring, or split), and N rates (78 to 260 kg N/ha). Each treatment was replicated three times using a randomized complete block design. The management practices grouped to evaluate RZWQM are summarized in Table 1. Six plots were omitted from analysis because of excessively high or low drainage. These included two plots that are dominated by Clyde soil and have excessively high drainage (Ma et al., 2007a-this issue).

Overall, the soils at this site are Kenyon loam (Fine-loamy, mixed, superactive, mesic Typic Hapludolls, USDA-NRCS, 2006), Readlyn loam (Fine-loamy, mixed, superactive, mesic Aquic Hapludolls, USDA-NRCS, 2006), Floyd loam (Fine-loamy, mixed, superactive, mesic Aquic Hapludolls, USDA-NRCS, 2006), and Clyde silty clay loam (Fine-loamy, mixed, superactive, mesic Typic Endoaquolls, USDA-NRCS, 2006). All have seasonally high water tables and thus benefit from subsurface drainage.

2.2. RZWQM parameterization and calibration

Plot 25 was used for model calibration because it was one of the few plots that had water table measurements and the management was varied throughout 1978–2003 (continuous corn and corn/soybean rotation; manure and inorganic fertilizer). Calibration, parameterization, and overall performance of RZWQM for the plot have been described in detail (Ma et al., 2007a-this issue). Soil hydraulic properties were determined by collecting three intact soil cores (5.4 cm diameter; 6 cm length) from the surface and at three subsurface depths (~38 to 59 cm; 64 to 77 cm; and 94–103 cm). The surface cores were collected from within the experimental plots, but intact cores for measuring the subsurface properties were obtained for each soil (Clyde, Readlyn, Floyd, Kenyon) from representative locations outside the experimental plots. Bulk density, particle density, saturated hydraulic conductivity (Ksat), and water retention parameters (slope of decreasing soil water content with increasing negative pressure- lambda; and bubbling pressure) were similar for the Readlyn, Floyd, and Kenyon soils (Ma et al., 2007b-this issue), therefore, the values were averaged and used as model input for each plot (Table 2). Vertical Ksat for the surface 90 cm was used as input for the lateral saturated hydraulic conductivity (LKsat) because these layers were fairly insensitive to adjustment (Ma et al., 2007a-this issue). The LKsat for 90–130 cm depth and the overall lateral hydraulic gradient (LHG) for plot 25 were adjusted so that measured and simulated tile drainage and depth to water table matched. The LHG controls how much shallow groundwater is lost from the system through lateral flow below the tile drains (Ma et al., 2007b-this issue). In this study, LHG was treated as a constant and was fitted to match total “tile” flow amount from 1990 to 2003. We choose to calibrate LHG so that other soil hydraulic properties (e.g., Ksat, LKsat) remained constant from plot to plot. We had difficulty calibrating 6 of the 36 plots due to differences in soil properties and other unknown reasons (Ma et al., 2007a-this issue). Therefore, only simulation results from 30 plots were analyzed and reported in this study as in Ma et al. (2007c-this issue).

Measured soil carbon content for the surface 20 cm depth was obtained at Nashua on a regular basis, and RZWQM soil carbon and microbial pools were calibrated to match these measurements. Soil carbon and microbial pools were initialized by starting the model in 1978 and running through 1989 with observed weather data and management practices to allow several years for the pools to initialize before model output was compared with observed data beginning in 1990. Plant growth was calibrated by adjusting several parameters to achieve reasonable predictions of corn and soybean yield, leaf area, biomass, and growth stages for plot 25 measurements using 1978–2003 data. The calibrated plant growth parameters, LKsat, and soil carbon were then used for the other 29 plots since the measured soil properties were similar for all plots. The observed tile drainage was substantially different between plots and cannot be explained by management differences or measured soil property differences, so the LHG was adjusted for each plot until predicted and total observed tile flow from 1990–2003 were equivalent. Description of the LHG calibration procedure for these plots is described in Ma et al. (2007a-this issue, b-this issue). Calibrating LHG for all plots using entire time period and calibrating crop parameters for one plot using entire time period was acceptable because our objectives did not include evaluating the hydrology component

Table 2
Measured and estimated soil parameters for RZWQM input through 120 cm

Soil depth (cm)	Bulk density (g/cm^3)	Porosity	Lambda[a]	Bubbling pressure[a] (cm water)	Ksat (cm/h)	Lksat (cm/h)	Plot 25 RZWQM soil carbon in 2004 (%)	Plot 25 RZWQM soil carbon in 1978 (%)
20	1.45	0.44	0.086	−1.9	3.6	3.6	1.9	1.5
41	1.51	0.43	0.070	−4.6	6.1	6.1	0.8	0.7
50	1.51	0.43	0.070	−4.6	8.5	8.5	0.6	0.5
69	1.60	0.41	0.092	−3.3	11.5	11.5	0.4	0.3
89	1.60	0.41	0.092	−3.3	14.5	14.5	0.3	0.2
101	1.69	0.37	0.060	−4.2	1.8	9.4	0.2	0.2
120	1.80	0.33	0.060	−4.2	1.8	17.2	0.2	0.2

[a] See Ma et al. (2007c-this issue) for a mathematical description of these water retention variables. Lambda is the slope of the soil water content as a function of tension; bubbling pressure (or air entry pressure) is the pressure when air will enter saturated soil.

of the model nor did they include testing year-to-year model yield predictions. Calibration did not include adjusting parameters to achieve optimum model response to management.

2.3. RZWQM response to N management

Ma et al. (2007a-this issue) reported that the calibrated RZWQM model responded reasonably well to year-to-year climate variability, so for this evaluation we focused on comparing predicted and observed corn yield, nitrate-N loss to subsurface “tile” drainage water (Nloss), subsurface “tile” drainage (drain), flow weighted nitrate-N concentration in subsurface “tile” drainage water (Nconc) in response to five chemical–fertilizer based and five swine manure-based N management treatments (Table 1). Data for the different crop rotations (corn/soybean or soybean/corn) and tillage (no-till or chisel plow) were averaged over plots and years because our focus was on the N management response. For an evaluation of RZWQM response to tillage and crop rotation treatments, refer to Ma et al. (2007c-this issue).

2.4. Quantification of long-term N-management effects using RZWQM

After calibrating and testing RZWQM against experimental data, the model was used to quantify management effects beyond the current experimental conditions (*i.e.* longer time period and additional management options). The average annual corn yield, drain, Nloss, and Nconc were determined for 1961 through 2003 for the 22 N management practices listed in Table 3 with chisel–plow (CP) after corn harvest.

The N management scenarios included five different rates of single UAN-N applications (100–200 kg/ha); five different rates of split UAN-N applications (100–200 kg N/ha); a single 150 kg N/ha application in the spring or fall in the form of AA or UAN; rate determined using Late Spring Nitrate soil Testing (LSNT, Blackmer et al., 1997); a single 150 kg N/ha (bio-available rate) spring or fall swine manure application prior to corn; a single 150 kg N/ha spring or fall swine manure application every year prior to corn and soybean; a single 150 kg N/ha spring or fall swine manure application prior to corn and 75 kg N/ha swine manure application prior to soybean; and winter wheat cover crop to reduce N loss that was planted after both corn and soybean harvest and killed in spring prior to crop planting.

Unless stated otherwise all swine manure application is reported at the assumed bio-available rate, which is ammonia-N plus 50% of organic N (Karlen et al., 2004). The average fraction of organic N to total N in 2001 and 2002 at Nashua was approximately 0.3, which was used for the long-term simulations and is within the range of applied swine manure organic N fractions at Nashua between 1992 and 1997 (Karlen et al., 2004).

For simplicity, the winter wheat cover crop was simulated with a simple RZWQM crop growth model (quickplant). “Quickplant” simulates an annual user-defined N uptake (30 kg N/ha), maximum LAI (1.0), maximum root depth (1000 mm), maximum plant biomass (1500 kg/ha), and C/N ratio of fodder (24). The values in parentheses were used for each year of cover crop simulation. Nitrogen uptake, rooting depth, LAI, and plant biomass values were determined based on typical APSIM simulations for the Nashua site (Malone et al., 2007a-this issue). Nitrogen uptake (30 kg ha^{-1}) includes 25 kg ha^{-1} for above ground wheat biomass and 5 kg ha^{-1} for roots. Minimum winter wheat stomatal resistance input was adjusted so that RZWQM-predicted transpiration was 26 mm yr^{-1}, which is similar to the APSIM prediction (27 mm yr^{-1}). APSIM is a process-based model that varies winter wheat growth to climate and soil conditions (e.g. soil water, soil N, solar radiation, temperature). Winter wheat was planted on November 1 after corn and soybean harvest and killed on May 1 prior to corn and soybean planting.

Table 3
N-management strategies selected for long-term quantification using RZWQM

N-type[a]	N-treatment[b]	Annual N-application rate	N-application date(s)
UAN	Single preplant	100, 125, 150, 175, 200[c]	May 5
UAN	Split[d]	100, 125, 150, 175, 200	May 5 and June 14
AA	Single preplant	150	May 5
UAN	Single fall	150	Nov. 10
AA	Single fall	150	Nov. 10
UAN	LSNT determined N-rate[e]	86-206	May 5 and June 14
SM	Single preplant	150	May 5
SM	Single fall	150	Nov. 10
SM	Single fall (corn/soy)[f]	150/150	Nov. 10/ Nov. 10
SM	Single preplant (corn/soy)	150/150	May 5/ May 23
SM	Single fall (corn/soy)	150/75	Nov.10/ Nov. 10
SM	Single preplant (corn/soy)	150/75	May 5/ May 23
SM	Winter wheat cover crop (corn/soy)	150/150	May 5/ May 23
UAN	Winter wheat cover crop[g]	150	May 5

[a] UAN is urea ammonia nitrate; AA is anhydrous ammonia; SM is injected liquid swine manure.

[b] Corn was planted on May 5 of even years (1952, 1954, etc.); soybean was planted on May 23 of odd years (1951, 1953, etc.).

[c] The range of N-rates were chosen because of the actual range of UAN applied at Nashua.

[d] 30 kg N/ha applied on May 5; 70-170 kg N/ha applied on June 14.

[e] 30 kg N/ha applied on May 5; 48-167 kg N/ha applied on June 14 as Late Spring soil Nitrate Testing indicated.

[f] Swine manure applied prior to both corn/soybean.

[g] Winter wheat planted on Nov. 1 after corn and soybean harvest; winter wheat killed on May 1 prior to corn and soybean planting.

3. Results and discussion

3.1. Predicted and observed N treatment effect

The predicted corn yield and Nconc were correlated with observed data and the slopes of the observed and predicted data were significantly greater than zero at $P < 0.05$ (Table 4; $R^2 > 0.83$ for the five chemical N treatments and five swine manure N treatments). These correlations and statistically significant slopes indicate that, in general, the model accurately predicted N treatment effects. The model was less responsive to corn yield than Nconc with slopes of 0.60 and 0.25 for corn yield from fertilizer and manure (Table 4), which is mostly due to overpredicted average yield from 1993–1999 where crop damage likely occurred in 1994 and 1995 that was not simulated by RZWQM (see discussion below). The Root Mean Square Errors (RMSE) were 15% and 18% of its observed average Nconc for chemical fertilizer and manure treatments, respectively. Corresponding RMSEs for corn yields were 8% and 10% of its observed average corn yields for chemical fertilizer and manure treatments (Table 4).

The manure and chemical fertilizer treatments were evaluated separately because for swine manure application, corn yield was under-predicted relative to chemical fertilizer (Figs. 1 and 2) and RZWQM possibly overpredicted winter nitrification in manure systems as discussed below. Singer et al. (2004) concluded composted swine manure increased corn yield compared to UAN-N fertilizer, and N application rate did not appear to be responsible for the yield difference. Liquid swine manure was also reported to produce higher corn yield than chemical fertilizer (McGonigle and Beauchamp, 2004) when early June mineral N levels were similar. Further support for separate evaluation of manure and chemical fertilizer is that relationship between RZWQM predicted corn yield and observed corn yield for the two fertilizer methods have significantly different regression coefficients using the “dummy” variable technique ($P<0.05$)

$$\mathrm{Cyield\_P} = 3591 + 0.60^{*}\mathrm{Cyield\_O} + 2923^{*}\mathrm{manure} - 0.35^{*}\mathrm{manure}^{*}\mathrm{Cyield\_O}$$

where Cyield_P is one of the 10 RZWQM corn yield predictions for manure or chemical fertilizer; Cyield_O is observed corn yield; and manure = 1 for manure fertilizer and manure = 0 for chemical fertilizer (see Table 4).

3.1.1. LSNT and split N application

On average, the LSNT observed and predicted corn yield and Nconc were higher than the single N application treatments (Table 4; observed and predicted yield differences are +13% and +10%; Nconc differences are +10% and +54%). The differences are partly due to higher N application rates on the LSNT treatments during the period 1993–1999. Observed and predicted corn yield was slightly higher and Nloss lower for the single N application plots (2000–2003) compared to the split N application plots with similar overall N application rates

Table 4
Observed (OBS) and RZWQM results for the pooled treatments (see Table 1)

Pooled N-treatment [a]	N-rate [b] (kg N/ha)	Corn yield OBS (kg/ha)	RZWQM (kg/ha)	Nloss [c] OBS (kg N/ha)	RZWQM (kg N/ha)	Drain OBS (cm)	RZWQM (cm)	Nconc OBS (mg N/L)	RZWQM (mg N/L)
Chemical fertilizer treatments									
AA;single;90–93	168(168–168)	8515	8866	27.4	30.8	17.7	16.5	15.4	18.7
UAN;LSNT;93–99	165(78–206)	7091	7988	15.4	20.1	13.7	13.7	11.2	14.6
UAN;single;93–99	110(110–112)	6279	7235	15.3	14.9	14.9	15.7	10.2	9.5
UAN;single;00–03	168(168–168)	8882	8774	9.0	8.8	4.9	4.6	18.2	19.1
UAN;split;00–03	172(168–184)	8628	8705	15.3	12.3	8.1	6.1	18.8	20.1
Average		7879	8313	16.5	17.4	11.9	11.3	14.8	16.4
Slope [d]		0.60	*0.24*	1.21	*0.76*	1.05	*0.37*	1.02	*0.80*
Intercept [d]		3591.2	*1908.3*	−2.6	*13.4*	−1.1	*4.7*	1.3	*12.2*
R^2		0.95		0.90		0.96		0.84	
RMSE		609.7		2.9		1.1		2.2	
Manure treatments									
SMF;single;93–97	153(80–251)	6317	8084	16.9	19.9	11.4	10.7	14.8	18.6
SMF;single;00–03	159(120–224)	9348	8626	13.0	9.9	6.1	5.4	21.3	18.5
SMS;single;00–03	160(116–203)	8800	8800	11.7	9.2	9.4	7.5	12.4	12.2
SMF;corn + soy;00–03	188(131–245)	9494	9030	15.2	19.0	4.7	4.9	32.3	38.5
SMF + UANS;00–03	160(149–177)	8916	8756	7.4	8.3	4.5	4.6	16.6	17.9
Average		8575	8659	12.8	13.3	7.2	6.6	19.5	21.1
Slope [d]		0.25	*0.20*	1.36	*1.44*	0.81	*0.38*	1.22	*0.71*
Intercept [d]		6514.2	*1722.3*	−4.2	*19.0*	0.8	*2.9*	−2.7	*14.7*
R^2		0.84		0.75		0.94		0.91	
RMSE		881.7		2.8		1.0		3.5	

[a] AA is anhydrous ammonia; single is single preplant N-application; 90–93 indicates 1990–1993; UAN is urea-ammonia-nitrate; LSNT indicates late spring soil nitrate testing to determine N rate; 93–99 indicates 1993–1999; split indicates a small preplant and greater late spring application; 00–03 indicates 2000–2003; SMF is fall injected liquid swine manure; corn + soy is N application to both corn and soybean; SMF + UANS indicates fall injected swine manure and spring applied UAN-N applications.

[b] Average (minimum-maximum). The reported swine manure N application is the sum of inorganic N in swine manure plus half the organic N in the manure. The calculated value for swine manure N rate was an estimate of the bio-available N to the crop. The RZWQM input included the total N in swine manure because the model estimates mineralization from organic matter in swine manure.

[c] Nloss is average annual nitrate-N loss to subsurface “tile” drainage water, Nconc is annual flow weighted nitrate-N concentration in subsurface “tile” drainage water, and drain is average annual subsurface “tile” drainage.

[d] The underlined value in *italics* to the right of the slope or intercept of RZWQM vs. OBS yield, Nloss, drain, and Nconc is the ±95% confidence interval. Therefore, the slope of chemical fertilizer RZWQM and OBS Nconc is 1.02 ± *0.80*.

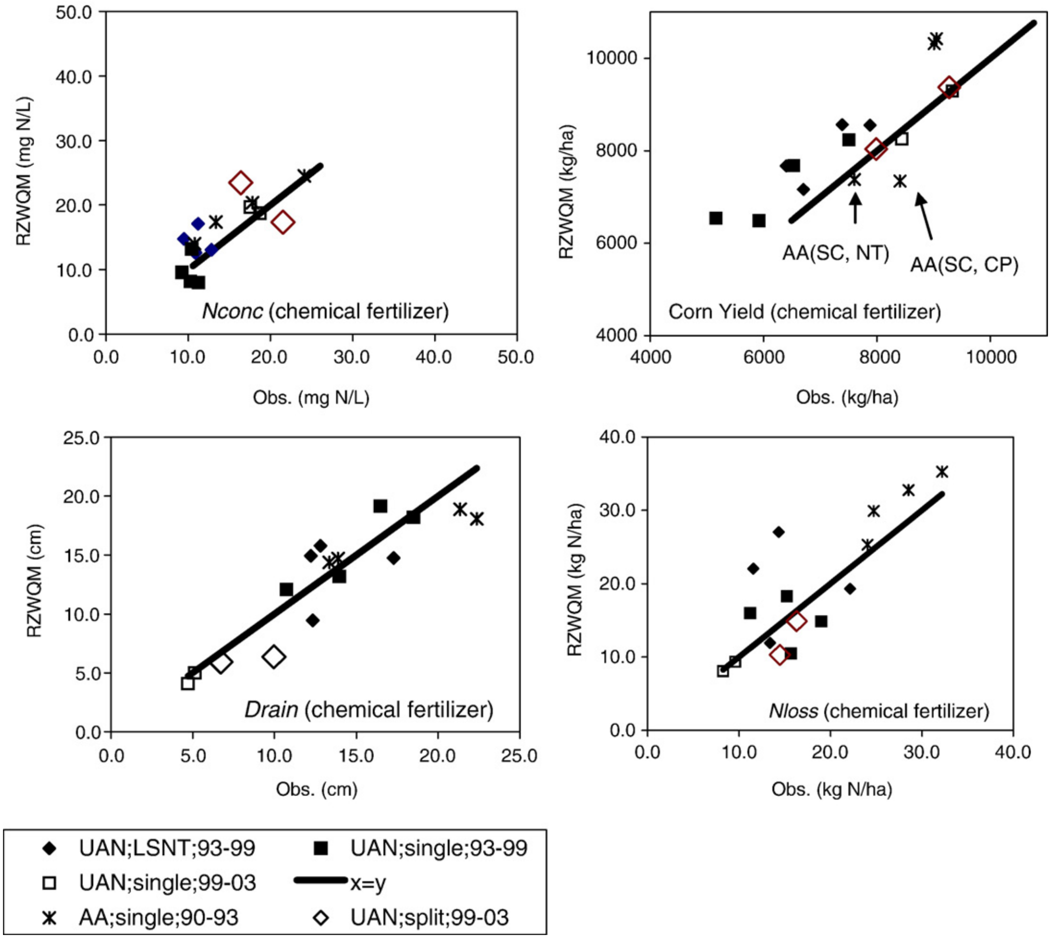

Fig. 1. Chemical fertilizer annual flow weighted nitrate-N concentration in subsurface "tile" drainage water (Nconc), corn yield, "tile" drainage amount (drain), and average annual nitrate-N loss to subsurface "tile" drainage water (Nloss). The different data points for a single treatment group (e.g., UAN;LSNT;1993–1999) includes an observation for different tillage and crop rotations (e.g., chisel and no-till; corn–soybean and soybean–corn — see Table 1). AA indicates anhydrous ammonia; CS indicates corn in even years and soybean in odd years; SC indicates soybean in even years and corn in odd years; NT indicates no-till; CP indicates chisel–plow.

(Table 4; observed and predicted Nloss differences are −41% and −28%). Over the long-term, however, split N and single preplant N application were predicted to produce nearly equivalent Nloss and corn yield at equivalent annual N rates (Table 5; Fig. 3). The observed and predicted higher Nloss under the split N application (2000–2003) is mostly because of higher average drainage (Nloss is a function of the product of Nconc and drain). The predicted and observed Nconc difference between split and single N application plots (2000–2003) was less than 6% whereas the drain difference was greater than 25% (Table 4). The predicted and observed corn yield difference between split and single N application treatments (2000–2003) was less than 3% (Table 4).

3.1.2. Anhydrous ammonia (AA) N application

The AA (1990–1993) treatments observed and predicted Nloss was more than 10 kg N/ha higher than the other four chemical fertilizer treatments (Table 4) because drought conditions in 1988 and 1989 reduced crop yield and produced no drain resulting in high soil N in 1990 and 1991 (Bjorneberg et al., 1996). Corn yield was generally over-predicted for chemical-N treatment groups except for the soybean/corn, chisel plow, AA treatment [AA(SC, CP), Fig. 1]. However, that treatment included only 1991 data (Table 1). The AA(SC, NT) corn yield was more accurately predicted because observed yield for NT was lower than CP (8404 vs. 7599 kg ha^{-1}). RZWQM predicted nearly identical yield between AA(SC, CP) and AA(SC, NT) (7343 and 7378 kg ha^{-1}). This agreed with Ma et al. (2007c-this issue), who reported that RZWQM did not accurately predict the yield differences between NT and CP.

3.1.3. Fall swine manure application to corn

Fall application of swine manure in 1993–1997 had lower observed and predicted corn yield than 00–03 from the same set of plots (1, 7, 11, 23; Table 1), partly because of the low reported bio-available N application rates in 1993–1997 (Table 4). In fact, the lowest observed and predicted overall corn yields among the five swine manure treatments were for fall application in 1993–1997 when the lowest reported bio-available N rates were applied (as low as 80 kg N/ha; Table 4). The low N application rates in 1993 and 1996 (<90 kg N/ha) affect crop production more than the high application rates in 1994 and 1995 (>200 kg N/ha) because increasing crop yield plateaus with increasing N rates as discussed below.

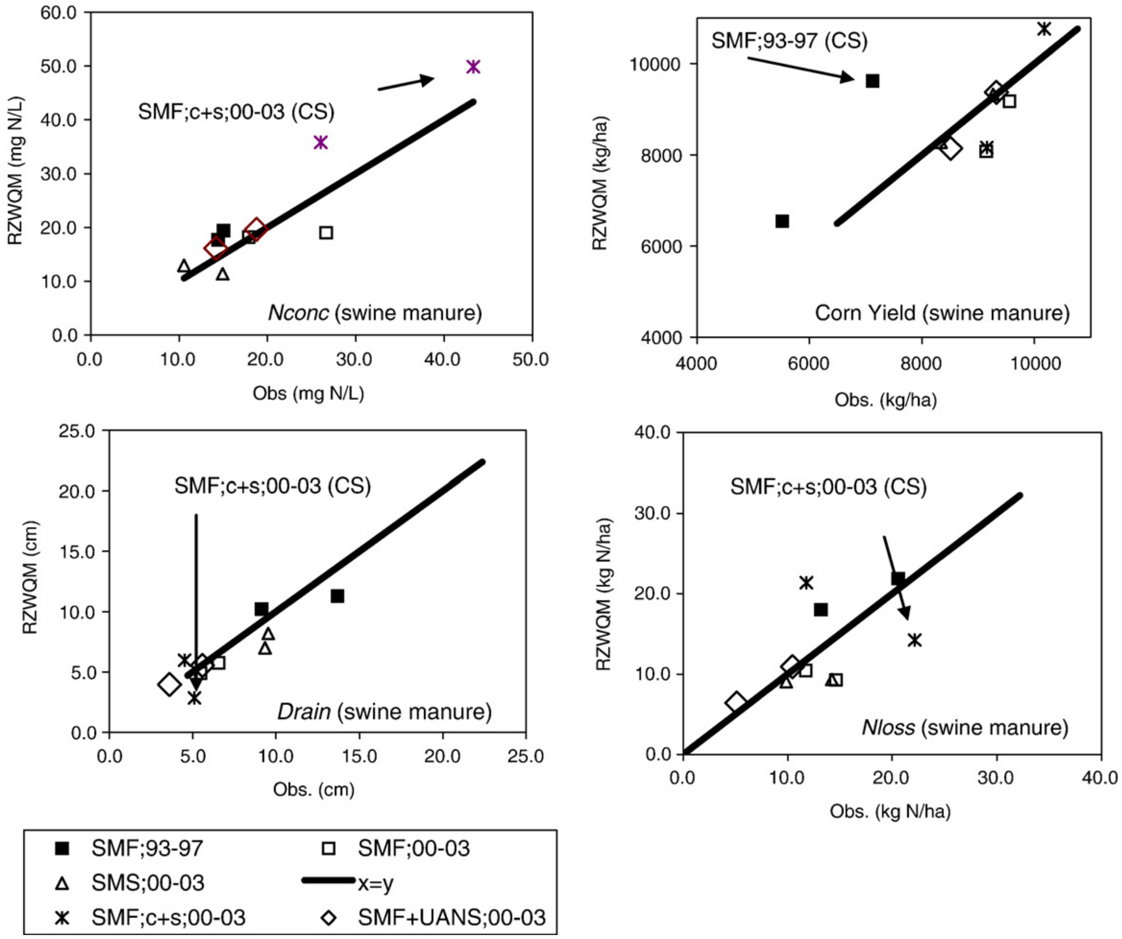

Fig. 2. Injected swine manure annual flow weighted nitrate-N concentration in subsurface “tile” drainage water (Nconc), corn yield, “tile” drainage amount (drain), and average annual nitrate-N loss to subsurface “tile” drainage water (Nloss). The different data points for a single treatment group (e.g., SMF;1993-1997) includes an observation for different tillage and crop rotations (e.g., chisel and no-till; corn–soybean and soybean–corn — see Table 1). SMF indicates swine manure injected in the fall; SMS indicates swine manure injected in the spring; UANS indicates UAN applied in the spring; c+s indicates swine manure applied to both corn and soybean; CS indicates corn in even years and soybean in odd years.

Unreported crop damage may contribute to the low observed (and overpredicted) corn yields in 93–97 because in 1994 the ratio of average experiment station to average county corn yield (0.88) is similar to the 1995 value of 0.78 when hail damage was reported. The average ratio of experiment station to county corn yield between 1996 and 2002 was 1.11 with the lowest ratio being 1.05. Unreported crop damage in 1994 may also explain the 2500 kg/ha over-predicted corn yield for the corn–soybean phase of this treatment (Fig. 2).

In contrast to the yield data, the observed and predicted Nloss was greater in 1993–1997 than 2000–2003 despite slightly lower average reported bio-available N rate in 1993–1997 (153 and 159 kg N/ha; Table 4). Bio-available N rate at Nashua was assumed to be the sum of inorganic N plus half of the organic N in manure, which may be an underestimate (Karlen et al., 2004). Removing organic N from swine manure simulations of Plot 1 and comparing to original plot 1 simulations reveals that RZWQM also computes about half of swine manure organic N mineralization within a year of fall application at Nashua. If calculated bio-available N is an underestimate, 1993–1997 is especially susceptible to error because organic N was 63% of total N rate for plots 1, 7, 11, and 23 while in 2000–2003 organic N was 30% of total N rate. Therefore, the 1993–1997 N-rate for manure reported in Table 4 may be low relative to the other four manure treatments.

3.1.4. Spring swine manure application to corn

With similar bio-available N rates (approximately 160 kg N ha^{-1}), observed and predicted spring injected swine manure (2000–2003) produced lower Nconc than 2000–2003 fall injected swine manure (Table 4; observed and predicted differences are −41% and −34%). The model, however, did not predict the lower corn yield with spring compared to fall swine manure applications (Table 4; observed and predicted differences are −6% and +2%). The spring applied swine manure plots (2000–2003) were no-till while the fall applied swine manure plots (2000–2003) were chisel plow (Table 1). Ma et al. (2007c-this issue) reported that RZWQM did not accurately predict lower observed corn yield on no-till compared to chisel plow, which complicates the analysis of the model predictions of swine manure applied in the spring and fall (SMS vs. SMF) at Nashua Iowa.

Table 5
RZWQM predictions for selected long-term treatments (1961–2003)

N type[a]	N rate[b] (kg N/ha)	N mgmt.[c]	Drain[d] (cm)	Nloss[d] (kg N/ha)	Corn yield (kg/ha)	Nconc[d] (mg NiL)
UAN	100	Preplant	11.3	11.0	7777	9.7
UAN	125	Preplant	11.3	13.4	8115	11.9
UAN	150	Preplant	11.4	16.0	8417	14.1
UAN	175	Preplant	11.4	19.0	8612	16.7
UAN	200	Preplant	11.4	22.0	8750	19.3
UAN	150	Fall	11.3	18.7	8088	16.5
AA	150	Fall	11.3	18.3	8341	16.1
AA	150	Preplant	11.4	16.7	8361	14.6
UAN	100	Split	11.3	11.4	7803	10.1
UAN	125	Split	11.3	13.9	8138	12.3
UAN	150	Split	11.4	16.7	8357	14.7
UAN	175	Split	11.4	19.6	8584	17.3
UAN	200	Split	11.4	22.9	8719	20.1
UAN	144	LSNT	11.3	16.3	8250	14.3
SM	150	Preplant	11.4	16.4	8409	14.4
SM	150/150	Preplant	11.3	24.8	8556	21.9
SM	150/75	Preplant	11.3	19.2	8482	17.0
SM	150	Fall	11.3	18.0	8284	15.9
SM	150/150	Fall	11.2	37.2	8306	33.3
SM	150/75	Fall	11.3	27.6	8235	24.5
UAN	150	Pre_cover	10.7	11.1	8268	10.4
SM	150/150	Pre_cover	10.6	19.3	8483	18.2

[a] UAN is urea ammonia nitrate; AA is anhydrous ammonia; SM is injected liquid swine manure.

[b] A single rate indicates N application to corn only; two rates in a single row indicates N application to both corn and soybean.

[c] Preplant is single spring N application; fall is November 10 N application; split is 30 kg N/ha applied on May 5 and a higher N application on June 14; LSNT includes a 30 kg N/ha application on May 5 and late spring soil testing to determine June 14 N rate (Blackmer et al., 1997); pre_cover is single spring N application and winter wheat cover crop with annual N uptake of 30 kg N/ha, maximum LAI of 1.0, maximum root depth of 1000 mm, maximum plant biomass of 1500 kg/ha, C/N ratio of fodder of 24, and average winter wheat transpiration of 27 mm.

[d] Nloss is average annual nitrate-N loss to subsurface “tile” drainage water, Nconc is annual flow weighted nitrate-N concentration in subsurface “tile” drainage water, and drain is average annual subsurface “tile” drainage.

3.1.5. Fall swine manure application to corn and soybean

The observed and predicted Nconc were more than 10 mg N/L higher on plots with N applied to both corn and soybean than on the other four swine manure treatments where N was not applied to soybean (Table 4). The observed and predicted corn yields were also highest on this treatment, partly because they received the highest bio-available N application to corn (188 kg ha^{-1}; Table 4). Two of the poorest Nloss predictions under swine manure application were for this treatment, where the average Nloss was under-predicted by −8 kg N/ha for the corn–soybean (CS) phase and over-predicted by nearly +10 kg N/ha for the SC phase (Fig. 2). The poor Nloss predictions for this treatment were caused in large part by poorly predicted drainage compared to field observations (-44% for CS and +32% for SC; Fig. 2); Nconc was over-predicted for both CS and SC (+15% and +37%; Fig. 2). Over-predicted Nconc could result from RZWQM over-predicted winter nitrification (Ma et al., 2007a-this issue; 1998), which may be especially problematic under fall injected swine manure application to soybean as discussed below.

3.2. Predicted long-term N treatment effect (1961-2003)

Nitrate loss in the U.S. Corn/Soybean Belt is influenced more by N management than tillage (Randall and Mulla, 2001). For the most part, RZWQM accurately predicted the N management effects at Nashua (Table 4), therefore, Nloss and corn yield were simulated for 22 different long-term N treatments (Tables 3 and 5). The average N application rate at Nashua was approximately 150 kg N/ha (Table 4). Considering this application rate as the base scenario, average predicted corn yield and Nloss over 43 years at Nashua are 8417 kg ha^{-1} and 14.1 kg N ha^{-1} for UAN spring preplant (Table 5).

3.2.1. UAN and AA fall N application

Corn yield was predicted to decrease −4% and Nloss was predicted to increase +16% for fall UAN application compared to spring preplant UAN (Table 5). Corn yield was predicted to decrease <1% and N loss was predicted to increase +9% for fall AA application compared to spring preplant AA (Table 5). Little Nloss or corn yield difference was predicted between AA and UAN at 150 kg N ha^{-1} (spring preplant or fall application; ≤4% difference; Table 5), but urea is generally considered inferior to anhydrous when fall applied (Randall and Schmitt, 1993). Randall and Vetsch (2005a, b) reported 7% higher corn yield and 14% lower Nloss with 135 kg N ha^{-1} spring AA compared to fall AA application in Southern Minnesota

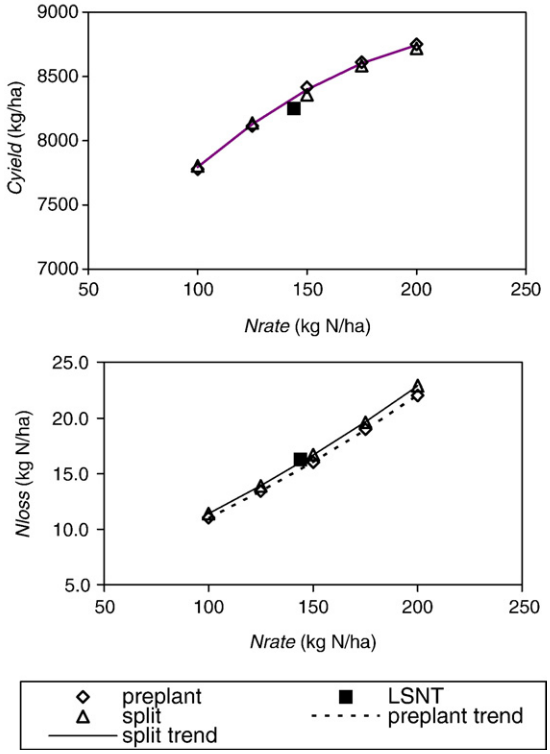

Fig. 3. Average long-term (1961-2003) RZWQM predicted annual nitrate-N loss to subsurface “tile” drainage water (Nloss) and corn yield (Cyield) under five single, five split, and yearly LSNT determined (average=145 kg N/ha) N application rates (Nrate). The trend lines were computed using equations 1 and 2. “preplant” indicates single spring N application and split indicates split spring N application.

(Randall and Vetsch, 2005a, b). If RZWQM over-predicts winter nitrification (Ma et al., 2007a-this issue; 1998), the benefit of fall AA compared to fall UAN to reduce Nloss and increase corn yield is under-predicted and the difference between fall and spring AA Nloss is over-predicted.

3.2.2. Different rates of split and single N application

Corn yield was not predicted to change and the Nloss was predicted to be slightly higher under split N application than single application (Fig. 3). Randall et al. (2003) also reported equal or greater Nloss with split spring 150 kg N/ha AA application compared to single spring AA application. The corn yield increase with increasing N rate was predicted to plateau as application approached 200 kg N/ha and the Nloss was predicted to accelerate as N rate increased (Fig. 3). The long-term predicted Nloss and corn yield trends with increasing N rates are functions of simple polynomial equations (variable inclusion of $P<0.05$):

$$\mathrm{Nloss} = 3.71 + 0.0540^{*}\mathrm{Nrate} + 0.00415^{*}\mathrm{Ntime}^{*}\mathrm{Nrate} + 0.000189^{*}\mathrm{Nrate}^{2} \qquad \left(R^{2} = 1.00\right) \tag{1}$$

$$\mathrm{Cyield} = 5819 + 24.9^{*}\mathrm{Nrate} - 0.0513^{*}\mathrm{Nrate}^{2} \qquad \left(R^{2} = 1.00\right) \tag{2}$$

where Nloss is the average long-term (1961–2003) RZWQM predicted N loss in tile drains (kg N/ha); Nrate is the annual N application rate (kg N ha^{-1}); Cyield is annual average corn yield (kg ha^{-1}), and Ntime = 1 for split and Ntime = 0 for single. The inclusion of Ntime (or dummy variable; $P<0.05$) in the regression equations suggest that the split and single N application result in significantly different RZWQM predicted Nloss over the long-term, although the average annual Nloss difference is only 0.6 kg N ha^{-1} at an application rate of 150 kg N ha^{-1}. The field data from Nashua suggest that split UAN-N applications of 150 kg N ha^{-1} may result in 3.3 kg N ha^{-1} lower annual Nloss compared to single N application (Malone et al., 2007b-this issue). Field research in Minnesota of the U.S. suggests that split spring applications may result in higher Nloss than single preplant application at equivalent rates (Randall et al., 2003). Therefore, field research is mixed concerning Nloss from split vs. single N application in the spring. The RZWQM predictions suggest that split application may slightly increase Nloss compared to single preplant application, but more research is necessary to confidently quantify the difference between these treatments.

The RZWQM long-term predicted corn yield and Nloss increase with increasing N rates (Fig. 3) agree with polynomial equations developed from 1994–2003 field observations at Nashua (Malone et al., 2007b-this issue). The average RZWQM predicted corn yield increase (from the long-term scenarios) for 1994, 1996, 1998, 2000, and 2002 with N rates of 100–200 kg N/ha is higher than the polynomial equations developed from the observations (Malone et al., 2007b-this issue) by around 300–400 kg/ha but the RZWQM-predicted and observed trends with increasing N rate are approximately parallel at rates over 100 kg N/ha (Fig. 4). The average RZWQM predicted Nloss increase (from the long-term scenarios) with increasing N rates using 1994–2003 weather, however, is over-predicted compared to observations (Fig. 4). Comparing 1993–1999 preplant and LSNT treatments where average N rate difference was more than 50 kg N/ha supports that the model over-predicts the effect of higher N rates on Nconc because the observed and RZWQM predicted differences are <1 and >3 mg N/L (Table 4). Over-predicted N in corn grain for low corn yield (Ma et al., 2007a-this issue) may contribute to over-predicted Nloss increase with increasing N rate. For example the corn–soybean rotation for 1994, 1996 and 1998 averaged: at 110 kg N/ha application rate (preplant), 116 kg N/ha RZWQM predicted removal in grain (preplant) compared to 104 kg N/ha observed removal in grain (preplant); at 177 kg N/ha application rate (LSNT), 128 kg N/ha RZWQM predicted removal in grain (LSNT) compared to 126 kg N/ha observed removal in grain (LSNT). Therefore, RZWQM over-predicted N removal in grain by about 12% for low N application and 2% for high N application.

3.2.3. LSNT

Late spring soil nitrate testing (Blackmer et al., 1997) to determine annual N application rate was predicted to produce slightly higher Nloss and lower corn yield to the split N application with similar rates (Fig. 4). RZWQM currently allows only UAN-N application with a nitrification inhibitor (N-serve) when using the LSNT option to determine N rate. The model was run twice: once to determine soil testing N rate then with the model determined UAN-N rate without nitrification inhibitor. Predicted corn yield and Nloss differences between split and LSNT treatments increased as N rate differences increased according to the equations (Fig. 5)

$$\mathrm{Nloss\_diff} = 0.085^{*}\left(\mathrm{Nrate\_diff}\right) - 0.18 \qquad R^{2} = 0.52 \tag{3}$$

$$\mathrm{Cyield\_diff} = 9.0^{*}\left(\mathrm{Nrate\_diff}\right) + 76.0 \qquad R^{2} = 0.49 \tag{4}$$

where Nloss_diff (kg N ha^{-1}), Cyield_diff (kg ha^{-1}), and Nrate_diff (kg N ha^{-1}) are the differences between split and LSNT treatments (split- LSNT). The Nloss_diff is the average between corn and the following soybean year. Watershed-scale research in Iowa reported nitrate concentration of 11.3 mg N L^{-1} for LSNT compared to 16.0 mg N L^{-1} for higher N application in the fall of 1999 and 2000 (Jaynes et al., 2004). Our long-term modeling results suggest that the fall applied AA compared to LSNT with average application rates of approximately 150 kg N ha^{-1} increases Nconc from 14.2 to 16.7 mg N L^{-1} but has minimal affect on corn yield (Table 5).

3.2.4. Swine manure spring application

Spring application of swine manure at bio-available rates of 150 kg N/ha result in similar long-term predicted corn yield and Nloss as preplant application of AA (<2% difference; Table 5). Applying preplant swine manure to corn and soybean at 150 kg N/

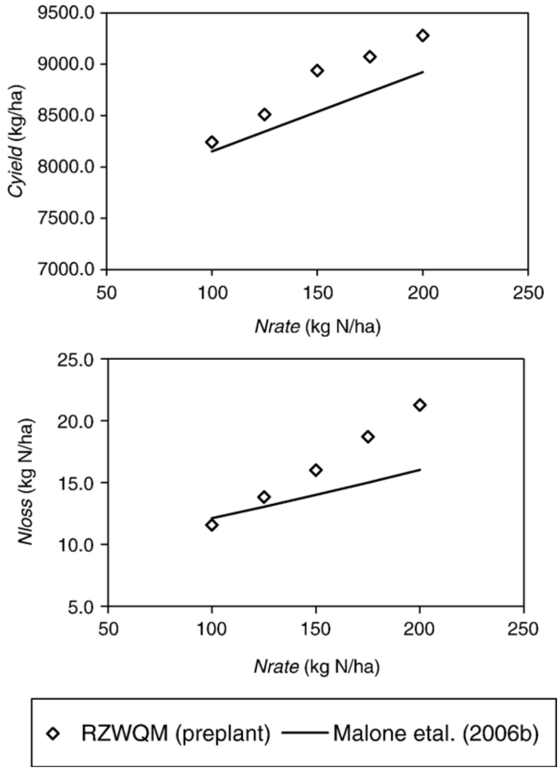

Fig. 4. Corn yield and annual nitrate-N loss to subsurface "tile" drainage water (Nloss) as functions of N application rate. The diamond shapes represent average RZWQM predicted values from 1994–2003. The thin lines are predicted from the polynomial equations reported in Malone et al. (2007b-this issue), which were developed from the field observations at Nashua from 1994–2003. The scenario used for development of this figure was single preplant UAN (Table 3).

ha results in 51% higher predicted Nloss (24.8 and 16.4 kg N/ha) and 2% higher corn yield compared to preplant application to only corn (Table 5). Applying 75 kg N/ha soybean preplant swine manure results in 22% higher predicted Nloss compared to preplant application to only corn (Table 5). The predicted Nloss is greater under swine manure application to soybean because the model only partially reduces fixation for additional soil N: predicted long-term average annual symbiotic fixation of atmospheric N is 120, 154, 208 kg N/ha with bio-available soybean preplant rates of 150, 75, and 0 kg N/ha, respectively.

3.2.5. Swine manure fall application

Fall swine manure application at 150 kg N/ha (bio-available rate) result in similar long-term predicted corn yield and Nloss as fall applied AA (<2% difference; Table 5). The highest long-term predicted Nloss of any scenario was fall applied swine manure of 150 kg N/ha (bio-available) to both corn and soybean (average annual Nloss of 37.2 kg N/ha; Table 5). The predicted Nloss under fall swine manure application to soybean is in contrast to the conclusion of Schmidt et al. (2000) — "manure applied to soybean at available N rates equal to or less than the amount of N accumulated in the crop appeared to be agronomically and environmentally sound". The model over-predicted Nloss and Nconc compared to field data for fall applied swine manure prior to both corn and soybean (Table 4 and Fig. 2), possibly because RZWQM over-predicts winter nitrification (Ma et al., 2007a-this issue; 1998). Predicted average October root zone soil nitrate after soybean was 76 kg N/ha for fall swine manure application prior to corn and soybean and 33 kg N/ha for fall application prior to only corn (150 kg N/ha). Fall swine manure application (150 kg N/ha) prior to soybean reduced predicted fixation only 53 kg N/ha, therefore, the model only partially reduces fixation to compensate for additional soil nitrate. The average predicted root depth of soybean in June and July 1995 (a typical soybean crop) were 20 and 62 cm while the peak soil nitrate concentration on June 15 and July 15 were deeper than 40 and 60 cm, thus RZWQM predicts nitrate leaching below the root depth when swine manure is fall applied prior to soybean. Over-predicted winter nitrification and subsequent Nloss is less of a problem with fall swine manure application prior to corn because the predicted long-term average corn root depth in June and July are deeper than 50 and 80 cm, respectively.

3.2.6. Winter cover crop

Adding winter wheat to the corn-soybean rotation reduced Nloss under preplant UAN-N application by 31% (11.1 vs.

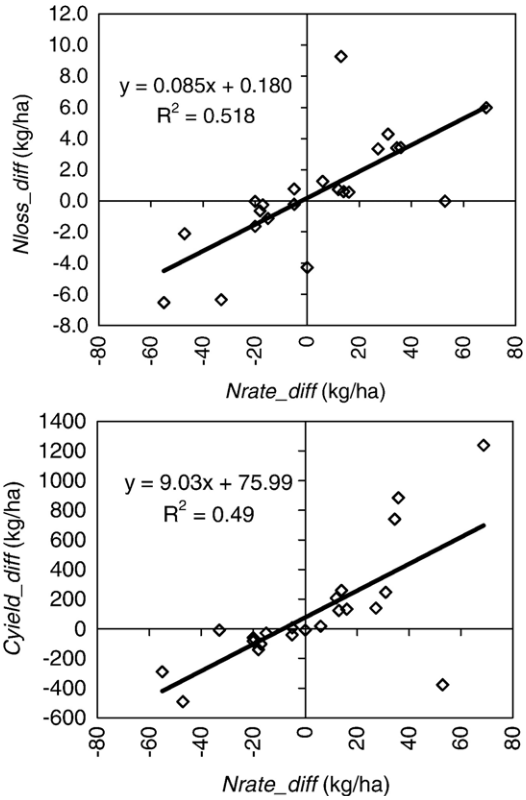

Fig. 5. RZWQM predicted relationship between long-term (1961–2003) annual LSNT N rate and split spring 150 kg N/ha rate. LSNT N rate is determined by soil testing and varies year-to-year with an average N application rate of 145 kg N/ha. Nrate_diff is difference between split (150 kg N/ha) and LSNT rate; Nloss_diff is Nloss_2yr difference between split and LSNT; Cyield_diff is corn yield difference between split and LSNT. The Nloss_2yr is the average annual nitrate-N loss to subsurface "tile" drainage water for corn and the following soybean year.

16.0 kg N ha^{-1}; Table 5). Using the APSIM model, winter wheat was predicted to reduce Nloss at Nashua Iowa on average 4.8 kg N ha^{-1} from 1963 through 2003 with spring application rates of 150 kg N ha^{-1} (Malone et al. 2007a-this issue). Therefore, the simple "quickplant" crop model available in RZWQM predicted nearly the same winter wheat cover crop effect on Nloss over the long-term as the more complex APSIM winter wheat model. A southwestern Minnesota field study reported Nloss reduction of 17 kg N ha^{-1} under winter rye planted in the fall of 1998 prior to soybean and after corn with 134 kg N ha^{-1} spring application, above ground rye N uptake of about 67 kg N ha^{-1}, winter rye biomass production of 2700 kg ha^{-1}, and biomass N concentration of 2.5% (Strock et al., 2004). In 1999 RZWQM predicted 46.3 kg ha^{-1} Nloss under single preplant UAN and 32.6 kg N ha^{-1} loss under winter wheat cover crop treatment (difference of 13.7 kg N ha^{-1}) with 150 kg N ha^{-1} applied and a cover crop, above-ground N uptake of 25 kg N ha^{-1}. Winter cover crop reduced predicted Nloss 5.5 kg N/ha under 150 kg N/ha preplant swine manure application to both corn and soybean (Table 5). The predicted Nloss reduction of adding winter wheat to swine manure application to corn and soybean may be under-predicted because the wheat likely suffers some nitrogen stress. If so, the increased soil N from swine manure application to soybean may contribute to increased N uptake by winter wheat. Adding 20 kg N/ha (UAN-N) after soybean harvest to the APSIM simulations of Malone et al. (2007a-this issue) results in 30 kg N/ha above ground N uptake by winter wheat compared to 25 kg N/ha for N application prior to only corn. The "quick-plant" routine in RZWQM does not adjust winter wheat growth to available N in soil but the APSIM model adjusts winter wheat growth to N stress.

4. Summary and conclusions

The predicted corn yield and Nconc were correlated with observed data and the slopes of the observed and predicted data were significantly greater than zero at $P<0.05$ (Table 4; $R^2>0.83$ for the five chemical N treatments and five swine manure N treatments). The long-term simulations also add confidence to the model predictions because several of the simulations appear consistent with Nashua field and/or other published studies. Adding a winter cover crop appears to reduce Nloss without reducing corn yield.

Although the model accurately responds to several field conditions, the results suggest that caution is necessary when using RZWQM to quantify some treatment effects. For example, nitrate leaching from fall swine manure application to soybean may be over-predicted because winter nitrification may be over-predicted. Over-predicted winter nitrification is more problematic for fall swine manure application prior to soybean than to corn because predicted soybean root growth is shallower throughout the growing season. Also, the predicted Nloss increase with N application rate increase may be over-predicted because predicted N removal in grain is over-predicted at low corn yield, thus Nloss may be under-predicted at low N application rates. The predicted Nloss under split N application was slightly higher than under single preplant N application but more research is necessary to determine the accuracy of this prediction because field results and other published studies are mixed concerning Nloss from these treatments.

Although RZWQM may over-predict Nloss under fall application and under-predict Nloss under low N application rates, the results suggest that after calibration and thorough testing RZWQM accurately quantifies the relative effects of corn production and Nloss under several alternative management practices.

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