A two-step modelling approach to reducing environmental risks in cropping systems: an example with maize rotation

HR Pasley[1], VA Nichols[1], MJ Castellano[1], MJ Helmers[2], ME Baum[1], EJ Kladivko[3], and SV Archontoulis[1]

[1] Department of Agronomy, Iowa State University, Ames, Iowa 50011, Email: https://www.agron.iastate.edu
[2] Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, Iowa 50011, Email: https://www.abe.iastate.edu
[3] Department of Agronomy, Purdue University, West Lafayette, Indiana 47907, Email: https://ag.purdue.edu/agry

Abstract

There is a direct relationship between how much N fertiliser is applied to annual crops and the amount of nitrate (NO_3-N) subsequently leached. The degree to which cropping system influences this leaching-fertiliser relationship is largely unknown. We calibrated the APSIM cropping system model using 56 site-years of leaching data sourced from eight field studies in the U.S. Midwest. We simulated a 20-year experiment, comparing the fate of N in two cropping systems (continuous maize and a two-year rotation of maize followed by unfertilised soybean) and fit bi-linear statistical models to the leaching-fertiliser response. We found that above the model breakpoint (the N rate at which the rate of leaching changes), leaching per kg N fertiliser applied increased by 300% in the 2-year maize-soybean rotation and 650% in continuous maize. This breakpoint occurred at 16% above the average agronomic optimum N rate (AONR) in continuous maize, but 66% in the rotation. The breakpoint was also higher than the N rate needed to optimise the amount of leaching per unit yield produced. Rotating maize with soybean increases the buffer around overestimating the AONR without drastically increasing NO_3-N leaching. Applying a statistical model to the outputs of process-based models is an effect way to target minimising environmental risks in agriculture.

Keywords

Nitrate leaching, modelling, APSIM, crop rotation, yield-scaled leaching

Introduction

Around 15% of the N fertiliser applied to maize leaches into the groundwater. Within a given field and season, there is a threshold N rate or “breakpoint” above which the rate at which nitrate (NO_3-N) leaches increases substantially (Christianson and Harmel, 2015; Pittelkow et al., 2017; Zhou and Butterbach-Bahl, 2014). The factors that determine the N rate at which that breakpoint occurs are not well understood. Nevertheless, it has been widely conjectured that the breakpoint occurs at or around the yield-optimizing N rate (known as the Agronomic Optimal N Rate or AONR) (Delin and Stenberg, 2013; Poffenbarger et al., 2017; Zhou and Butterbach-Bahl, 2014).

The aim of this study was to determine how the response of NO_3-N leaching to increases in the N fertiliser rate relates to the AONR and how it changes across sites and cropping systems. This relationship can both define the environmental costs of over-fertilisation and provide targeted guidance to improve management strategies.

The agriculture process-based model Agricultural Production Systems sIMulator (APSIM) has been found to accurately predict both AONR (Puntel et al., 2018) and NO_3-N leaching (Martinez-Feria et al., 2019) in the U.S. Midwest. Such models can bring critical information to investigate the various factors driving NO_3-N leaching. A statistical model used in combination with a process-based model can significantly improve the accuracy and scope of the process-based model’s predictions (Roberts et al., 2017). By applying a statistical model to APSIM’s outputs, we aim at answering the following questions: (1) is the leaching breakpoint related to the AONR? (2) does this relationship differ with site location and/or cropping system and, if so, what are the practical implications for farmers?

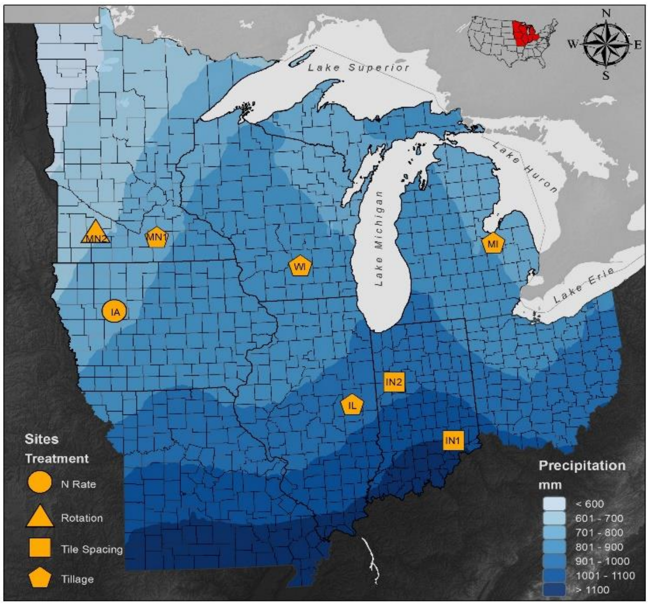
Methods

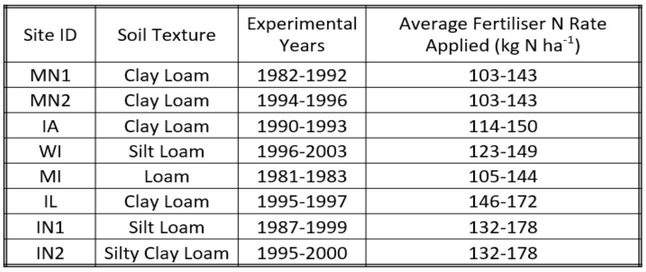
Model Calibration and Simulation

We calibrated APSIM (version 7.9) using 56 site-years of NO_3-N leaching data sourced from eight artificially subsurface-drained field experiments in the U.S. Midwest (Figure 1) using the management scheme of the original study (i.e. cropping system, N source/timing/rate, tillage, subsurface drain depth/spacing etc.). Input to the model included field-specific soil and weather data (daily air temperature, precipitation, and solar radiation) extracted from publications or public soil-weather sources.

Two cropping systems were considered: continuous maize and maize rotated with unfertilised soybean. The model was run for 20 years (2000-2019) at seven different N fertiliser rates (0, 56, 112, 168, 224, 250, 300 kg N/ha). These rates encompassed the range of N fertiliser rates applied in the U.S. Midwest.

Figure 1. Location, 35-year average annual precipitation (1985-2019), and original treatments investigated in the studies modelled in this analysis. (Data source: USDA ERS 2019)





Site ID	Soil Texture	Experimental Years	Average Fertiliser N Rate Applied (kg N ha^{-1})
MN1	Clay Loam	1982-1992	103-143
MN2	Clay Loam	1994-1996	103-143
IA	Clay Loam	1990-1993	114-150
WI	Silt Loam	1996-2003	123-149
MI	Loam	1981-1983	105-144
IL	Clay Loam	1995-1997	146-172
IN1	Silt Loam	1987-1999	132-178
IN2	Silty Clay Loam	1995-2000	132-178

Statistical Analysis

All statistical analysis was conducted using R version 3.6.2 (R Core Team, 2019). The model's accuracy was evaluated based on its grain yield, drainage, flow-weighted NO_3-N and NO_3-N load (kg.ha^{-1}) outputs by calculating the correlation coefficient r^2, root mean square error (RMSE) and modelling efficiency (ME).

For all systems, the leaching from maize sowing to maize sowing was compared (one Julian year in the continuous maize system and two Julian years (one with maize in it, one with soybean) in the maize-soybean rotation). For the cropping system consisting of maize rotated with soybean, the data from the following soybean year were added onto that of the maize year to include in the analysis any residual N from the fertiliser applied in the maize year that leached out during the soybean year.

We fit three candidate non-linear models to N leaching as a function of N fertiliser rate using the nlraa package (Miguez et al., 2020). The three models investigated were (1) bi-linear, (2) exponential, and (3) exponential-linear (Miguez et al., 2018). We fit a bi-linear model to the yield response to N fertiliser rate to determine the AONR. This fit results in a much lower AONR than the more widely used quadratic plateau model but was more appropriate for our analysis. The difference between the leaching and yield breakpoints was defined as the "buffer."

Results

Model Calibration and Simulation

The APSIM model simulated yield, drainage, flow-weighted NO_3-N, and NO_3-N leaching load well with ME values falling primarily between 0.7 and 0.95. The average AONR was 111 kg N.ha^{-1} and 70 kg N.ha^{-1} for continuous and rotated maize, respectively.

Leaching Model

The bi-linear model fit was the best for 92% of those site-years and so, will be used in the rest of the analysis (Figure 2c).

The baseline leaching load (when no N fertiliser was applied) was greater in the maize-soybean rotation than the continuous maize (13 kg N.ha^{-1} vs. 6 kg N.ha^{-1}) and varied with the site and year. The leaching breakpoint and rate of leaching below and above the breakpoint were consistent across sites and years. Below the breakpoint, continuous maize lost less than the maize-soybean rotation (0.08 vs. 0.1 kg NO_3-N). The breakpoint occurred at the fertiliser N rate 129 kg N.ha^{-1} for continuous maize and at 116 kg N.ha^{-1} for the maize-soybean rotation. Above the breakpoint, continuous maize lost an average of 0.6 kg NO_3-N per kg N applied in contrast to only 0.4 kg NO_3-N per kg N applied in the maize-soybean rotation. The buffer between the leaching breakpoint and the AONR was 46 kg N.ha^{-1} in the maize-soybean rotation, but only 17 kg N.ha^{-1} in continuous maize (Figure 2a). The smaller buffer between the AONR and the breakpoint in continuous maize suggests that the risk of negatively impacting water quality via over-fertilisation in continuous maize is much greater than in a maize-soybean rotation.

In both cropping systems, the leaching breakpoint was higher than the N rate needed to optimise the leaching load per kg grain produced. Therefore, farmers are less likely to lose yield to offset environmental N losses in a maize-soybean rotation than in a continuous maize system.

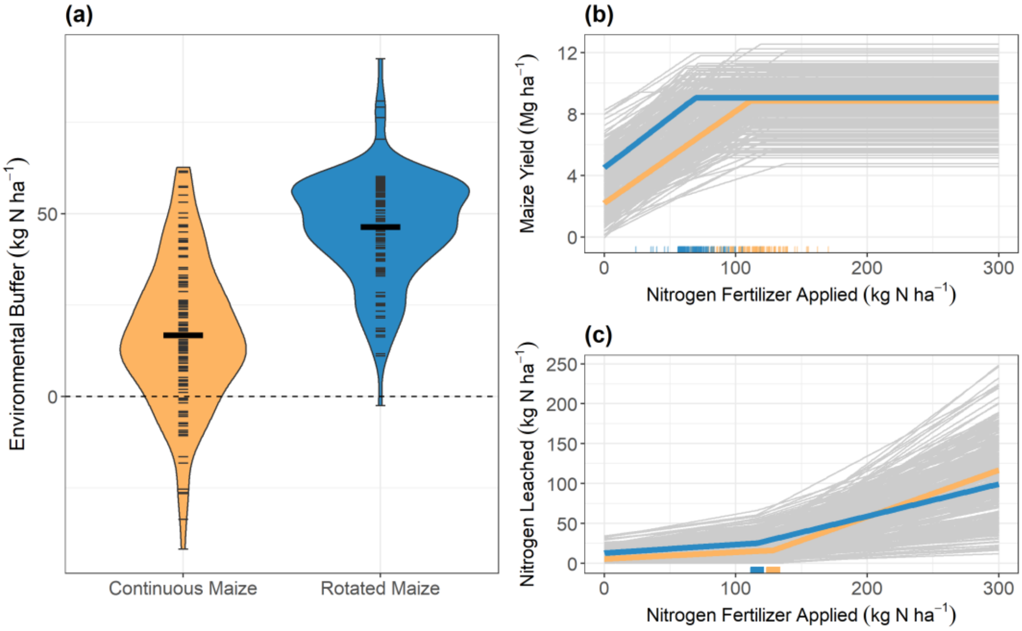


Figure 2. (a) Violin plot of the difference/buffer between the leaching breakpoint and the agronomically-optimum nitrogen rate (AONR) in continuous maize (*Zea mays*) and rotated maize (i.e. maize rotated with soybean (*Glycine max*) in a two-year cycle). The long thick horizontal line in the middle of the violin is the median. The shape and finer lines show the distribution of the data. (b) Maize yield and (c) NO_3-N leaching response to N fertiliser. Gray lines in (b) and (c) are the bilinear model predictions for each site-year, coloured lines are statistical model predictions at the rotation level. Coloured bars along the x-axis indicate the statistical model predicted breakpoints for continuous (orange) and rotated (blue) maize for each site.

Discussion

In our analysis, we found that the breakpoint was not a function of site or year, only cropping system, whereas AONR was strongly influenced by both site and year.

Above the breakpoint, leaching per unit N applied in a single year of continuous maize increased at a rate 1.5 times that of a full 2-year cycle of a maize-soybean rotation. There was also a larger buffer between the AONR and breakpoint in the maize-soybean rotation than in continuous maize.

The smaller buffer under continuous maize suggests that the risk of negatively impacting groundwater quality in continuous maize is much greater than in a maize-soybean rotation.

Conclusion

According to APSIM model predictions, farmers experience less risk of losing yield by reducing their N fertiliser input to minimise environmental N losses in a maize-soybean system than in a continuous maize system. Cropping system models used in conjunction with statistical models can expand upon field experiments to delineate the complex relationships between management strategies and their environmental risks.

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