

Rotating Maize Reduces the Risk and Rate of Nitrate Leaching
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Abstract

There is a strong link between how much nitrate (NO₃-N) is leached from fertilized annual crops and the rate of N fertilizer input. This leaching-fertilizer relationship, however, is poorly understood and the degree to which soil type, weather, and cropping system influence it is largely unknown. We calibrated the APSIM process-based cropping system model using 56 site-years of data sourced from eight field studies that monitored NO₃-N leaching from artificial subsurface drainage systems in one year of continuous maize and summed over a 2-year rotation of maize followed by unfertilized soybean (maize-soybean rotation) across six states in the U.S. Midwest. We then ran a factorial simulation experiment (20 years x 8 locations x 7 fertilizer rates x 2 cropping systems (continuous maize and maize-soybean rotation)) and fit statistical models to the leaching-fertilizer response. A bi-linear model provided the best fit to the relationship between NO₃-N leaching load (kg/ha) and N fertilizer rate (kg/ha). We found that the cropping system dictated the shape of this relationship, but the site and year determined the magnitude of the leaching. Above the model breakpoint, NO₃-N leaching per kg N fertilizer input increased by 300% in the 2-year maize-soybean rotation and by 650% in continuous maize. Moreover, the model breakpoint occurred at only 16% above the average agronomic optimum N rate (AONR) in continuous maize in contrast to 66% in the maize-soybean rotation. Rotating maize with soybean, therefore, allows for a greater buffer than continuous maize around overestimating a given field's AONR without drastically increasing NO₃-N leaching.

Key Words

Nitrate leaching, modeling, APSIM, crop rotation

1. Introduction

Globally, nitrogen (N) fertilization has been a crucial variable in increasing crop yields. This increase, however, comes at a high environmental cost, considering that around 15% of the N fertilizer applied to maize (*Zea mays* L.) leaches into the groundwater as nitrate (NO₃-N) [1-5]. There is inherent risk to the environment in applying N fertilizer at any rate as the ecosystem processes that determine the fate of N fertilizer are both complex and dynamic. Within a given field and season, however, there is a threshold N rate or “breakpoint” above which the risk increases substantially [1,6-13]. Which factors determine the N rate at which that breakpoint occurs are not well understood as the NO₃-N leached each year is not only derived from that

year's N inputs, but also from soil organic matter as well as residual N from applied fertilizer and returned crop residue from previous seasons [14,15].

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) [1,6,12,16]. The ecosystem dynamics that determine the AONR, however, are similar to those of the breakpoint in that they are the result of complex interactions with the weather, soil quality, soil N, and residue from the previously planted crop [17,18]. As both the breakpoint and the AONR are products of complex systems, their relationship may not be as simple as previously conceived.

The aim of this study was to determine how the response of leaching to increases in the N fertilizer rate relates to the AONR. This relationship can both define the environmental costs of over-fertilization and provide targeted guidance for improving management strategies.

The size of soil N storage capacity provides a proportional buffer between the AONR and the leaching breakpoint [19,20]. Any analysis of the leaching breakpoint-AONR relationship, therefore, needs to be conducted across a wide range of environments and management variables as differences in soil characteristics, climate, tillage, and cropping system may be influencing both the AONR and the leaching breakpoint and, thus, the size of the corresponding buffer [6]. Understanding how and why the breakpoint may differ across sites is also important when considering scaling up N fertilizer recommendations to mitigate NO₃-N leaching on a regional scale [21,22].

As NO₃-N leaching originates from residual soil N, organic matter, and additional applications of N fertilizer, it is likely that the leaching breakpoint in a given season is influenced by the previously planted crop i.e. the cropping system. The two cropping systems that account for about 72% of cultivated land in the top 12 maize-producing states in the U.S. (comprising the U.S. Midwest) are continuous maize and a two-year rotation of maize with soybean in which, typically, no N fertilizer is applied to the soybean phase [23,24]. Maize rotated with soybean tends to yield 15% higher than continuous maize despite receiving 30% less N fertilizer input, raising questions about how the fate of N inputs differs between the two systems [25]. Moreover, the organic N inputs, both from previous crop residue and soybean N fixation may have an additive effect on how much N is lost from N fertilizer. Previous studies that have looked at system effects on leaching are often short-term (3-4 years) and have noted that extreme variability in seasonal precipitation appears to influence the fate of NO₃-N in the soil profile, particularly during a soybean year, potentially masking any differences in the relationship between fertilizer N rate and NO₃-N leaching load in these two cropping systems [11,13,26-30]. There is need to expand on these previous findings to know if cropping system selection alters the impact N fertilizer rate selection has on NO₃-N leaching and if this relationship is consistent across multiple environments (climate and soil).

Cropping system models have been successfully used to simulate NO₃-N leaching [31]. These process-based models can investigate the factors driving NO₃-N leaching independent of each other without losing the complexity of the full cropping system. Specifically, Agricultural Production Systems sIMulator (APSIM) ([32]; www.apsim.info) has been found to accurately predict both AONR [17] and NO₃-N leaching [15] in the U.S. Midwest. In their 2014 analysis, Laan et al. [31] called upon researchers to use such process-based models in conjunction with data from multi-year field studies to improve our understanding of the processes driving NO₃-N

leaching. Roberts et al. [33] found that using a statistical model in combination with a process-based model significantly improves the accuracy and scope of the process-based model's predictions. Therefore, in this study, by fitting a statistical model to the outputs from APSIM, we distilled APSIM's complexity into select parameters that we then used to answer two targeted 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?

2. Methods and Materials

2.1 Model Description

2.1.1 The APSIM Model

The APSIM model is an open source field-scale cropping systems modeling platform capable of simulating soil-crop-atmospheric interactions [32]. The platform is customizable to different environments and management strategies and can be run sequentially to capture multi-year legacy effects [34]. It comprises of integrated crop and soil modules that accurately simulate water, temperature, carbon (C), and N dynamics [35-37]. In this project, we used a modified APSIM version 7.9 with waterlogging capabilities [38-39].

2.1.2 Model Setup and Calibration

We calibrated the APSIM model using 56 site-years of NO₃-N leaching data sourced from 8 artificially subsurface-drained field experiments located in the U.S. Midwest (Figure 1; study details can be found in Supplementary Table 1). These experiments measured leaching as well as yield and/or drainage responses to changes in cropping system, tillage, fertilizer N rate, and subsurface drain spacing. As there is a wide variety of approaches to measuring drainage flow and NO₃-N leaching, we selected only studies that used artificial subsurface drain outlets to gather their data rather than lysimeters or suction cups in order to maintain consistency in the data across sites. The other criteria in study selection were that they were multi-year experiments and applied inorganic (not manure) N fertilizer with a single late winter/spring application. All experiments were rain-fed systems. The research design details and data used to model these experiments were primarily sourced from their corresponding publications [11, 40-47]. 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 ([48-50], <https://power.larc.nasa.gov/>). The soil profiles and weather summaries are provided in the supplementary materials (Supplementary Tables 2-3). The model was calibrated using the management scheme of the original study (i.e. cropping system, N source/timing/rate, tillage, subsurface drain depth/spacing etc.).

2.1.3 Model Simulation Experiment

Two cropping systems were considered: continuous maize and maize rotated with unfertilized soybean. For the 2-year rotation, the model was run twice: one set of simulations with maize followed by soybean and the other with soybean followed by maize such that we could compare the outputs from rotated maize with continuous maize each year.

For each site and cropping system combination, the calibrated model was run for 5 years (1994-1999) with standard management per location in the corresponding rotation to stabilize fast decomposing N and C pools and estimate initial conditions [51-53]. The model was then run for

20 years (2000-2019) at 7 different N fertilizer rates (0, 56, 112, 168, 224, 250, and 300 kg N/ha). Maize and soybean cultivars were sourced from the APSIM database with different maturity groups per location (Supplementary Tables 4-5; [54]). The USDA-NASS 50% planting dates for each respective state were used for each season and simulation [55]. Tillage, N fertilizer source/timing, subsurface drain depth/spacing and soils parameters were kept consistent with the original calibrated study.

2.2 Statistical Analysis

2.2.1 Metrics for APSIM Model Calibration

In the calibration process, to test the model's accuracy in capturing grain yield, drainage, flow-weighted $\text{NO}_3\text{-N}$, and $\text{NO}_3\text{-N}$ load (kg/ha), we compared the simulated data from the calibrated models with the corresponding observed data. The statistical analysis of the model's performance was conducted using R version 3.6.2 [56]. Goodness of fit analysis was measured by calculating r^2 , root mean square error (RMSE) and modelling efficiency (ME) [57].

2.2.2 Analysis of APSIM Model Outputs

All processing of the APSIM simulation outputs and statistical analyses were done using the tidyverse meta package [58] in R version 3.6.2 [56]. All other packages are cited below. APSIM runs on a calendar year, but to facilitate comparisons between the rotations we wanted drainage and nitrate leaching to be summed from crop sowing to crop sowing. In order to accommodate this timeline drainage and $\text{NO}_3\text{-N}$ leaching were categorized into two groups: season/post-harvest (sowing to the end of year, December 31) and pre-season (January 1 to the day before sowing). The season/post-harvest data of one calendar year were then combined with the pre-season data of the next year to capture the full effect of the sown crop on drainage and leaching both during the season and following harvest.

For all systems, the leaching from maize sowing to maize sowing was compared. 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 fertilizer applied in the maize year that leached out during the soybean year. A diagrammatic representation of this method is presented in supplementary materials.

Leaching

Data were grouped into experimental units, which were defined as a site-year-rotation combination, resulting in a total of 294 units. We fit three candidate non-linear models to N leaching as a function of N fertilizer rate using the nlraa package [59]. The three models investigated were (1) bi-linear, (2) exponential, and (3) exponential-linear [60]. We chose these three models because they offer meaningful parameters and/or are commonly found in literature. Final model selection was based on Akaike's Information Criteria (AIC) [61], examination of residual plots, and knowledge of biophysical constraints to these systems.

To assess the impact of rotation on the statistical model parameters, we fit a non-linear mixed effect model using the nlme package [62]. We used a fixed effect for rotation (continuous, rotated) and random effects for site and experimental unit nested within site. Estimates and contrasts for the effect of rotation on the parameters were assessed using the emmeans package [63]. Contributions of random effects were assessed using interclass correlation.

Yields

Several models have been proposed to determine the AONR for maize. We chose to use a bi-linear model for its simplicity and applicability to a range of scenarios [64]. While this model may not capture the nuances of real-world relationships, in our simulations it provided a more robust estimation of the yield breakpoint, which is representative of the AONR. We fit a non-linear mixed effect model as described above.

A bi-linear model outputs lower AONR values than the more conventionally used quadratic plateau model [64]. As such, we have included quadratic plateau model-derived AONR values for all site-years in the supplementary materials for comparative purposes (Supplementary Table 6).

Relationship between leaching breakpoint and AONR

The difference between the leaching and yield breakpoints was defined as the “buffer,” with positive values indicating the leaching breakpoint occurred at a higher N fertilizer rate than the yield breakpoint. The conditional breakpoint parameter estimates for the leaching and yield experimental units were calculated on a per-experimental-unit basis. The buffer for each rotation was compared using a linear model with rotation as a fixed effect.

3. Results

3.1 Model Calibration and Simulation

The APSIM model simulated yield, drainage, flow-weighted NO₃-N, and NO₃-N leaching load well. The ME values falling primarily between 0.7 and 0.95 with the exception of MI [43], which had an ME of 0.46 due to its limited amount of reported data (Supplementary Figures 2-5; Supplementary Table 7). Most importantly, the model captured treatment differences such as till vs no-till, narrow vs wide subsurface drain spacing, and cropping systems (Supplementary Figures 6-8). There was a wide range of AONR values found for both continuous (66-170 kg N/ha) and rotated maize (24-119 kg N/ha); the average AONR, however, was 111 kg N/ha and 70 kg N/ha for continuous and rotated maize, respectively (Figure 2b; Supplementary Figure 9; Supplementary Table 6).

3.2 Leaching Model

Of the 294 simulated site-years, 277 had all three tested non-linear models (bi-linear, linear-exponential, and exponential) converge for the NO₃-N leaching load’s response to fertilizer N rate. For 92% of those site-years, the bi-linear model fit was best and for 8%, the linear-exponential fit was best. The exponential fit was not found to be the best fit for any of the site-years. The rest of our analysis, therefore, will be based on the bi-linear model fit (Figure 2c).

When no fertilizer was applied, significantly more NO₃-N was leached from the maize-soybean rotation than from continuous maize (13 kg N/ha and 6 kg N/ha, respectively). Both systems’ leaching loads varied significantly by site (28% of variation) and, to a lesser extent, by year (16%).

The parameters defining the slope below and above the breakpoint as well as the breakpoint itself differed significantly with system. Site location and year, however, did not have a significant influence on these parameters. Continuous maize lost 0.08 kg NO₃-N per kg N applied below the breakpoint and above the breakpoint, lost an average of 0.6 kg NO₃-N per kg N applied (95% CI: 0.54-0.63) above, while the maize-soybean rotation lost 0.1 kg NO₃-N and 0.4 kg NO₃-N per kg N applied (95% CI: 0.37-0.43), respectively. The breakpoint occurred at 129 kg N/ha (SE: 0.6) for continuous maize and at 116 kg N/ha (SE: 1.9) for the maize-soybean rotation.

3.3 Relationship between AONR and Leaching Breakpoint

There was a greater margin for error in rotated maize than in continuous maize around overestimating a given field's AONR without drastically increasing the rate of NO₃-N leaching. The leaching breakpoint in the model occurred at 46 kg N/ha (95% CI: 44-49) or 66% above the AONR in the maize-soybean rotation and 17 kg N/ha (95% CI: 14-20) or 16% above in continuous maize (Figure 2a).

Within the maize-soybean rotation, at N rates above the breakpoint, leaching loads during the soybean seasons were higher than those under maize, pointing to the residual effects of applying excessive amounts of N during the maize season (Figure 3). However, the leaching per year from the rotated system (be it the maize or soybean year) was always lower than that of continuous maize.

4. Discussion

4.1 AONR-Leaching Breakpoint Relationship

In this study, we used long-term model simulation experiments to understand the role of cropping system selection in determining the response of N leaching to fertilizer N rate across 8 rain-fed environments. The environmental and financial implications of losing N via leaching at a greater rate above the breakpoint than below makes estimating this breakpoint crucial for policy makers and farmers alike.

Our findings were consistent with that of Zhou and Butterbach-Bahl's [1] meta-analysis: the leaching breakpoint occurs at N rates that are at least 15% above AONR in maize. We were able to expand upon this previous finding as they made no distinction between continuous and rotated maize and we found that system selection impacts where that breakpoint occurs. Moreover, in our analysis, we found that the breakpoint was not a function of site or year, only cropping system, whereas AONR was strongly dictated by both site and year. As mentioned earlier, the strength of our analysis that allows us to make such conclusions confidently sources from our ability to simulate long-term experiments rather than rely on data from shorter-term experiments.

4.2 Rotation Effect

Above the breakpoint, leaching per unit N applied in a single season 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.

In APSIM, the size of the leachable N pool in each soil layer is calculated as the balance of mineralized soil N (either sourcing from soil organic matter or N fertilizer) that is not immobilized, denitrified, or taken up by the plant. The actual fate of this N is driven by the drainage of water through the soil profile. The model showed that at low N rates, the mineralized soil N pool was smaller under continuous maize than under the rotated system. When the fertilizer input exceeded the breakpoint, the mineralized N pool under continuous maize increased to the same size as that under rotation. This increase has also been found in field experiments where increasing the applied N rate above a certain threshold N rate (between 100 and 200 kg N/ha) increased the mineralized soil N pool under continuous maize systems more than under rotated systems [65,66]. This system-dependent effect of fertilizer on the mineralized N pool size is further evidence of a greater leaching risk under continuous maize in response to increases in N fertilizer rates.

In the model, rotated maize took up more N than the continuous maize. This gap in uptake efficiency increased as the N rate increased. Varvel and Peterson [65, 67] found that in a maize-soybean rotation, maize took up around 50% of the N applied to the crops regardless of the N rate. Meanwhile, when grown continuously, maize took up 50% of N applied at low N rates but only 30% at higher N rates [65]. The smaller buffer we found between AONR and the leaching breakpoint under continuous maize, therefore, stems from both N saturated soil and low N uptake efficiency.

When evaluating the fate of N in a 2-crop rotation, it is important to consider how much leaching occurs throughout the 2-year cycle, as much of the NO₃-N that was not leached during the maize year may be lost during the soybean year [30]. Our simulations found that soybeans experienced more drainage and leaching than maize (rotated or continuous) (Figure 3). Higher drainage levels correspond to more leaching, but that is likely not the only reason for the greater leaching loads during the soybean phase. While soybean took up the same amount of N as rotated maize, much of that N sources from N fixation, leaving the residual N fertilizer from the maize phase of the rotation to leach from the soil profile (68). Carryover N from the previous maize year and high drainage levels during soybean year can increase the leaching load in soybean years almost to the level of continuous maize [4,7].

At high N rates, like those above the breakpoint, continuous maize accumulated a greater pool of mineralized soil N (leachable N) relative to the rotated cropping system. High drainage loads in the soybean years of the maize-soybean rotation resulted in the loss of more N than in rotated maize years, but still less than in the continuous maize system.

4.3 Model Robustness

We found that the cropping system dictated the shape of the leaching response and breakpoint while the site and year explained the variability in the magnitude of the leaching. As such, our leaching model can be applied across multiple sites and years to determine the degree to which increasing the N fertilizer rate impacts the leaching load but should not be used to calculate the total leaching load from multiple sites/years at a given N rate. The significant effect of site and precipitation on the baseline leaching load is further evidence of the important role soil and weather have in determining the fate of residual N over multiple seasons. These legacy effects may explain why previous studies have found inconsistent and/or inconclusive differences in

leaching response to N fertilizer between cropping systems depending on the site, system, and year [13,26-30].

Establishing and maintaining long-term field drainage experiments with as many different N-rates and cropping systems as we simulated (7 N rates x 3 phases x 4 replication = 84 plots x 20 years) is practically impossible due to the financial burden it presents. Moreover, artificially drained experiments tend to be constrained by field size more than other field experiments: for instance, the drainage experimental site with the most plots in the US Midwest has 72 plots, but the plots are small (~0.05 ha) [11]. Using cropping system and statistical models to expand upon field experiments is the only way to delineate the complex relationships between N rate, AONR, and leaching.

4.4 Implications of Findings

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. After conducting a state-wide survey, Sellars et al. [69] reported that 67% of fields in Illinois received N fertilizer rates that exceeded the AONR. Combining their findings with our own can provide a sense of the potential impact replacing continuous maize with a maize-soybean rotation can have on NO₃-N leaching in the U.S. Midwest. Assuming that statistic is consistent across cropping systems and states (i.e. 67% of all continuous/rotated maize in the U.S. Midwest receives too much N), changing from continuous maize to rotated maize could greatly reduce the leaching from around 5 million hectares (16%) of cropland across the U.S. Midwest. A larger buffer between the AONR and breakpoint can reduce the risk that fertilizer over-application leads to groundwater contamination.

This cropping system approach to reducing N leaching is an inexpensive but effective N leaching-mitigating strategy [70]. Nevertheless, there is room for improvement as there has been very little research on what might be a more desirable rotation crop in simple U.S. Midwestern two-crop rotations from a leaching perspective.

5. Conclusion

The cropping system selection plays a significant role in defining the degree to which fertilizer N rate impacts NO₃-N leaching as well as the rate above which leaching increases significantly. Our findings were robust across both environment and climate variability and can provide sound guidance for how farmers can mitigate groundwater contamination.

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Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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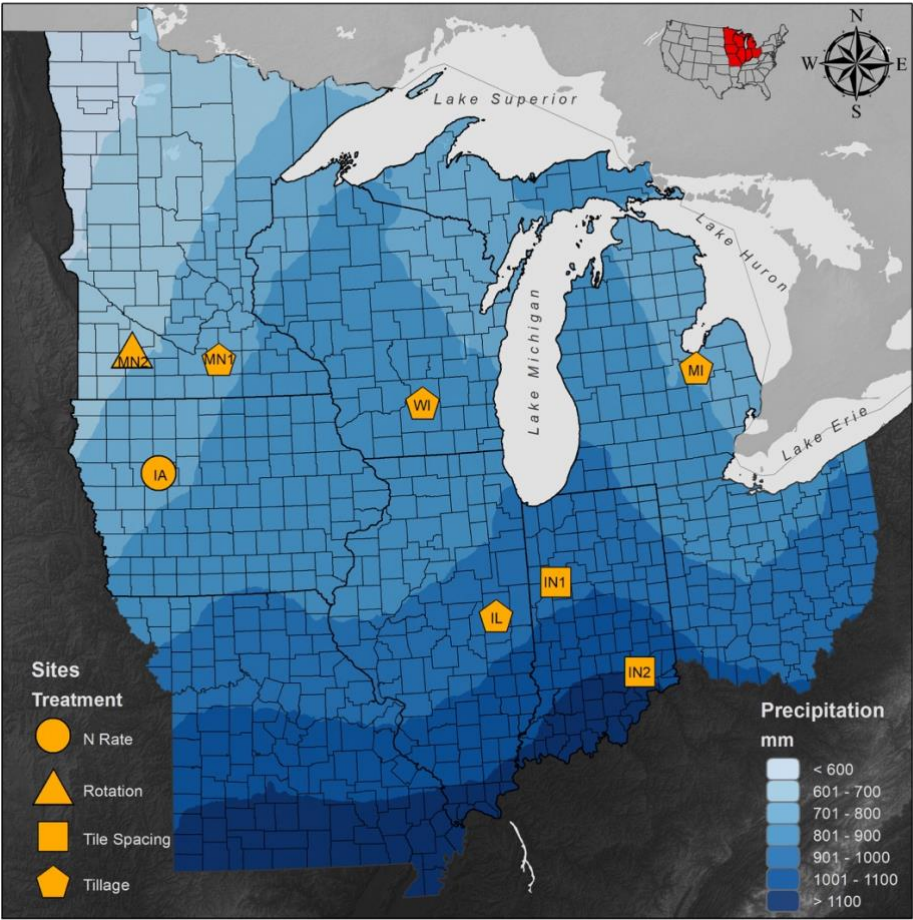
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Figures



Site ID	Reference	Soil Texture	Experimental Years
MN1	[40]	Clay Loam	1982-1992
MN2	[41]	Clay Loam	1994-1996
IA	[11]	Clay Loam	1990-1993
WI	[42]	Silt Loam	1996-2003
MI	[43]	Loam	1981-1983
IL	[44]	Clay Loam	1995-1997
IN1	[45,46]	Silt Loam	1987-1999
IN2	[47]	Silty Clay Loam	1995-2000

Figure 1: Location, 35-year average annual precipitation (1984-2019), and general details of studies modelled in this analysis.

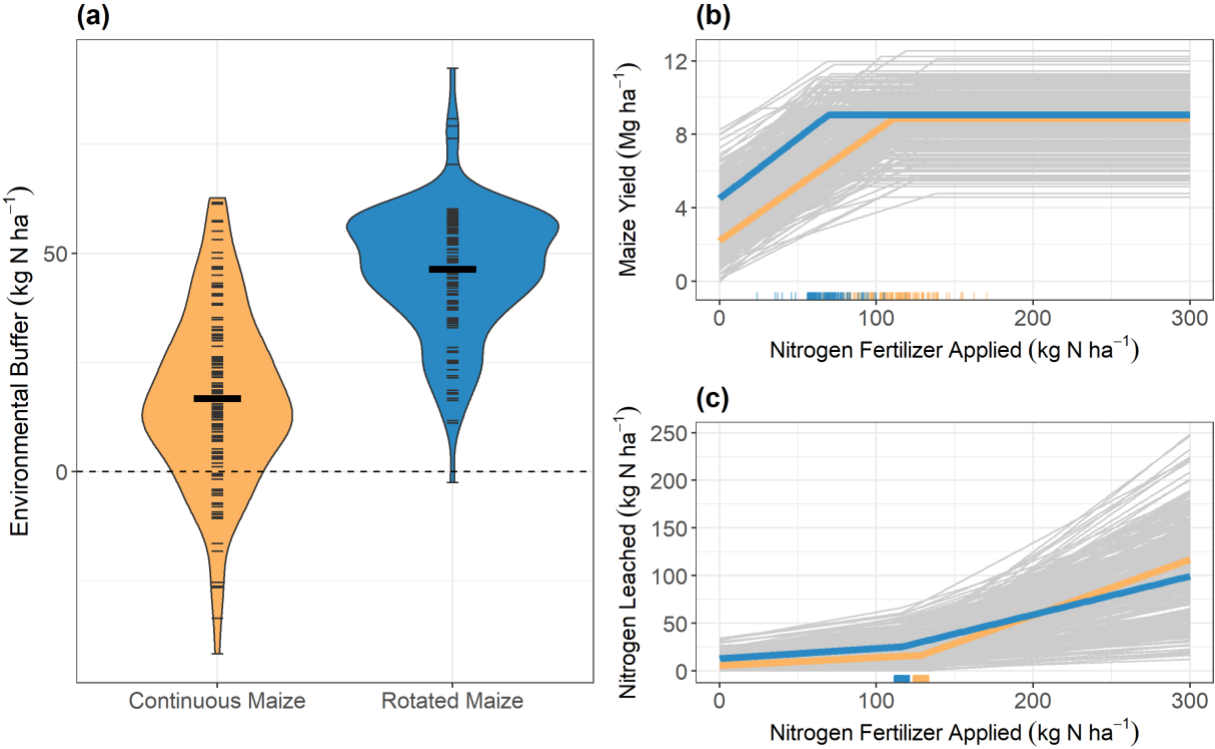


Figure 2: Violin plots (a) of the difference/buffer between the leaching breakpoint and the agronomically-optimum nitrogen rate (AONR) in continuous maize (*Zea mays*) and maize rotated with soybean (*Glycine max*). Maize yield (b) and NO₃-N leaching (b) response to N fertilizer. Gray lines are the bilinear model predictions for each site-year, colored lines are marginal estimated responses at the rotation level. Colored bars along the x-axis indicate the marginal estimated pivot points for continuous (blue) and rotated (orange) maize for each site.

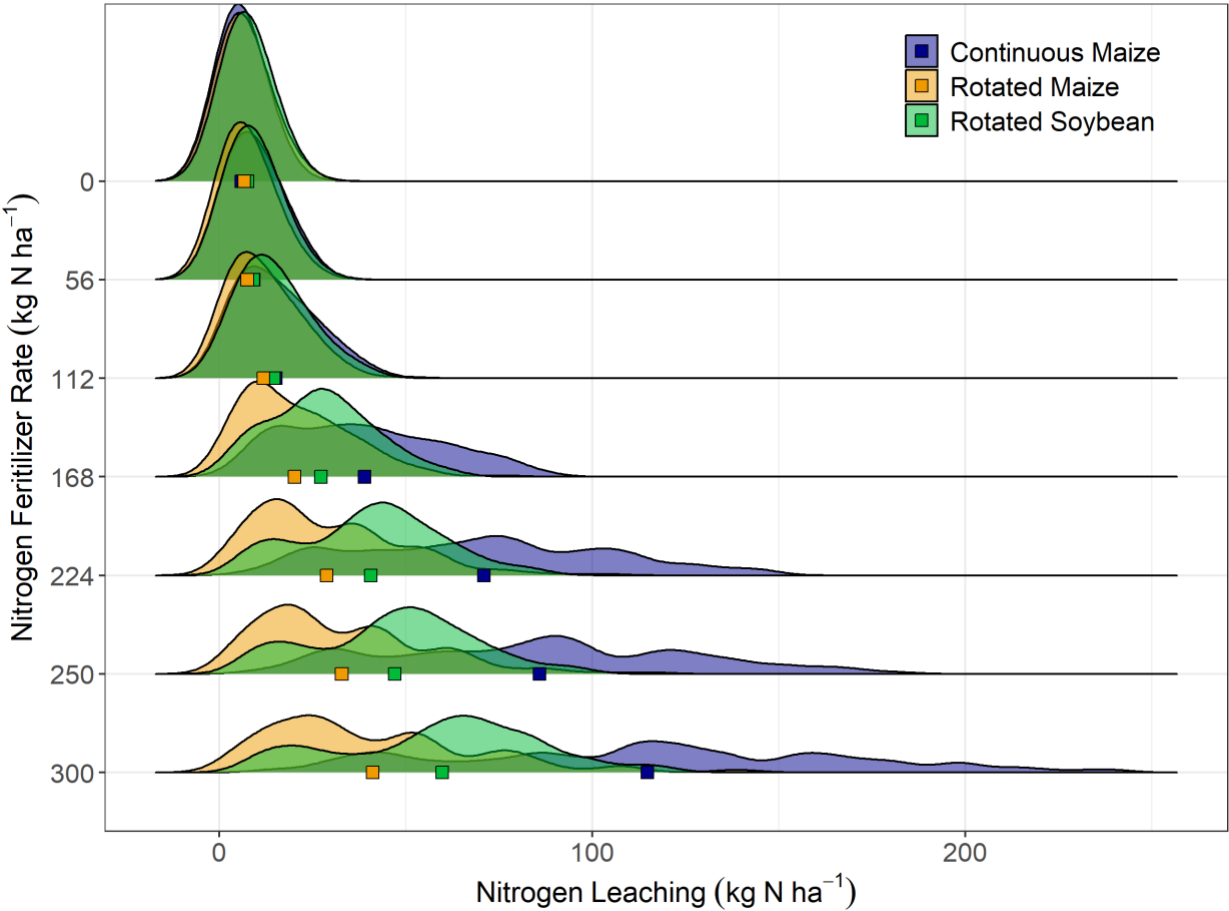


Figure 3: Distribution of $\text{NO}_3\text{-N}$ leaching under continuous maize, rotated maize, and rotated soy at different fertilizer N rates with mean values indicated by squares on the x-axes. For context, the average AONR for continuous maize was 111 kg N/ha and for rotated maize, 70 kg N/ha.