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## Empirical analysis and prediction of nitrate loading and crop yield for corn–soybean rotations

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### Abstract

Nitrate nitrogen losses through subsurface drainage and crop yield are determined by multiple climatic and management variables. The combined and interactive effects of these variables, however, are poorly understood. Our objective is to predict crop yield, nitrate concentration, drainage volume, and nitrate loss in subsurface drainage from a corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) rotation as a function of rainfall amount, soybean yield for the year before the corn–soybean sequence being evaluated, N source, N rate, and timing of N application in northeastern Iowa, U.S.A. Ten years of data (1994–2003) from a long-term study near Nashua, Iowa were used to develop multivariate polynomial regression equations describing these variables. The regression equations described over 87, 85, 94, 76, and 95% of variation in soybean yield, corn yield, subsurface drainage, nitrate concentration, and nitrate loss in subsurface drainage, respectively. A two-year rotation under average soil, average climatic conditions, and 125 kg N/ha application was predicted to lose 29, 37, 36, and 30 kg N/ha in subsurface drainage for early-spring swine manure, fall-applied swine manure, early-spring UAN fertilizer, and late-spring split UAN fertilizer (urea ammonium nitrate), respectively. Predicted corn yields were 10.0 and 9.7 Mg/ha for the swine manure and UAN sources applied at 125 kg N/ha. Timing of application (i.e., fall or spring) did not significantly affect corn yield. These results confirm other research suggesting that manure application can result in less nitrate leaching than UAN (e.g., 29 vs. 36 kg N/ha), and that spring application reduces nitrate leaching compared to fall application (e.g., 29 vs. 37 kg N/ha). The regression equations improve our understanding of nitrate leaching; offer a simple method to quantify potential N losses from Midwestern corn–soybean rotations under the climate, soil, and management conditions of the Nashua field experiment; and are a step toward development of easy to use N management tools.

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### 1. Introduction

Nitrogen is a naturally occurring element and adequate amounts are essential for optimal plant growth and crop production. Excessive N application or poor N management in Midwestern agricultural basins that have subsurface drainage, however, have been linked to increased nitrate loading in the Mississippi river (Dinnes et al., 2002). Nitrogen enrichment of estuaries and coastal marine environments contribute to hypoxia, which appears to be increasing (Diaz, 2001). Hypoxia in

the northern Gulf of Mexico occurs because of low dissolved oxygen (<2 mg/L) and trawlers are usually unable to harvest shrimp or demersal fish at these low levels (Rabalais et al., 2001). In addition to hypoxia, poor fertilizer management is linked to increased nitrous oxide concentrations, which contribute to ozone depletion and the greenhouse effect (Mosier et al., 2002).

Improved timing and rates of fertilizer application can significantly reduce nitrate losses under drained soils (Randall and Mulla, 2001; Jaynes et al., 2004). Lower N application may result in less nitrate loading, but if the amount is too low, crop yields and soil N content may be reduced (Jaynes et al., 2001; Dinnes et al., 2002). Spring application generally results in

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lower nitrate loading than fall application and crop yield may not be adversely affected (Randall and Mulla, 2001; Jaynes et al., 2004). Precipitation is another factor that clearly affects nitrate leaching and concentration under corn/soybean production (Owens et al., 2000; Randall and Mulla, 2001).

Better tools are needed to predict the combined effects of variables such as N timing, N rate, and precipitation on nitrate loading and crop yield. The Executive Director for the Soil and Water Conservation Society stated, "... quantifying conservation may be among the most important challenges currently confronting the conservation science community" (Cox, 2002). Effective quantification of conservation practices would result in tools that are based on the best available science and can be easily utilized by practitioners who face time constraints. Predicting nitrate transport in artificially drained soils currently requires complex process-based models such as RZWQM (Shaffer and Delgado, 2002). Direct use of these models is too time-consuming for conservation planners and land managers. Simple to use tools may lead to increased adoption of best management practices that enhance water quality and profitability.

A relatively simple to use empirical model for estimating nitrate leaching as affected by crop type and long-term N fertilizer rate was developed by Simmelsgaard and Djurhuus (1998). This model, however, did not predict nitrate leaching as a function of N timing. Easy to use, regression-type models have been developed recently to predict a variety of natural phenomena (e.g., Bowden et al., 1998; McIsaac et al., 2001; Lee et al., 2002; Kaspar et al., 2003), but doing so requires identifying an appropriate dataset.

Data from Iowa State University's Northeast experiment station near Nashua Iowa suggests nitrate leaching and/or corn yield was significantly affected by N application, N timing, and precipitation. Other attractive qualities of the Nashua dataset are that: it is thoroughly investigated with over 20 peer-reviewed manuscripts, it includes numerous nitrogen managements, it is relatively long-term (1990–2003) with a range of yearly precipitation, and the soil association present on these 0.4-ha plots represent approximately 575,000 ha where corn or soybean were grown in Iowa in 2001. Even with the extent of previously reported research from the Nashua study (e.g., Karlen et al., 1998; Bakhsh et al., 2000, 2002), quickly, confidently, and objectively quantifying crop yield and nitrate leaching effects from different long-term or average conditions (e.g., N management, climate) at Nashua is not currently possible.

Nitrogen is essential to agricultural sustainability but poor nitrogen management may lead to environmental contamination. Clearly N application timing, rate, and precipitation significantly affect nitrogen transport and corn yield, but the combined or interactive effects of these variables is not clear. Accurate quantification of nitrate loading and crop yield, as affected by multiple variables at sensitive Midwest locations, is a first step toward developing relatively simple predictive tools. Our objective is to develop multivariate polynomial regression equations to predict nitrate loading and crop yield as affected by rainfall, N application timing, N application source (UAN or swine manure), and N application rate. The equations are then

used to quantify nitrate loading and crop yield for a corn–soybean rotation with several typical N management scenarios for northeastern Iowa.

## 2. Materials and methods

### 2.1. Site description and management

A long-term dataset that included fourteen years (1990 to 2003) of weather records, crop yields, and tile drainage volume and N concentrations was used. The dataset also contained different N treatments such as application sources, rates, and timing of application. The data were 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). The field research site was initiated in 1977 with tillage (moldboard plow, chisel plow, ridge-tillage, and no-tillage) and cropping system (continuous corn and both phases of a corn/soybean rotation) treatments. From 1993 to 2003, chisel plow and no-till practices were evaluated using different N sources (swine manure, UAN, or both), times of N application (fall, spring, or split), and N rates (78 to 260 kg ha<sup>-1</sup>). Each treatment was replicated three times using a randomized complete block design. For this study, chisel-plow and no-tillage treatment results were combined to simplify the analysis and reduce the number of variables in the developed regression equations. However, predominate tillage does indirectly affect the predicted drainage (see Eq. (5) below).

The soils at this site are Kenyon loam (fine-loamy, mixed, superactive, mesic Typic Hapludolls, USDA-NRCS, 2001a), Readlyn loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls, USDA-NRCS, 2001b), Floyd loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls, USDA-NRCS, 2000), and Clyde silty clay loam (fine-loamy, mixed, superactive, mesic Typic Endoaquolls, USDA-NRCS, 2004). These soils have seasonally high water tables, and thus benefit from subsurface drainage. According to ISU (2004) and USDA-NASS (2002) surveys, approximately 575 thousand hectares of corn or soybean were planted on these soil types in 2001 (personal communication, David James, GIS Specialist, NSTL, August 2004). The soils and major management practices applied to each plot from 1993 through 2003 are summarized in Table 1.

### 2.2. Regression analysis

Multivariate regression was used to evaluate the effect of selected variables (plus variable interactions and exponents) from corn–soybean rotations on yearly crop yield (yield<sub>c</sub> and yield<sub>s</sub>), total drainage from the two-year corn/soybean cycle (drain<sub>total</sub>), flow-weighted nitrate concentration over the two-year corn–soybean cycle (Nconc), and nitrate load over the two-year corn–soybean cycle (Nload<sub>total</sub>). Corn yield<sub>c</sub> was predicted as a function of six independent variables: sum of July and August rainfall (rain<sub>ja</sub>, Karlen et al., 1998), average July and August maximum temperature (temp<sub>ja</sub>, Karlen et al., 1998), N application rate (Nappli), the type of N (type=0 for UAN and type=1 for swine manure), timing of N application

Table 1  
Soils and major management practices applied to each plot from 1993 to 2003\*

Treat group	Plots	Dominant soils per plot	Drainage Index per plot	Crop rotation		Fertilizer type (application timing)		Tillage	
				93–98	99–03	93–98	99–03	93–98	99–03
1	1 7 30	R/K R/F F/C	0.26 0.15 0.62	CS	CS	SM (Fall prior to corn)	SM (Fall prior to corn)	CP	CP
2	2 16 20	R/K R F	0.22 0.28 0.55	CS	CS	UAN (Spring preplant)	SM (Spring preplant)	NT	NT
3	3 24 28	R/K R/K K	0.17 0.19 0.14	SC	SC	UAN (LSNT)	UAN (Spring preplant)	NT	CP
4	4 18 33	K K F/R	0.17 0.14 0.18	CS	CS	UAN (Spring preplant)	SM (Fall)+UAN (late-spring)	CP	CP
5	5 21 26	R/K R/F F/K	0.10 0.22 0.21	CC	SC	UAN (Spring preplant)	SM (Fall, corn and soybean)	CP	CP
6	6 32 36	R/K F/R F/K	0.17 0.15 0.14	SC	SC	UAN (Spring preplant)	SM (Fall)+UAN (Late-spring)	CP	CP
7	8 9 19	R/F R/K F/K	0.48 0.16 0.25	CS	CS	UAN (LSNT)	UAN (Split spring, LCD)	CP	CP
8	10 15 29	K R/K K/F	0.18 0.18 0.21	CS	CS	UAN (LSNT)	UAN (Spring preplant)	NT	CP
9	11 23 27	K R/K F/K	0.17 0.18 na	SC	SC	SM (Fall prior to corn)	SM (Fall prior to corn)	CP	CP
10	12 17 34	K/F R/K R/K	0.31 na 0.19	SC	SC	UAN (LSNT)	UAN (Split spring, LCD)	CP	CP
11	13 22 35	R/F R/K R/K	0.23 0.16 0.16	CC	CS	SM (Fall prior to corn)	SM (Fall, corn and soybean)	CP	CP
12	14 25 31	R/K R/K F/R/C	0.28 0.17 0.33	SC	SC	UAN (Spring preplant)	SM (Spring preplant)	NT	NT

\* R: Readlyn; K: Kenyon; F: Floyd; C: Clyde; CS: Corn–Soybean Rotation; SC: Soybean–Corn Rotation; CC: Continuous Corn; CP: Chisel Plow; RT: Ridge Till; MP: Moldboard Plow; NT: No Till; UAN: Urea–Ammonia–Nitrate; LSNT: Late-Spring N test, includes small preplant application and larger Late-spring application; Split spring application includes both small preplant and greater Late-spring application; LCD: Localized Compaction and Doming; SM: swine manure application.

weighted for application rates (Ntiming), and the soybean yield prior to corn in the corn–soybean rotation (yield<sub>sy1</sub>). Soybean yield (yield<sub>s</sub>) was predicted as a function of rain<sub>ja</sub> and temp<sub>ja</sub>; different N rates applied to corn have not been found to affect soybean yield (Stone et al., 1985; Bundy et al., 1993; Jaynes et al., 2001). Regression equations were developed for total drainage amount from the corn–soybean rotation (drain<sub>total</sub>) as a function of drainage index (DI) and observed rainfall amount adjusted for crop transpiration (rainnet<sub>total</sub>). Both DI and rainnet<sub>total</sub> are described below. Nconc was predicted as a function of Nappli, type, Ntiming, yield<sub>sy1</sub>, the calendar year (January–December) rainfall from the soybean crop (rain<sub>s</sub>, cm), and calendar year rainfall from the previous corn crop (rain<sub>c</sub>). Regression equations were developed for nitrate load (Nload<sub>total</sub>) as a function of drain<sub>total</sub> and regression predicted flow-weighted nitrate concentration (Nconcp). A stepwise procedure was used for variable selection (P<0.01). Through exploratory data analysis, we selected a second-order multivariate polynomial to describe the dependent variables yield<sub>c</sub>, yield<sub>s</sub>, Nconc, drain<sub>total</sub>, and Nload<sub>total</sub>:

$$\begin{aligned}
 DV = & a_0 + a_1(v_1) + \dots + a_x(v_x) + a_{12}(v_1^*v_2) + \dots + a_{yx}(v_y^*v_x) \\
 & + a_{11}(v_1)^2 + \dots + a_{xx}(v_x)^2 + a_{0t}(type) + a_{1t}(type*v_1) \\
 & + \dots + a_{xt}(type*v_x) + a_{12t}(type*v_1^*v_2) + \dots \\
 & + a_{yxt}(type*v_y^*v_x) + a_{11t}(type*v_1)^2 + \dots + a_{xxt}(type*v_x)^2
 \end{aligned}
 \tag{1}$$

Where DV is the dependent variable, a<sub>x</sub> are linear effect coefficients, a<sub>xx</sub> are quadratic effect coefficients, a<sub>yx</sub> are interaction effect coefficients, v<sub>x</sub> are the independent variables, the subscript<sub>y</sub> is the number of interactions in the equation, and the subscript<sub>x</sub> is the number of independent variables in the equation. An indicator (or dummy) variable was included in the development of equations to predict yield<sub>c</sub> and Nconc that adjusts for the type of N application (type=0 for UAN and type=1 for swine manure). The interaction variables (i.e., terms with coefficients of a<sub>yx</sub> and a<sub>yxt</sub>) were not considered for Nconc

nor Nload<sub>total</sub> because they were not significant at P<0.15 using the RSREG procedure in SAS (Freund and Littell, 1991).

The independent variable Ntiming is a function of N application rate and N-application dates

$$Ntiming = [(date_1^*app_1 + date_2^*app_2)/(app_1 + app_2)] + 450.
 \tag{2}$$

Where app<sub>x</sub> are nitrogen application amounts and date<sub>x</sub> are application dates in number of days before January 1 of the soybean planting year in the corn–soybean rotation. For example, a May 1 single nitrogen application to corn is equivalent to date<sub>1</sub> of – 244; a single fall application prior to corn is equivalent to date<sub>1</sub> of day – 423. Nitrogen was applied at two different times and two different rates for split applications, which is the reason for app<sub>2</sub> and date<sub>2</sub>. Ntiming is calculated to more heavily weigh the higher N application rates (e.g., app<sub>2</sub>) under split applications. To maintain positive Ntiming values, Eq. (2) includes adding the constant +450.

A single drainage index (DI) was calculated for each plot as DI = Σrainnet<sub>i</sub><sup>\*</sup>drain<sub>i</sub>/Σrainnet<sub>i</sub><sup>2</sup>, where rainnet<sub>i</sub> was equal to annual rain<sub>c</sub> or rain<sub>s</sub> minus annual estimated crop transpiration, drain<sub>i</sub> is annual subsurface drainage, and the subscript<sub>i</sub> indicates the year (1994–2003). Annual crop transpiration for corn and soybean was estimated as 24+yield<sub>c</sub><sup>\*</sup>0.0007 and 12+yield<sub>s</sub><sup>\*</sup>.005; relationships between crop yield and transpiration were developed from the long-term simulations of Malone et al. (2007-this issue). Total rainfall (rain<sub>total</sub>) over the two year corn–soybean rotation adjusted for crop transpiration was then computed as

$$\begin{aligned}
 rainnet_{total} = & rain_c - (24 + yield_c^*.0007) + rain_s \\
 & - (12 + yield_s^*.005).
 \end{aligned}
 \tag{3}$$

All variables and equations are summarized in Appendix A.

Data splitting is often used for model validation (e.g., Montgomery and Peck, 1982). One method of data splitting is double cross-validation, which involves splitting the dataset



into two subsets, using the two subsets alternately as datasets for regression equation development and prediction, and examining the resulting regression equations (e.g., Montgomery and Peck, 1982; Kaspar et al., 2003). Briefly this process includes developing regression equations from dataset 1; examining the variables included in the equations compared to variables included in the entire dataset; predicting  $yield_c$ ,  $yield_s$ ,  $drain\_total$ ,  $Nconc$ , and  $Nload\_total$  for dataset 2 from the equations developed from dataset 1; then examining the slope and intercept of the correlation between dataset 2 predictions and observations. The regression equations were then developed from dataset 2 and the process repeated by applying the new equations to dataset 1. Double cross-validation was performed on all of the regression equations. Note, however, that information presented in this manuscript is from the entire dataset rather than the split datasets unless otherwise stated.

### 2.3. Data selection

Only data from 1994 through 2003 are analyzed in this paper because of flood and drought conditions that affected data from 1990 to 1993 (Table 2). Other data were excluded from the analysis because some management practices are not analyzed in this study (e.g., continuous corn; combined UAN and swine manure fertilizer to corn), hail damage, limited observations, extraordinary drainage, or unexplained outliers (Table 2). Corn yield data from 1994 was removed from analysis because unreported crop damage may have occurred. The evidence supporting 1994 crop damage is the ratio of average experiment station to average county corn yield (0.88), which 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.

Exclusion of “extraordinary” data allows analysis under “ordinary” conditions. Of course, regression equations could be

developed that included all data and the extreme conditions could be accounted for by additional variables or data normalization. Including extraordinary conditions, however, complicates the analysis, and increases the number of regression equations and variables. Furthermore, inclusion of extraordinary data may increase the possibility of bias for extreme conditions at the expense of ordinary conditions. The extensive, long-term dataset allowed sufficient points for analysis even after excluding several years of extraordinary data.

### 2.4. Scenario development

After the regression equations were determined, they were used to develop a set of predictions that quantify the effects of  $temp_{ja}$ ,  $rain_c$ ,  $rain_s$ ,  $yield_{sy1}$ ,  $Nappli$ , N source type (UAN or manure),  $Ntiming$ , and  $DI$  on  $yield_c$ ,  $drain\_total$ ,  $Nconc$ , and  $Nload\_total$ . These simulation results were then used to investigate best management practices and to produce three-dimensional needle and surface plots under the management and conditions of the Nashua dataset. The three-dimensional plots facilitated investigation of the interaction of two variables on a dependent variable.

To develop the model scenarios, the dependent variables were predicted in the order  $yield_s$ ,  $yield_c$ ,  $drain\_total$ ,  $Nconc$ , and then  $Nload\_total$  because  $drain\_total$  is a function of  $yield_s$  and  $yield_c$  and  $Nload\_total$  is a function of  $drain\_total$  and  $Nconc$ . The scenario development required prediction of each dependent variable on the same set of independent variables, therefore  $drain\_total$  was predicted as a function of predicted  $yield_c$  and  $yield_s$  (not observed yield) and  $Nload\_total$  was predicted as a function of predicted  $drain\_total$  (not observed  $drain\_total$ ). Thus, the only independent variables for scenario development were  $yield_{sy1}$ ,  $Nappli$ ,  $Ntiming$ ,  $DI$ ,  $rain_s$ ,  $rain_c$ , and  $temp_{ja}$ . To avoid including both  $rain_{ja}$  and  $rain_x$  (either  $rain_c$  or  $rain_s$ ) as independent variables in scenario development,  $rain_{ja}$  was predicted as a function of  $rain_x$ . The variables  $rain_{ja}$

Table 2  
Data exclusion

Plots	Years	Dependent variables	These data were excluded because:
All	1990–1993	All	Flow did not occur in 1988 and 1989 because of drought, resulting in a nitrate buildup that leached in subsequent years (Bjorneberg et al., 1996). 1993 was removed because it was a flood year (Shen et al., 1998)
5, 21, 26	1993–1999	All	Continuous corn plots are not analyzed in this study.
13, 22, 35	1993–2000	All	Continuous corn plots are not analyzed in this study.
4, 18, 33	2000–2003	All	UAN and swine manure combined application prior to corn is not analyzed in this study (see Table 1)
6, 32, 36	2001–2003	All	UAN and swine manure combined N application prior to corn is not analyzed in this study (see Table 1)
All	1995	$Yield_c$ , $yield_s$	The crop suffered hail damage (Andales et al., 2000).
All	1994	$Yield_c$	Experiment station corn yield was much lower than average county corn yield, possibly because of unreported crop damage.
27 and 17	All	$Drain\_total$	These plots were known to drain differently from the other plots (Bakhsh et al., 2000).
8, 9, 19	2000–2001	$Nconc$ , $Nload\_total$ , $yield_c$	Only one late-spring N application to corn on June 19, 2000. These were the only plots to receive late-spring N application without preplant N application.
5, 21, 26	2000–2003	$Yield_c$ , $yield_s$ , $Nconc$ , $Nload\_total$	Nitrogen applied in the fall after corn harvest and prior to soybean planting, which is not analyzed in this study.
13, 22, 35	2001–2003	$Yield_c$ , $yield_s$ , $Nconc$ , $Nload\_total$	Fall N application after corn harvest and prior to soybean planting, which is not analyzed in this study.
2, 16, 20	1999	$Yield_c$	Clearly outside of the 99% confidence interval.
17	2001–2002	$Nconc$ , $Nload\_total$	Clearly outside of the 99% confidence interval
9, 19	2002–2003	$Nconc$ , $Nload\_total$	Clearly outside of the 99% confidence interval

and  $\text{rain}_x$  are different independent variables in the observed dataset but they are correlated ( $R^2=0.76$ )

$$\text{Rain}_{ja} = -198 + 7.50 * \text{rain}_x - 0.0864 * \text{rain}_x^2 + 0.000337 * \text{rain}_x^3 \quad (4)$$

A cubic equation was used to predict  $\text{rain}_{ja}$  so that the largest values of  $\text{rain}_{ja}$  were included in the developed scenarios.

Production of the three-dimensional plots involved plotting a dependent variable as a function of two independent variables while keeping the other independent variables constant. The independent variables when held constant were assigned to approximately average values for the Nashua data unless otherwise noted:  $\text{yield}_{sy1}=3500$  kg/ha,  $\text{rain}_s=85$  cm,  $\text{rain}_c=85$  cm,  $\text{temp}_{ja}=27$  °C,  $\text{DI}=0.3$ ,  $\text{Ntiming}=200$ ,  $\text{Nappli}=150$  kg/ha.

### 3. Results and discussion

#### 3.1. Regression equations and cross-validation

Applying regression to the Nashua, Iowa data resulted in equations to predict yearly crop yield ( $\text{yield}_s$  and  $\text{yield}_c$ ), total drainage from the two-year corn–soybean cycle ( $\text{drain\_total}$ ), flow-weighted nitrate concentration over the two-year corn–soybean cycle ( $\text{Nconc}$ ), and nitrate load over the two-year corn–soybean cycle ( $\text{Nload\_total}$ ). See Table 3 and Fig. 1 for regression results and note that the equations and figures are

derived from the entire dataset rather than one of the split dataset used for cross-validation. The regression equations described 87, 85, 94, 76, and 95% of variation in  $\text{yield}_s$ ,  $\text{yield}_c$ ,  $\text{drain\_total}$ ,  $\text{Nconc}$ , and  $\text{Nload\_total}$ , respectively (Table 3 and Fig. 1). Predicting  $\text{Nload\_total}$  using predicted yield (including poor 1994 and 1995 predictions) and predicted  $\text{drain\_total}$  results in slightly less accurate predictions than using observed  $\text{drain\_total}$ , but the ratio between the RMSE and the mean of  $\text{Nload\_total}$  (approximately 30 kg N/ha) is still less than 0.25 (model statistics using predicted yield and predicted  $\text{drain\_total}$  to predict  $\text{Nload\_total}$  are:  $R^2=0.86$ ;  $\text{RMSE}=7.0$  kg N/ha; dependent variable mean = 30.8 kg N/ha;  $N=113$ ). The observations were reduced from  $N=120$  (Table 3) to  $N=113$  when using predicted  $\text{drain\_total}$  to predict  $\text{Nload\_total}$  because plot 17 and 27 were excluded due to poor drainage predictions (see Table 2). The effect of selected independent variables and selected interactions on the dependent variables ( $\text{yield}_s$ ,  $\text{yield}_c$ ,  $\text{drain\_total}$ ,  $\text{Nconc}$ ,  $\text{Nload\_total}$ ) is discussed after cross-validation.

The relationship between regression-predicted and observed  $\text{yield}_c$  and  $\text{Nconc}$  can be improved by differentiating between chisel- and no-tillage. Bakhsh et al. (2002) report higher nitrate concentration and higher corn yield from chisel-plow than no-till under spring pre-plant N application using the 1993–1998 Nashua data (reported nitrate concentration was 10.4 vs. 8.3 mg/L,  $P<0.05$ ). The most important effect of tillage driving nitrate loading, however, may be increased drainage from no-till compared to chisel-till. Using the 1993–1998 Nashua data,

Table 3  
Multivariate polynomial regression results for the Nashua, Iowa data

Dependent variable symbol and description <sup>a</sup>	Polynomial regression equations <sup>b</sup>	Model statistics <sup>c</sup>
$\text{Yield}_s$ Soybean yield	$-117349 - [1544 * \text{rain}_{ja}] - [2.76 * \text{rain}_{ja}^2] + [10276 * \text{temp}_{ja}] - [2.16\text{E}+02 * \text{temp}_{ja}^2] + [6.09\text{E}+01 * \text{temp}_{ja} * \text{rain}_{ja}]$	$N=126$ $R^2=0.87$ $\text{RMSE}=221$ , kg/ha DV mean = 3434, kg/ha
$\text{Yield}_c$ Corn yield	$5.32\text{E}+03 + [3.96\text{E}+02 * \text{rain}_{ja}] - [5.82 * \text{rain}_{ja}^2] - [4.52\text{E}+01 * \text{type} * \text{rain}_{ja}] + [3.00\text{E}-03 * \text{type} * \text{yield}_{sy1} * \text{Nappli}] + [3.35\text{E}-01 * \text{temp}_{ja} * \text{Nappli}] - [2.83\text{E}-02 * \text{temp}_{ja} * \text{yield}_{sy1}]$	$N=90$ $R^2=0.85$ $\text{RMSE}=395$ , kg/ha DV mean = 9831, kg/ha
$\text{Drain\_total}^{0.5}$ Square root of drainage over the two-year corn/soybean cycle	$3.28\text{E}-02 + [1.10\text{E}+01 * \text{DI}] + [3.55\text{E}-02 * \text{DI} * \text{rainnet\_total}] - [8.06 * \text{DI}^2] + [1.23\text{E}-04 * \text{rainnet\_total}^2]$	$N=124$ $R^2=0.94$ $\text{RMSE}=5.00$ , cm DV mean = 26.0, cm
$\text{LN}(\text{Nconc})$ Natural logarithm of flow-weighted nitrate concentration over the two-year corn/soybean cycle	$1.46 + [1.93\text{E}-04 * \text{yield}_{sy1}] - [7.56\text{E}-03 * \text{rain}_s] + [3.70\text{E}-03 * \text{Nappli}] - [6.16\text{E}-03 * \text{Ntiming}] + [4.25\text{E}-02 * \text{rain}_c] - [2.37\text{E}-04 * \text{rain}_c^2] - [1.08\text{E}-03 * \text{type} * \text{yield}_{sy1}] + [2.16\text{E}-07 * \text{type} * \text{yield}_{sy1}^2] + [4.30\text{E}-03 * \text{type} * \text{Ntiming}]$	$N=120$ $R^2=0.76$ $\text{RMSE}=1.90$ , mg/L DV mean = 12.5, mg/L
$\text{Nload\_total}^{0.5}$ Square root of nitrate loss in drainage over the two-year corn/soybean cycle	$-5.68 + [1.35 * \text{drain\_total}^{0.5}] + [2.11 * \text{ln}(\text{Nconcp})] - [3.30\text{E}-02 * \text{drain\_total}]$	$N=120$ $R^2=0.95$ $\text{RMSE}=4.20$ , kg N/ha DV mean = 29.7, kg N/ha

<sup>a</sup> Note that the dependent variables  $\text{drain\_total}$ ,  $\text{Nconc}$  and  $\text{Nload\_total}$  were transformed to conform to assumptions associated with polynomial regression analysis: 1) equal variance for all values of dependent variables (homoscedasticity) and 2) dependent variables are normally distributed.

<sup>b</sup> *Climatic variables*:  $\text{rain}_{ja}$  is the yearly July and August rainfall;  $\text{temp}_{ja}$  is the average July and August maximum temperature;  $\text{rain}_s$  is the yearly rainfall during soybean;  $\text{rain}_c$  is the yearly rainfall during corn;  $\text{rainnet\_total}$  is rainfall during the two-year corn–soybean cycle adjusted for estimated crop transpiration. *Management variables*:  $\text{Nappli}$  is total yearly "bio-available" N application (see text for description of "bio-available");  $\text{Ntiming}$  is timing of N application weighted for application rate. *Miscellaneous variables*:  $\text{Nconcp}$  is the regression predicted nitrate concentration in drainage over the two-year corn–soybean cycle;  $\text{drain\_total}$  is the observed drainage over the two-year corn–soybean cycle;  $\text{DI}$  is plot Drainage Index;  $\text{yield}_{sy1}$  is soybean yield prior to corn in the corn/soybean rotation. *Note*: All included variables are significant at the  $P<0.01$  level.

<sup>c</sup> Model statistics are reported for inverse of transformed data (e.g.,  $\text{drain\_total}$  not  $\text{drain\_total}^{0.5}$ ).  $N$  is # of observations; DV mean is Dependent Variable Mean; RMSE is Root Mean Square Error.

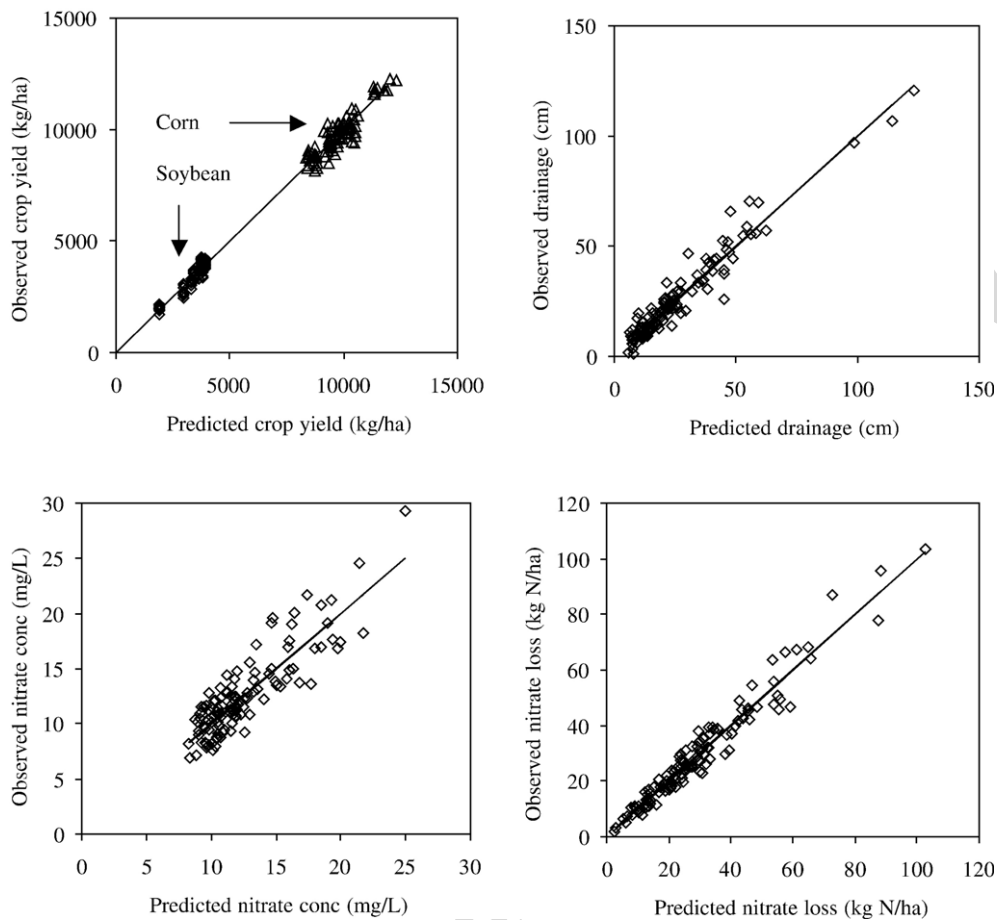


Fig. 1. Regression predicted vs. field observed yield<sub>c</sub> (kg/ha), yield<sub>s</sub> (kg/ha), drain<sub>total</sub> (cm), Nconc (mg/L), and Nload<sub>total</sub> (kg N/ha).

Bakhsh et al. (2002) report about a two-fold drainage increase under no-till (25 cm vs. 12 cm,  $P < 0.05$ ) and a slightly smaller non-significant nitrate load increase (20 vs. 13 kg N/ha). Regression equation predicted drain<sub>total</sub> is indirectly affected by chisel- and no-till because DI is a function of predominant tillage (see Eq. (5) below).

The double cross-validation analysis shows that the regression equations for predicting yield<sub>s</sub>, yield<sub>c</sub>, drain<sub>total</sub>, Nconc, and Nload<sub>total</sub> are reasonably stable within the confines of the Nashua dataset. The slopes and intercepts were within the 95% confidence intervals, suggesting they are not statistically different from one and zero. The double cross-validation analysis also confirms that the variables listed in Table 3 contribute to yield<sub>s</sub>, yield<sub>c</sub>, drain<sub>total</sub>, Nconc, and Nload<sub>total</sub>. All variables and interactions were included in both splits of the cross-validation at  $P < 0.15$  except DI\*rainnet<sub>total</sub> was not included in one of the splits predicting drain<sub>total</sub>. Note that the SAS default value for variable inclusion in multiple regression is  $P < 0.15$  and  $P < 0.01$  was used in the stepwise procedure (Table 3).

### 3.2. Corn and soybean yield (yield<sub>c</sub> and yield<sub>s</sub>)

Nappli, temp<sub>ja</sub>, yield<sub>sy1</sub>, rain<sub>ja</sub>, and type (UAN or swine manure N source), were included variables to predict yield<sub>c</sub> ( $P < 0.01$ ) but Ntiming was not (Table 3). Yield<sub>c</sub> increased slightly with decreasing temp<sub>ja</sub> and increased more obviously

with increasing rain<sub>c</sub> and Nappli (Fig. 2a,b). Although corn yield can increase with above average July and August maximum temperatures when rainfall is sufficient (Runge, 1968), below average July and August temperatures and above average July and August rainfall are generally associated with higher corn yield (Hu and Buyanovsky, 2005; Wilhelm and Wortmann, 2004; Thompson, 1986; Thompson, 1969).

Yield<sub>c</sub> increased as yield<sub>sy1</sub> decreased but the trend is less pronounced for high swine manure N rates (Nappli, Fig. 2b). This relationship also holds if 1994 corn data is included in the development of the regression equations. One possible explanation is that higher yield<sub>sy1</sub> results in higher biomass, higher microbial N immobilization, and subsequent net N mineralization more out of sync with corn N demand. Net N immobilization accompanying crop residue decomposition can affect corn N fertilizer requirement and the time frame of net immobilization may influence year-to-year and site-to-site variability in corn N fertilizer requirement (Green and Blackmer, 1995). A period of “excess asynchrony” between crop N demand and N supply occurs following crop harvest in northern temperate legume-based cropping systems (Crews and Peoples, 2005). Possibly “excess asynchrony” increases as yield<sub>sy1</sub> increases, but further research is needed to test this hypothesis.

The swine manure plots generally produced greater yield<sub>c</sub> than the UAN plots, especially at the higher application rates (Fig. 2a,b). In addition, Nconc was lower in the manure plots

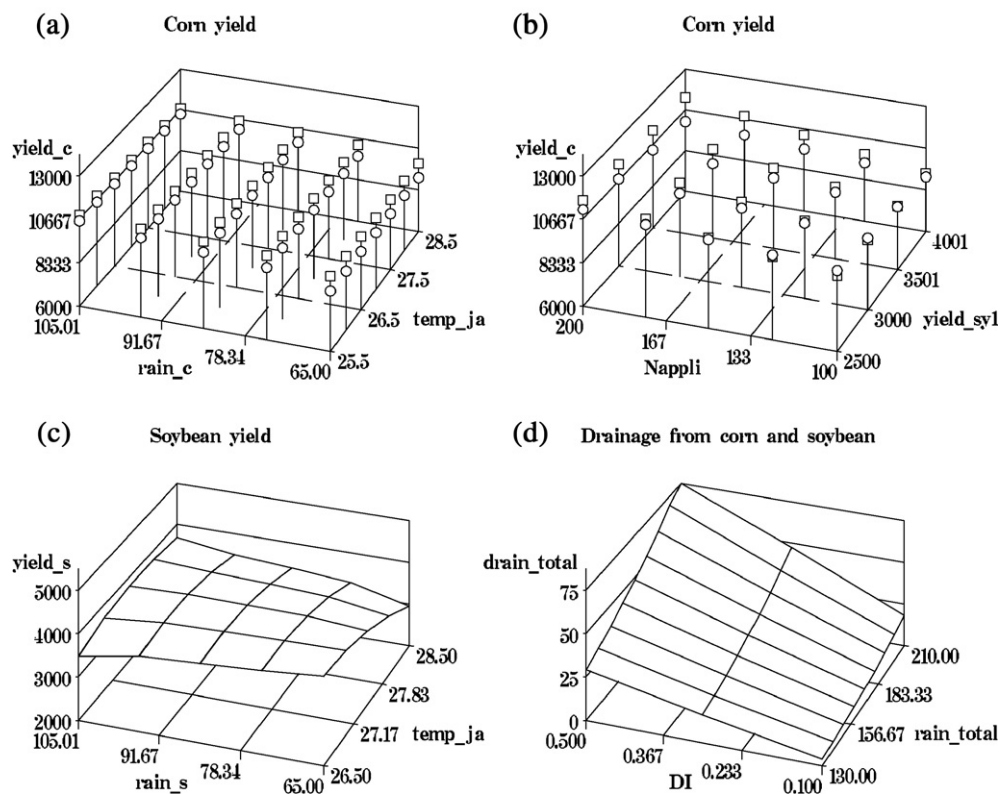


Fig. 2. Three-dimensional representation of regression predicted  $yield_c$  (kg/ha),  $yield_s$  (kg/ha), and  $drain\_total$  (cm), as affected by selected variables. The circles represent UAN application and the squares represent swine manure application. Note that surface plots rather than needle plots were produced for  $yield_s$  and  $drain\_total$  because  $Nappli$  was not an included variable for prediction (Table 3). Needle-plots were produced for  $yield_c$  because it was a function of  $Nappli$ , and thus fertilizer type — UAN or swine manure (Table 3). Independent variable units are:  $yield_c$  (kg/ha),  $yield_s$  (kg/ha),  $temp_{ja}$  (C),  $Nappli$  (kg N/ha),  $yield_{sy1}$  (kg/ha),  $drain\_total$  (cm), DI (unitless),  $rain_c$  (cm),  $rain_s$  (cm), and  $rain\_total$  (cm).

than the UAN plot as discussed below. Singer et al. (2004) concluded composted swine manure increased corn yield compared to UAN fertilizer, and the data suggested that N application was not responsible for the yield difference. It is possible that N uptake efficiency from improved soil physical, chemical, and biological properties may interact to increase crop yield in swine compost applications (Singer et al., 2004).

$yield_s$  increased with increasing  $rain_s$  at high  $temp_{ja}$  and  $yield_s$  decreased with increasing  $temp_{ja}$  at low  $rain_s$  (Fig. 2c). Yamoah et al. (1998) reported increasing soybean yield in corn–soybean rotations in Nebraska with decreasing August temperature and increasing June–August precipitation.

### 3.3. Subsurface drainage from the corn–soybean rotation ( $drain\_total$ )

As DI and  $rain\_total$  increased,  $drain\_total$  increased substantially (Fig. 2d). For example,  $drain\_total$  under swine manure application increased from 8.2 to 47.2 cm with an increase of DI from 0.1 to 0.5 under otherwise average conditions. The substantial effect DI has on  $drain\_total$  is due to the variability in drainage classification among the 36 plots. The soils are classified as poorly and very poorly drained (Clyde), somewhat poorly drained (Floyd and Readlyn), and moderately well and well drained (Kenyon) (USDA–NRCS, 2000, 2001a, 2001b, 2004 — Official Soil Series Descriptions for the three soils).

Drainage index (DI) is correlated with the approximate soil fractions within each plot and tillage according to the equation ( $R^2=0.72$ ; variable inclusion of  $P<0.1$ ;  $N=28$ )

$$DI = 0.27 + 0.11*(f - k) - 0.09*till - 22.6*c*(f - k) + 76.2*c^2 + 0.10*(f - k)^2 \quad (5)$$

where  $c$ ,  $f$ , and  $k$  are the approximate fractions of Clyde, Floyd, and Kenyon soil for each plot (Bakhsh and Kanwar, 2004) and  $till$  is 1 for chisel-plow and 0 for no-till. Plots 3, 24, 28, 10, 15, 29, 17, and 27 were excluded from this analysis either because of extraordinary drainage patterns or because they had both no-till and chisel-plow between 1994 and 2003 (see Tables 1 and 2). DI increases as the fraction of Clyde and Floyd soil increases, and DI decreases as the fraction of Kenyon soil increases. In addition, chisel-till produces less drainage than no-till, which is consistent with Bakhsh et al. (2002). Note that only plots 30 and 31 contained Clyde soil (Table 1). Computing a drainage index for each plot was a simple method to index plots for drainage propensity, which appears to be a function of the predominant tillage and soil differences. Although DI is specific to the Nashua field data, it may be more generally applicable because it is correlated with the lateral hydraulic gradient (LHG) calibrated by Ma et al. (2007–this issue) on the Nashua data ( $DI=0.11[LN(LHG)]+0.29$ ;  $R^2=0.78$ ;  $N=30$ ). Ma et al. (2006) did not calibrate LHG for the highest drainage plots; if these



were determined the correlation between DI and LHG would likely improve.

### 3.4. Nitrate conc. in subsurface drainage from the corn-soybean rotation (Nconc)

Ntiming, yield<sub>sy1</sub>, rain<sub>s</sub>, rain<sub>c</sub>, Nappli, and type were selected as independent variables to predict flow-weighted nitrate concentration ( $P < 0.01$ , Table 3). Nconc decreased with increasing Ntiming and decreasing Nappli under both manure and UAN fertilizer applications (Fig. 3a,b). For example under average conditions and swine manure application Ntiming of 30 and 200 result in Nconc of 15.8 and 11.5 mg/L (Fig. 3a,b). Randall and Vetsch (2005) report lower N loss with spring compared to fall anhydrous application in southern Minnesota.

Nconc decreased with increasing rain<sub>s</sub>, possibly because of dilution (Fig. 3a). Owens et al. (2000) also reported higher

nitrate concentration under lower precipitation. Also, Nconc increased with increasing rain<sub>c</sub> at low rain<sub>c</sub> and then plateaued (Fig. 3b). When rain<sub>c</sub> was low, possibly less mineralization occurred resulting in lower Nconc. Mineralization may be greatest with soil moisture near field capacity and decline with soil drying (Cassman and Munns, 1980).

The second most influential variable with a partial  $R^2$  of 0.12 was yield<sub>sy1</sub>. Nconc increases with increasing yield<sub>sy1</sub> (Fig. 3c). This relationship appears consistent with the “excess asynchrony” hypothesis discussed above that increasing yield<sub>sy1</sub> may increase microbial N immobilization and thus increase nitrogen asynchrony resulting in: less nitrogen availability when corn demand is high, more nitrogen becomes available when crop demand is low or after harvest, and thus more N is lost through drainage. More rapid Nconc increase with increasing yield<sub>sy1</sub> under swine manure compared to UAN (Fig. 3c) may also be consistent with the “excess asynchrony” hypothesis because the

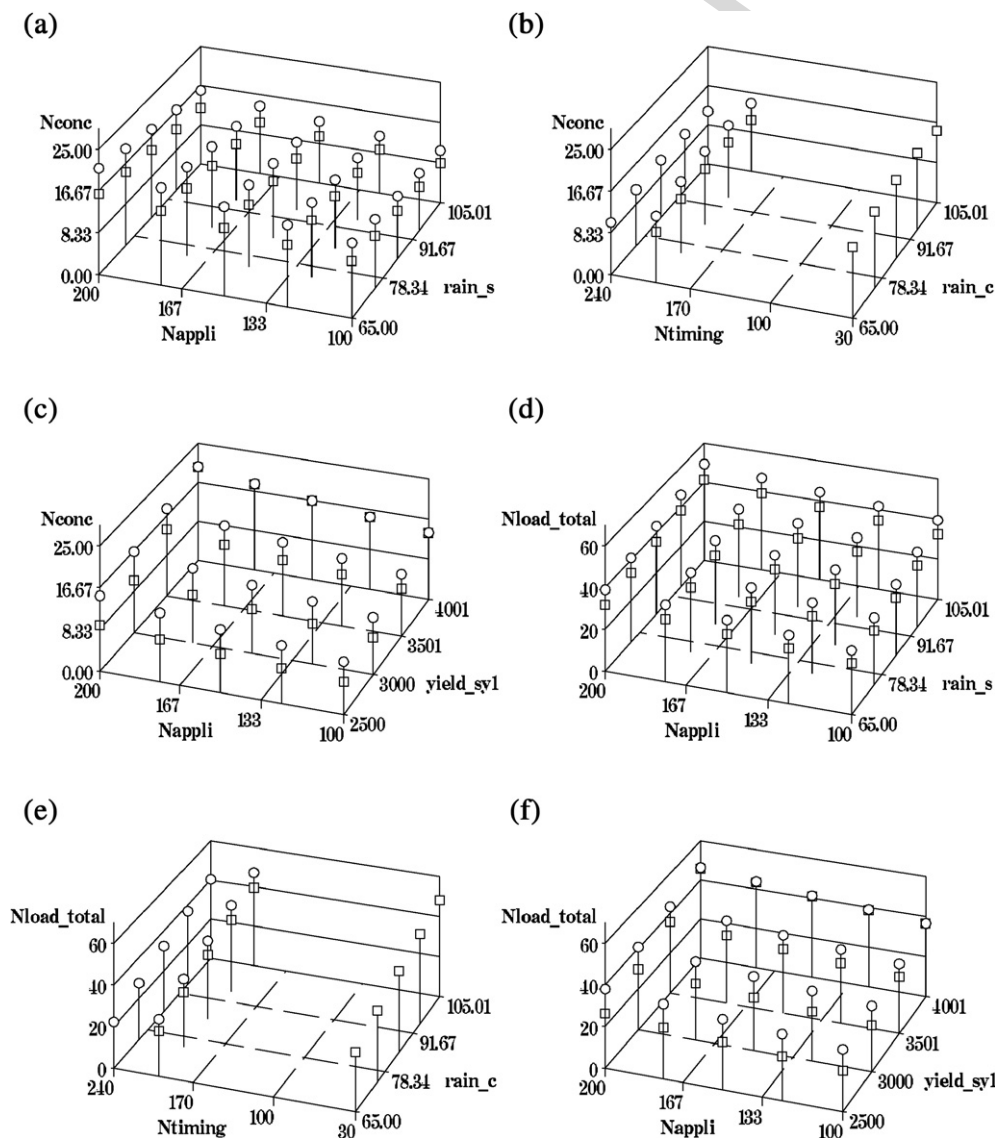


Fig. 3. Three-dimensional representation of regression predicted Nconc (mg/L) and Nload<sub>total</sub> (kg N/ha), as affected by selected variables. The circles represent UAN application and the squares represent swine manure application. Independent variable units are: Ntiming (day of year), rain<sub>c</sub> (cm), rain<sub>s</sub> (cm), Nappli (kg N/ha), yield<sub>sy1</sub> (kg/ha).

carbon content of swine manure favors the immobilization process (Dauden and Quilez, 2004). Further research is necessary to confirm this hypothesis.

Under all variable combinations, manure application resulted in lower Nconc compared to UAN application (Fig. 3a,b,c). Dauden and Quilez (2004) report less nitrate leaching under swine manure application than inorganic fertilizer application, possibly because of decreased available N due to enhanced immobilization and/or fixation. Another explanation is that bio-available N from swine manure was an overestimate because Nappli from swine manure was the sum of inorganic N in swine manure plus half the organic N in the manure. The average Nappli from swine manure was about 150 kg/ha while the average total organic N applied was about 60 kg/ha. Enhanced crop N uptake efficiency in swine manure systems because of improved soil physical, biological, and chemical properties (Singer et al., 2004) may also contribute to lower Nconc.

### 3.5. Nitrate load in subsurface drainage from the corn–soybean rotation (Nload\_total)

The most sensitive single variable for Nload\_total was rain<sub>c</sub> (Fig. 3d,e,f). Under average conditions, Nload\_total increased by nearly a factor of two as rain<sub>c</sub> increased from 65 to 105 cm (Fig. 3e).

Nload\_total under swine manure application is equally sensitive to yield<sub>sy1</sub> as to rain<sub>c</sub> under the variable range reported (Fig. 3e,f). For example, under average conditions and swine manure application, Nload\_total increased about 18 kg N/ha under the reported range of yield<sub>sy1</sub> and rain<sub>c</sub>. Also, under swine manure N application, Nload\_total has similar sensitivity to the variable ranges reported for Ntiming and Nappli (Fig. 3e,f). For example under average conditions and swine manure application, Nload\_total increased from 31.1 to 39.0 kg/ha with an Ntiming decrease of 200 to 30 while Nload\_total increased from 27.2 to 35.4 kg/ha with a Nappli increase of 100 to 200 kg/ha.

### 3.6. Regression predicted effects of N management scenarios

The N-application strategy that resulted in the lowest predicted Nload\_total under average weather conditions and yield<sub>c</sub> > 10,000 kg/ha was Ntiming=200, Nappli=125 kg N/ha, and type=swine manure (Table 4). The Nload\_total under this management was 29.1 kg/ha. In comparison, Nload\_total under average conditions and fall swine manure Nappli of 125 kg N/ha was 36.8 kg/ha (Table 4). Nload\_total=35.8 kg N/ha and yield<sub>c</sub>=9742 kg/ha under Nappli=125 kg N/ha, Ntiming=200, and type=UAN (Table 4). Nload\_total was 29.9 kg N/ha under average conditions and late-spring split UAN application (Ntiming=240, Table 4). Therefore, the best predicted strategy for the highest yield<sub>c</sub> and lowest Nload\_total is spring swine manure applications. Nload\_total calculations were not extrapolated beyond their observed Ntiming; i.e., UAN-fertilizer was not applied in the fall and swine manure was not applied as a split application at the Nashua experiment station.

The 1994–2003 (corn in 1994 and soybean in 1995) regression predicted Nload\_total was calculated using the observed

Table 4

Regression predicted effect of N-management scenarios (data are sorted by Nload\_total)

Ntiming	Nappli (kg N/ha)	Type	Yield <sub>c</sub> (kg/ha)	Drain_total (cm)	Nconc (mg/L)	Nload_total (kg N/ha)
200	100	SM	9550	27.0	9.6	27.2
240	100	UAN	9515	27.0	9.8	27.8
200	125	SM	10039	26.9	10.5	29.1
240	125	UAN	9742	27.0	10.8	29.9
200	150	SM	10527	26.8	11.5	31.1
240	150	UAN	9968	26.9	11.8	32.0
200	175	SM	11016	26.6	12.6	33.2
200	100	UAN	9515	27.0	12.6	33.6
240	175	UAN	10194	26.8	13.0	34.1
30	100	SM	9550	27.0	13.1	34.6
200	200	SM	11505	26.5	13.8	35.4
200	125	UAN	9742	27.0	13.8	35.8
240	200	UAN	10421	26.8	14.2	36.4
30	125	SM	10039	26.9	14.4	36.8
200	150	UAN	9968	26.9	15.1	38.1
30	150	SM	10527	26.8	15.8	39.0
200	175	UAN	10194	26.8	16.6	40.5
30	175	SM	11016	26.6	17.3	41.4
200	200	UAN	10421	26.8	18.2	42.9
30	200	SM	11505	26.5	19.0	43.7

Note that data is sorted by Nload\_total and that the different N-management strategies are: Ntiming of 30 or 200 for SM and 200 or 240 for UAN; Nappli of 100 to 200 kg N/ha; and type of SM or UAN.

DI=0.3; rain<sub>c</sub> and rain<sub>s</sub>=85 cm; temp<sub>ja</sub>=27 °C; yield<sub>sy1</sub>=3500 kg/ha.

See Table 3 and/or Appendix A for variable descriptions.

yearly rain<sub>c</sub>, rain<sub>s</sub>, rain<sub>ja</sub>, and temp<sub>ja</sub> on a field with DI of 0.3 to determine if the yearly average climate conditions result in representative nitrate loading over an extended period with typical precipitation and temperature fluctuations. Fall and early-spring (Ntiming of 30 and 200) swine manure applications of Nappli=125 kg N/ha result in ten year average Nload\_total of 35.8 kg N/ha and 28.4 kg N/ha. Therefore, the average Nload\_total difference over ten years using observed weather (7.4 kg N/ha) is similar to the 7.7 kg N/ha difference for average weather conditions discussed above. The Nload\_total difference between early and late-spring UAN application using average weather conditions and observed weather are also very similar (average Nload\_total differences of about 6.0 kg N/ha).

Nload\_total reduction of 7.7 or 6.0 kg N/ha may appear small (5.1% and 4.0% of N application), but it could be significant when considering the Iowa Kenyon–Floyd–Clyde soil association in corn and soybean—approximately 575,000 ha. In addition, seemingly small edge-of-field nitrogen loading reductions may result in substantial nitrate loading reductions to the Gulf of Mexico because of in-stream processes such as denitrification (McIsaac et al., 2001).

Compiling a set of regression results under local Nashua conditions to quantify the effects of agricultural management on yield and nitrogen loading on the Kenyon–Floyd–Clyde soil association may be a first step toward development of a simple to use tool to predict the effect of management alternatives under different conditions such as climate and soil. A set of predictions such as this may be a useful tool to help accelerate adoption of best management practices. Developing tools to objectively quantify the tradeoffs of management alternatives is

an urgent need of practitioners, program managers, budget officials, and policy makers (e.g., Cox, 2002).

### 3.7. Limitations and further research

The development of regression equations from the Nashua data is a step beyond qualitatively differentiating between treatments, such as concluding spring N application reduces nitrate loading compared to fall N application. These equations offer a method to quantitatively evaluate limited treatment and weather differences under the conditions of northeast Iowa. However, regression equations are limited. One limitation is that extrapolation beyond the experimental data is problematic. Applying the equations beyond the observed climate and soil conditions would require thorough testing and modification of the regression models for those conditions. In addition, important management variables were not evaluated such as fall and/or split fall/spring UAN application because they were not part of the experimental design.

The development of the regression equations also required ignoring data and outliers that could be important to fully quantify nitrate loading under the observed Nashua conditions. For example, data from floods and high nitrate loading after drought were excluded from equation development. Other important weather variability that drives nitrate loading such as rainfall distribution within the season was not considered because additional variables would increase the complexity and the limited years of observations poses difficulty. Even long-term experiments of over ten years may give biased estimates of long-term water balance because of decadal level climate variability and a few years can account for most of the runoff and drainage (Keating et al., 2002). Finally, the variable determination performed in this research may be difficult to transfer to other sites (e.g., DI).

To overcome some of the limitations of regression-based modeling and to more comprehensively evaluate and quantify yield and nitrate loading requires use of process-based models. For example, process-based models allow extrapolation of management and climate effects to conditions (climate, soil, management) where observed data is sparse or non-existent. Process-based models also allow cause and effect analysis because observed data is necessarily limited. For example, process-based models simulate daily crop variables and soil conditions (e.g., crop phenology, N uptake, transpiration; soil N, C, and water), which allow greater understanding of treatment and/or climate differences on end-points of interest such as nitrate loading or corn yield. Successful use of process-based models will allow a more comprehensive understanding of agricultural systems and will enhance development and optimization of sustainable systems.

Direct use of process-based models to predict nitrate transport in artificially drained soil, however, is too time-consuming for conservation planners and land managers. An option is to enter simulation results of nitrate leaching and crop yield under different conditions (soils, management, and climate) into a database to use for economic and risk analysis. It is unrealistic to simulate every combination of soil type, crop rotation,

fertilization schedule, climate scenario, etc. using deterministic models (Haberlandt et al., 2002). Recent research has suggested using a metamodeling approach to upscale field scale modeling results of nitrogen leaching to regions (Wu and Babcock, 1999; Borgesen et al., 2001; Haberlandt et al., 2002). A metamodel is a relatively simple mathematical function that approximates the results of complex model simulations (Law and Kelton, 2004). Types of metamodels include polynomial regression, splines, and neural networks (e.g., Kleijnen and Sargent, 2000). Development of the polynomial regression equations to the Nashua field observed data suggests metamodels can be developed to quantify nitrate leaching and crop yield under a variety of climate and management conditions in artificially drained soil. In the current research, quantifiable independent variables were identified (e.g., nitrogen application rate, nitrogen application timing, rainfall amount, soybean yield prior to corn) that significantly affected the dependent variables nitrogen leaching and crop yield, and dependent variables were predicted with reasonable accuracy. Therefore, the developed regression equations are a step toward development of a simple, accurate, and objective method to quantify management and climate effects on nitrate loading and crop yield for a region.

### Appendix A. Equation and variable summary

$$\begin{aligned} DV = & a_0 + a_1(v_1) + \dots + a_x(v_x) + a_{12}(v_1*v_2) \\ & + \dots + a_{yx}(v_y*v_x) + a_{11}(v_1)^2 + \dots + a_{xx}(v_x)^2 \\ & + a_{0t}(\text{type}) + a_{1t}(\text{type}*v_1) + \dots + a_{xt}(\text{type}*v_x) \\ & + a_{12t}(\text{type}*v_1*v_2) + \dots + a_{xyt}(\text{type}*v_y*v_x) \\ & + a_{11t}(\text{type}*v_1)^2 + \dots + a_{xxt}(\text{type}*v_x)^2 \end{aligned} \quad (1)$$

$$\text{Ntiming} = [(\text{date}_1^*\text{app}_1 + \text{date}_2^*\text{app}_2)/(\text{app}_1 + \text{app}_2)] + 450 \quad (2)$$

$$\begin{aligned} \text{Rainnet\_total} = & \text{rain}_c - (24 + \text{yield}_c^*.0007) + \text{rain}_s \\ & - (12 + \text{yield}_s^*.0005) \end{aligned} \quad (3)$$

Description of selected variables (in order of presentation above):

DV are the dependent variables yield<sub>s</sub>, yield<sub>c</sub>, drain<sub>total</sub>, Nconc, Nload<sub>total</sub>.

$a_x$  are linear effect coefficients.

$v_x$  are the independent variables.

$a_{yx}$  and  $a_{yxt}$  are interaction effect coefficients.

$a_{xx}$  are quadratic effect coefficients.

$a_{xt}$  are type\*linear effect coefficients.

$a_{xyt}$  are type\*interaction coefficients.

$a_{xxt}$  are type\*quadratic effect coefficients.

The subscript  $x$  is the number of independent variables in the equation.

The subscript  $y$  is the number of interactions in the equation.

The subscript  $t$  indicates a type coefficient.

Type indicates the type of N application (0 for UAN and 1 for swine manure).

Yield<sub>s</sub> and yield<sub>c</sub> are the yearly corn and soybean yield in the corn–soybean rotation (kg/ha).



Drain<sub>total</sub> is the total drainage from the two-year corn–soybean cycle (cm).

Nconc is the flow-weighted nitrate concentration over the two-year corn–soybean cycle (mg/L).

Nload<sub>total</sub> is the nitrate load over the two-year corn–soybean cycle (kg N/ha).

Ntiming is the application rate weighed timing of N application (d).

Date<sub>x</sub> are N application dates relative to January 1 of the soybean planting year.

App<sub>x</sub> are nitrogen application amounts.

Rainnet<sub>total</sub> is the total rainfall over the two year corn–soybean rotation adjusted for crop transpiration (cm).

Rain<sub>s</sub> and rain<sub>c</sub> are the calendar year rainfall from the soybean and previous corn crop (cm).

Other variables (in alphabetical order):

DI is the drainage index.  $DI = \sum \text{rainnet}_i^* \text{drain}_i / \sum \text{rainnet}_i^2$ , where rainnet<sub>i</sub> was equal to annual rain<sub>c</sub> or rain<sub>s</sub> minus annual estimated crop transpiration, drain<sub>i</sub> is annual subsurface drainage, and the subscript *i* indicates the year (1994–2003).

Nappli is the N-application rate (kg N/ha).

Nconcp is regression predicted nitrate concentration in drain flow (mg/L).

Rain<sub>ja</sub> is the July and August rainfall amount (cm).

Temp<sub>ja</sub> is the average maximum July and August daily temperature (C).

Yield<sub>sy1</sub> is the soybean yield prior to corn in the corn–soybean rotation (kg/ha).

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