Predicted nitrate-N loads for fall, spring, and VRN fertilizer application in southern Minnesota

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Abstract. *Nitrate-N from agricultural fields is a source of pollution to fresh and marine waters via subsurface tile drainage. Sensor-based technologies that allow for in-season monitoring of crop nitrogen requirements may represent a way to reduce nitrate-N loadings to surface waters by allowing for fertilizer application on a more precise spatial and temporal resolution. However, little research has been done to determine its effectiveness in reducing nitrate-N losses. In this study, the field scale hydrologic and nitrogen simulation model Drainmod-NII was used to estimate nitrate-N loads for different fertilizer application rates and timings to corn for a field site in Waseca, Minnesota. The results of the simulation, along with results from two other locations in southern Minnesota (Lamberton and Willmar) were used in a regression analysis to develop equations that predict nitrate-N load for the region as a function of climate and fertilizer timing and application rate in southern Minnesota. Fertilizer timing treatments used in model simulation included fall, spring, and variable rate nitrogen (VRN) applications, where the VRN application involved half of the fertilizer applied before planting and the remaining half at approximately corn V6 growth stage. Drainmod results showed the highest nitrate loads occurred for all fall application rates, followed by spring, with VRN having the lowest nitrate loads. An exponential regression model which used fertilizer application rate and growing season precipitation as the dependent variables showed good agreement with Drainmod results, with R^2 of 0.46, 0.49, 0.52 for spring, split-VRN, and fall application timing respectively. The regression model showed that the variation in nitrate-N load between the timing treatments was highly related to annual precipitation and fertilizer application rates. For a growing season precipitation of 60 cm, the “best-case” scenario of split-VRN, applied at a rate of 100 kg N/ha results in 14 kg N/ha less nitrate lost than the “worst-case” scenario of fall application at a rate of 180 kg N/ha (a 58% reduction). At 100 cm of precipitation, the “best-case” split-VRN, low rate application results in 67 kg N/ha less field nitrate losses compared to the “worst-case” fall, high rate application (59% reduction).*

Keywords. *Drainmod-NII, variable rate nitrogen, nitrate load, fertilizer management, subsurface drainage.*

Introduction

Nitrate-nitrogen (N) from fertilizer applied to subsurface tile drained corn cropping systems in the Upper Mississippi river basin is a cause of impairment to both fresh and marine water systems (David et al. 2010; Schulte et al. 2006). Its role in the development of one of the largest hypoxic zones in the world in the Gulf of Mexico has drawn intense scrutiny of N losses from agricultural lands in the Upper Midwest, with an estimate that nitrate-N entering the Mississippi River from upstream farm fields needs to decrease by at least 45% in order to reduce its size to a more reasonable extent (Committee on Environment and Natural Resources, 2010, US EPA, 2007).

In the Upper Mississippi river basin, nitrate-N loading from farm fields to surface waters is a function of subsurface drainage and soil nitrate concentration (Randall and Goss 2008). Subsurface drainage rates peak in the months of April through June when soils thaw and plant evapotranspiration rates are low (Randall 2004). Conventional fertilizer application occurs in the spring or fall before planting, greatly increasing the amount of nitrate-N present in the soil when drainage rates are high, and increasing the potential for nitrate loss. In a 15 year study in Minnesota, this 3-month period accounted for 71% of the annual drainage volume and 73% of the annual nitrate loss from a corn-soybean rotation (Randall 2004). In addition to timing mismatches, farm fields in the upper Midwest can display significant within-field variability in soil organic matter and nitrogen content (Mamo et al. 2003; Scharf et al. 2005), yet more than two-thirds receive a blanket N application (Erickson and Widmar 2015). This practice of uniform fertilizer application over fields with non-uniform soil-sourced nitrogen can result in higher losses of N (Power et al. 2000).

Nitrogen management practices which focus on applying the right rate at the right time have been proposed to reduce N loads to surface waters for a number of years (i.e. Nelson 1985). Split-variable rate nitrogen fertilizer (VRN) application addresses both the temporal and spatial mismatches that occur with single uniform pre-plant applications. In this management, part of the total N amount is applied at or before planting, and part as side-dress during the growing season, delaying full application of fertilizer until corn growth stage V6-V8. Side dressing rates are based on spatial variations in plant N requirements, which can be variable based on crop sensing (Mulla 2013) or in-season modeling of plant available N, reducing over-application of fertilizer on areas with high soil nitrogen content.

Though split-VRN fertilizer application has the potential to reduce nitrate-N loads to surface waters from agricultural fields, there has been little research on how it compares to conventional single, uniform application in this regard. In this study, we used the hydrologic and nitrogen simulation model Drainmod-NII to predict nitrate-N losses for fields managed with a single spring or fall fertilizer application, or split-VRN applications for three sites in southern Minnesota: Waseca, Lamberton, and Willmar. Simulations were done for various nitrogen rate applications and over several years of climate data. The results of these simulations were used to develop regression equations that could be used to estimate nitrate-N loss for spring, fall, and VRN application for southern Minnesota more generally.

Methods

Drainmod-NII

Model Description

The hydrologic model Drainmod-NII was used to simulate subsurface drainage and nitrate losses at three sites in southern Minnesota: Waseca, Willmar, and Lamberton. Drainmod is a process-based, distributed, field-scale model, developed to describe the hydrology of poorly or artificially drained lands (Skaggs et al. 2012). It conducts water balances on hourly and daily time scales, and predicts hydrologic parameters including infiltration, runoff, evapotranspiration, seepage, water table depth, and subsurface drainage on a daily, monthly, and annual time step. The companion model, Drainmod-NII predicts nitrogen transport and transformation processes in the vadose zone, including processes such as mineralization, immobilization, nitrification, as well as nitrogen flows out of the system in the form of plant uptake, denitrification, volatilization, and losses from surface runoff and subsurface drainage (Youssef et al. 2005).

Model Calibration

Drainmod-NII was calibrated for measured subsurface drainage flow depths and nitrate-N loads at each of the three sites. Drainage flow and nitrate losses over multi-year periods had been measured at Waseca, Willmar and Lamberton as part of other research projects. The measured datasets were used to calibrate the model at each site for subsurface drainage and nitrate losses. Initial Drainmod-NII input parameters for simulations of all three sites were based on values reported by Luo et al. (2010), with additional calibration of parameters done for each location to ensure good fit between the model-simulated and measured datasets.

Model performance was evaluated by calculating the Nash-Sutcliffe Coefficient of Efficiency (NSCE) and percent bias (PBIAS), which are defined as:

$$NSCE = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2} \tag{1.1}$$

$$PBIAS = \frac{\sum_{i=1}^{n}(O_i - P_i)}{\sum_{i=1}^{n} O_i} \times 100 \tag{1.2}$$

Where O_i is the observed (measured) data, $\bar{O}$ is the mean of the observed data, and P_i is the corresponding model-predicted value.

Site Descriptions and Model Calibration

Waseca

The subsurface drainage and nitrate-N loss data used to calibrate Drainmod for the Waseca site were measured at the University of Minnesota Southern Research an Outreach Center, located in Waseca, MN. The drainage experiment site at Waseca consists of nine plots ranging in size from 0.8 to 2.4ha. Half of the plots have drainage intensities of 13 mm d^{-1} (conventional or "low" intensity), while the other half have a higher drainage rate of 51 mm d^{-1} (high intensity). More detail on the drainage design can be found in Sands et al. (2008). Corn (Zea mays L.) and soybean (Glycine max L.) were grown in rotation for four years, starting with soybean in 2003, with corn following corn for the fifth year (a soy-corn-soy-corn-corn rotation). The major soil types at the site include Webster silty clay loam (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) and Nicollet clay loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls). Average annual precipitation is approximately 900 mm; precipitation during the growing season (May through September) is approximately 533 mm (averages are the 30 year normal, 1981-2010; NOAA 2016). Plots were outfitted with tipping buckets to provide a continuous measurement of subsurface drainage flow rates for the years 2003-2008. Nitrogen concentrations were recorded on an event basis for the years 2003 to 2008, and on a weekly basis in 2016. Nitrogen load data for the years 2003-2008 set was estimated using the Army Corps of Engineers model, FLUX, using the daily flow and sampled nitrogen concentration measurements.

Drainmod was calibrated for the years 2003-2008, corresponding to period of continuous observed drainage and nitrate load measurements. Model calibration was done for one plot within each depth/spacing treatment (plots 3, 4, 6, and 7), and validated for the remaining plots (1, 5, 8, and 9). For calibration, ammonium fertilizer was applied only during corn years, 7 days before planting, at a rate of 135 kg N/ha. Climatic data measured at the Waseca experiment station site for the years 2003-2016 was used as model input and for calculating daily potential evapotranspiration (PET) using the Penman-Monteith method. Measured climatic data used as model input included hourly precipitation and daily maximum and minimum temperatures, while daily temperatures, relative humidity, solar radiation, and wind speed were used to calculate PET. Parameters calibrated from the initial values included: saturated hydraulic conductivity, and soil organic matter.

Willmar

The subsurface drainage and nitrate loads used to calibrate Drainmod for Willmar were obtained from a study by Ghane et al. (2016). This work took place at Goran's Discovery Farm, a privately owned farm located just southeast of the town of Willmar, MN. In their study, daily subsurface flow and nitrate load data were collected for the period 2007-2013 from a 50 ha field with subsurface drainage installed at an average depth of 1.2 m with 24 m spacing. Located in this field was also a surface inlet that connected to the subsurface drainage system. The dominant soil type in the field was poorly drained Canisteo (fine-loamy, mixed, calcareous, mesic Typic Endoaquolls), and Harps loam (fine-loamy, mixed, mesic Typic Calciaquolls). Average annual precipitation is approximately 748 mm; precipitation during the growing season is approximately 510 mm. More detailed information on soil measurements, field measurement of drainage flow and nitrate load, and field management can be found in Ghane et al. (2016).

Lamberton

Measured drainage and nitrate loads for the years 1990-1998 were obtained from plot studies at the University of Minnesota Southwest Research and Outreach Center (SROC) in Lamberton, MN and used for Drainmod calibration. Plots at this site were planted in a corn-soybean rotation, and had dimensions of 13.7 m by 15.24 m, with subsurface tile drainage placed at a depth of 1.2 m, and spacing of approximately 27 m (personal communication, Jeff Strock, University of MN Extension). Soils at SROC in Lamberton are predominately poorly draining Webster silty clay loam (fine-loamy, mixed, superactive, mesic Typic Endoaquolls), moderately well drained Normania loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls), and well drained Ves loam (fine-loamy, mixed, superactive, mesic Calcic Hapludolls) (Oquist et al., 2006). Average annual precipitation is approximately 709 mm; precipitation during the growing season (May through September) is approximately 497 mm.

Drainmod Simulation and Regression Analysis

Model Simulation

Following calibration, Drainmod was run for all three sites for a spring, fall, and split-VRN fertilizer application. For Waseca, simulations were only done for two of the overall 9 plots (plots 4 and 6), representing both high and low intensity drainage plots (table 1).

In order to capture the nitrate-loss response with regard to fertilizer application rate, several fertilizer application rates were used in the simulations. For the spring application simulations, nitrogen fertilizer was applied as ammonium in the spring 7 days before planting corn (occurring in late April), at rates of: 10, 100, 150, 160, and 200 kg N/ha. For the split-VRN application, half the total N fertilizer was applied 7 days before planting, and the remaining half applied at approximately the V6 stage for corn, 60 days after planting (mid-June). The application rates used for the split-VRN applications were: 10, 100, 150, and 200 kg N/ha. For the fall application, fertilizer was applied 120 days after soybean (mid-October), at rates of 10, 100, 150, and 200 kg N/ha. The rates of 150 and 160 kg N/ha were chosen for these simulations are similar to those used by farmers in the region (Bierman et al., 2011). However, the rate of 160 kg N/ha was not used in the split-VRN or fall simulations because the spring simulations showed little difference in the application of 150 compared to 160 kg N/ha (figure 1). The application rate of 100 kg N/ha was equal to the fertilizer rate applied to split-VRN fields in a 2016 field experiment at Waseca

(Wilson et al., 2017). The upper and lower amounts (10 and 200 kg N/ha) were arbitrarily chosen to ensure a large range of possible nitrogen fertilizer rates. Simulation rate and timing for each site are summarized in table 1.

Table 1. Fertilizer rates and timings used for Drainmod-NII simulations. For fall application, the fertilizer was applied in the fall after harvesting soybean, which occurred 120 days after the crop was planted.

Location	Fertilizer Application Timing		Total Fertilizer Rate (kg N/ha)	Years Used in Simulation
Waseca (Plots 4 and 6)	Spring	7 days before planting corn	10, 100, 150, 160, 200	2003-2016
	VRN	½ of total 7 d before planting, ½ of total 60 d after planting corn	10, 100, 150, 200	
	Fall	120 days after planting soybean	10, 100, 150, 200	
Willmar	Spring	7 days before planting corn	10, 100, 150, 160, 200	2008-2013
	VRN	½ of total 7 d before planting, ½ of total 60 d after planting corn	10, 100, 150, 200	
	Fall	120 days after planting soybean	10, 100, 150, 200	
Lamberton	Spring	7 days before planting corn	10, 100, 150, 160, 200	1995-2005
	VRN	½ of total 7 d before planting, ½ of total 60 d after planting corn	10, 100, 150, 200	
	Fall	120 days after planting soybean	10, 100, 150, 200	

Regression Analysis

The results of the Drainmod-NII simulations were combined in a regression analysis to predict the nitrate loss for spring, fall, and split-VRN fertilizer application. The regression analysis used climate data (including annual and seasonal temperature and precipitation), and fertilizer application rates as potential independent variables.

Results and Discussion

Drainmod Calibration

Model performance for predicting subsurface drainage and nitrate losses following calibration are shown in table 2. Waseca had been calibrated for an earlier study based on monthly NSCE (Wilson et al., 2017). For flow, model performance is considered satisfactory for a NSCE greater than 0.50, or PBIAS between +/- 10 to 15%. For nitrogen loss, satisfactory model performance is for NSCE greater than 0.35, and PBIAS between +/- 20 to 30% (Moriasi et al., 2015). Unlike the NSCE, PBIAS does not take into account variability in the observed data, and so can bias against datasets that show significant variability.

Table 2. Summary of Drainmod-NII model performance for predicting subsurface drainage and nitrate losses following calibration. For Waseca, model performance was evaluated using monthly NSCE. Model calibration results are shown here only for plots 4 and 6—those used in the model simulation for the different rate treatments.

	Model Goodness-of-Fit for Waseca	
	Waseca—Plot 4	Waseca—Plot 6
	NSCE	NSCE
Drainage	0.49	0.50
Nitrate Loss	0.55	0.60

Nitrate Losses Predicted by Drainmod-NII

The results of Drainmod prediction for each of the nitrogen rate treatments at Waseca are shown in figure 1 for the spring application, figure 2 for the split-VRN application, and figure 3 for fall application. In general, nitrate losses are greatest for fall applications, and least for spring split-VRN applications, with spring application nitrate losses falling between these two alternative practices. For all application timings, nitrate loss is related to growing season precipitation, with greater losses corresponding to greater growing season precipitation (months of April-September). Additionally, nitrate losses are also related to the application rate, with greater rates showing greater nitrate losses. This trend is most obvious with higher precipitation rates; during dry years, there is less of a difference in nitrate losses for the different application rates.

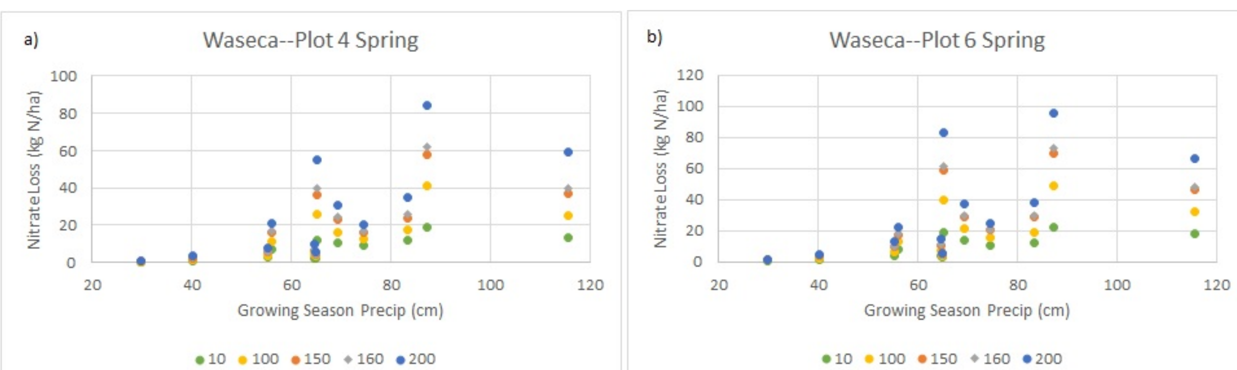

Fig1. Drainmod simulated nitrate load for spring fertilizer application vs. growing season precipitation for a) Plot 4 at Waseca and b) Plot 6 at Waseca.

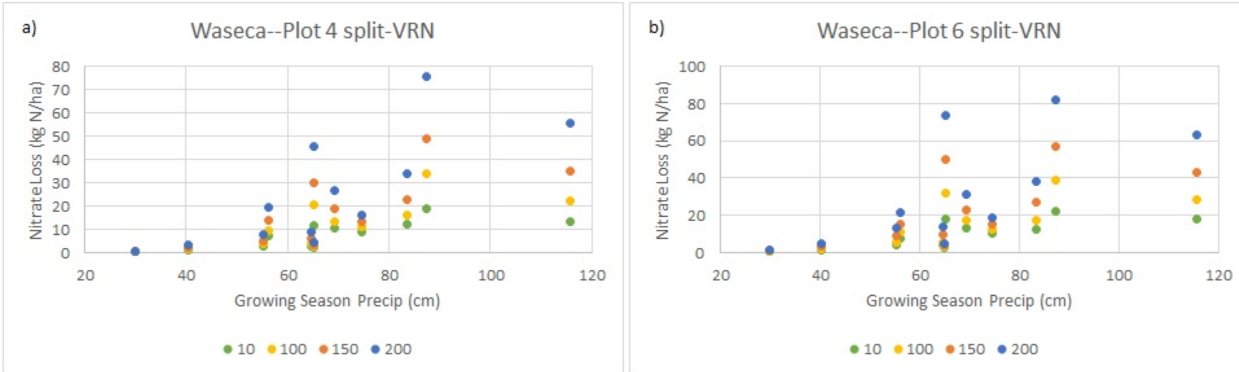

Fig 2. Drainmod simulated nitrate load for split-VRN fertilizer application vs. growing season precipitation for a) Plot 4 at Waseca, and b) Plot 6 at Waseca.

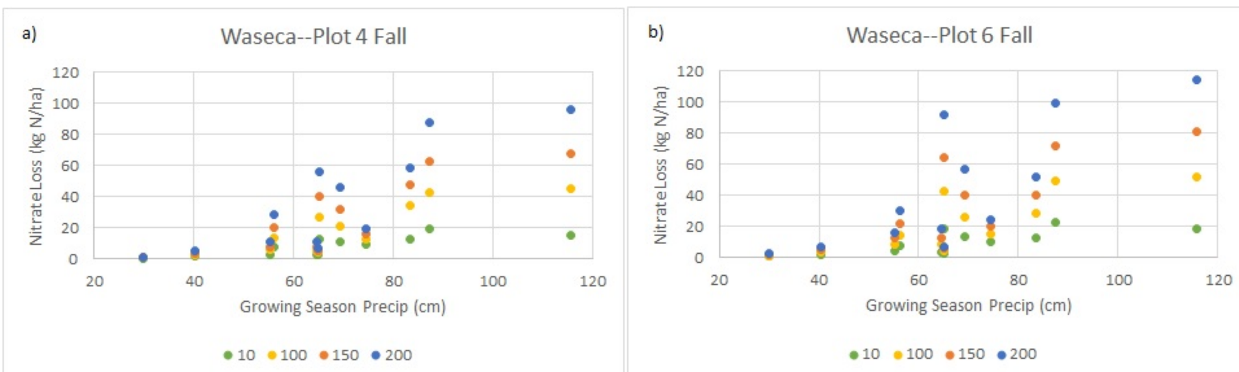

Fig 3. Drainmod simulated nitrate load for fall fertilizer application vs. growing season precipitation for a) Plot 4 at Waseca, and b) Plot 6 at Waseca.

Regression Equations

Predictive Equations

Using the nitrate loss results from the Drainmod simulations for sites at Waseca, Willmar, and Lamberton and fertilizer application rate in a regression analysis, the nitrate losses for a corn-soybean rotation were best predicted by an exponential equation that used the fertilizer rate applied during corn years and growing season precipitation as the independent (x) variables. Equations best predicting nitrate loss (y) for spring, split-VRN, and fall application timing are shown in equations 2.1, 2.2, and 2.3, respectively:

$$y_{spring} = exp(-0.32022 + 0.005867x_1 + 0.03667x_2) \tag{2.1}$$

$$y_{VRN} = exp(-0.38152 + 0.004852x_1 + 0.0371x_2) \tag{2.2}$$

$$y_{fall} = exp(-0.32192 + 0.006959x_1 + 0.037938x_2) \tag{2.3}$$

Where x_1 is equal to the rate of nitrogen fertilizer applied (in kg N/ha), and x_2 is equal to the precipitation for the months April through September (in cm). The above equations meet standard statistical assumptions.

The spring-application predictive equation had an R^2 equal to 0.46, split-VRN had an R^2 equal to 0.49, and fall R^2 equal to 0.52. The fit of Drainmod and regression predictions are shown in figure 4.

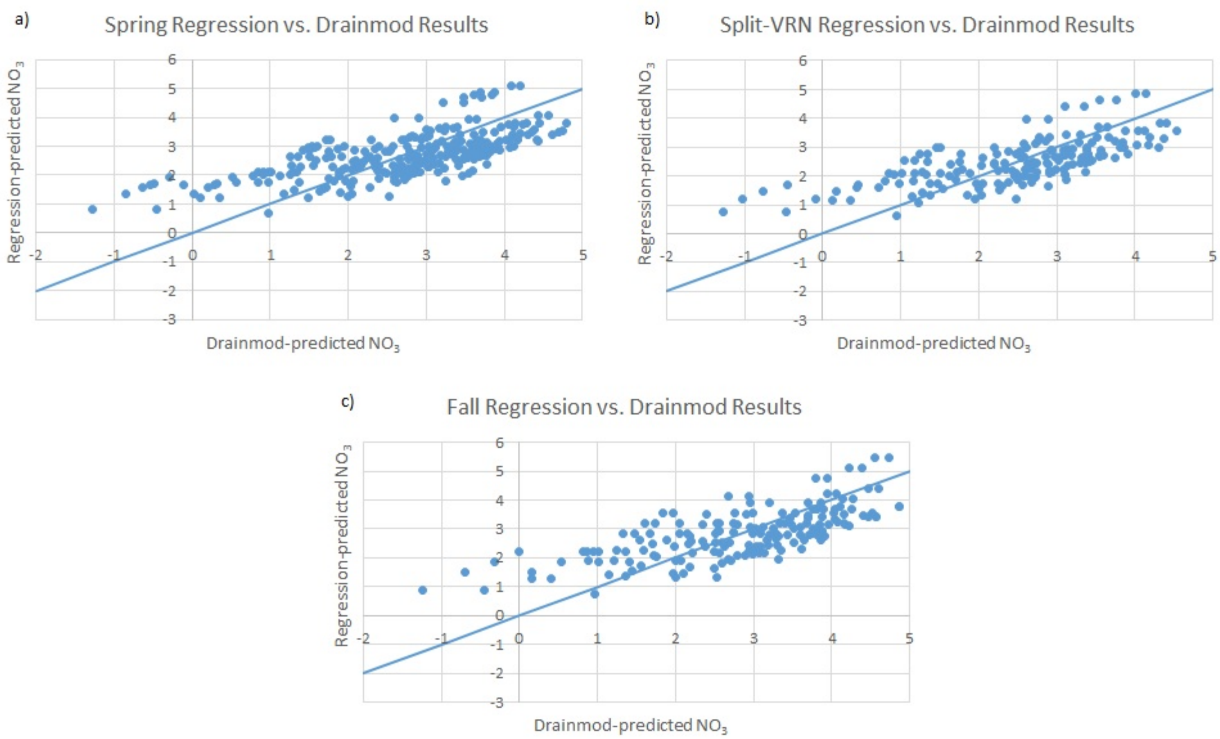

Fig 4. Ln-ln plots of the results for regression predicted nitrate losses compared to original Drainmod-NII simulated data for: a) spring application, 2) split-VRN application, and c) fall application. A natural log (ln) scale was used to achieve the best fit of the residuals. The straight line indicates a 1:1 ratio of Drainmod and regression predictions and a perfect fit between the regression and Drainmod results.

Comparison of spring vs. split-VRN application

Using equations 2.1, 2.2, and 2.3, the predicted nitrate losses for southern Minnesota for spring, split-VRN, and fall application under a low (100 kg N/ha) and high (180 kg N/ha) fertilizer rate are shown in figure 5. The higher application rate results in larger predicted nitrate load for all timings (spring, split-VRN, and fall) compared to the low application rate. For a given precipitation and fertilizer rate, the split-VRN application has the least predicted nitrate loss, with fall application having the highest, though the low fall fertilizer rate has nearly the same nitrate load as the high VRN application. As precipitation increases, there is an increasing trend in nitrate load. For example, for a growing season precipitation of 60cm under the low (100 kg N/ha) fertilizer application rate, the spring application results is 2.37 kg /ha less nitrogen lost than the fall application (a 17% reduction), and the split-VRN application results in 3.88 kg/ha less nitrogen than fall (27% reduction). Increasing the fertilizer application rate to 180 kg N/ha, the reductions in N losses become larger. For the same growing season precipitation of 60 cm with the high fertilizer application rate, the spring application results in 5.85 kg/ha less nitrogen lost than the fall application (a 24% reduction), while the VRN application results in 9.55 kg/ha less N lost (a 39% reduction).

As precipitation increases, the difference between the “best-case” (low fertilizer rate, split-VRN application), and “worst-case” (high fertilizer rate, fall application) scenarios increases. For a growing season precipitation of 60 cm, the “best-case” scenario of split-VRN, applied at a rate of 100 kg N/ha results in 14 kg N/ha less nitrate lost than the “worst-case” scenario of fall application at a rate of 180 kg N/ha (a 58% reduction). At 100 cm of precipitation, the “best-case” split-VRN, low rate application results in 67 kg N/ha less field nitrate losses compared to the “worst-case” fall, high rate application (59% reduction).

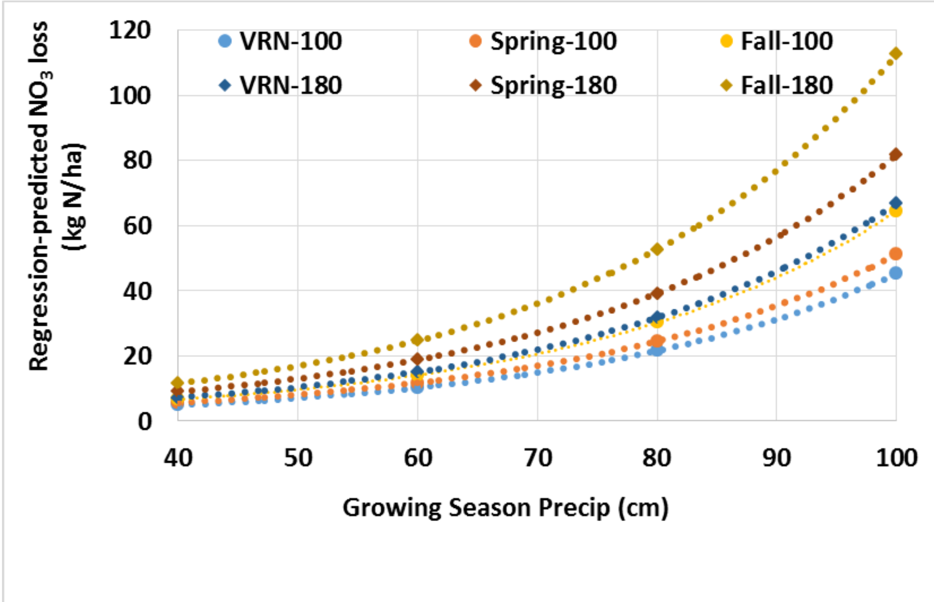

Fig 5 Regression predicted nitrate loss for southern Minnesota under spring, fall, or split-VRN fertilizer timings. Shown here are the results for a low application rate of 100 kg N/ha (VRN-100, Fall-100, and Spring-100), and a high application rate of 180 kg N/ha (VRN-180, Fall-180, and Spring-180).

Conclusions

Drainmod simulations show that nitrate load for three sites in southern Minnesota (Lamberton, Waseca, and Willmar) is related to both the timing and application rate of nitrogen fertilizer. Model results indicate that split-VRN application has the potential to greatly reduce nitrate load compared to fall and spring pre-plant application. Drainmod predicted nitrate loads for each fertilizer application timing were well represented by a regression model with fertilizer application rate and growing season precipitation as the dependent variables. The regression equation can be used in future work to predict nitrate loads in southern Minnesota given known fertilizer application and rate, and growing season precipitation.

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