**Rotating Maize Reduces the Risk and Rate of Nitrate Leaching**

HR Pasley1\*, VA Nichols1, MJ Castellano1, MJ Helmers2, ME Baum1, EJ Kladivko3, SV Archontoulis1

1 Department of Agronomy, Iowa State University, Ames, Iowa

2 Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, Iowa

3 Department of Agronomy, Purdue University, West Lafayette, Indiana

\*Correspondence:

Dr. Heather R. Pasley

hrpasley@iastate.edu

**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. However, this leaching-fertilizer relationship 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 across six states in the U.S. Midwest that monitored NO3-N leaching from artificial subsurface drainage systems. We then ran a factorial simulation experiment (20 years x 8 locations x 7 fertilizer rates x 2 cropping systems (continuous maize and a 2-year rotation of maize followed by unfertilized soybean (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) (from one year of continuous maize or summed over the 2-year maize-soybean rotation) and N fertilizer rate (kg/ha). We found that the cropping system dictated the shape of this model, but the site and year determined the magnitude of the leaching. Above the model breakpoint (the point at which the slope changes), 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](http://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 subsequentially 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 (maize in the 2-year maize-soybean rotation) 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 NO3-N, and NO3-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 r2, 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 NO3-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 Figure 1.

*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 with ME values falling primarily between 0.7 and 0.95. In two studies, however, model accuracy evaluation metrics reflected modeling limitations caused by a lack of reported data: leaching and flow-weighted NO3-N data from MI [43] were reported as 3 year averages, resulting in an ME of 0.46 and yield data from IN2 [47] were reported as 6 year averages, resulting in a high RMSEYield (11.22 kg/ha) (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%) (Figure 2c).

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. Below the breakpoint, continuous maize lost 0.08 kg NO3-N per kg N applied while the maize-soybean rotation lost 0.1 kg NO3-N. re was then athe fertilizer N rate at which the rate of leaching changed Above the breakpoint, continuous maize lost an average of 0.6 kg NO3-N per kg N applied (95% CI: 0.54-0.63), but the maize-soybean rotation only lost 0.4 kg NO3-N per kg N applied (95% CI: 0.37-0.43).

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 margin for error was 46 kg N/ha (95% CI: 44-49 kg N/ha) in the maize-soybean rotation but only 17 kg N/ha (95% CI: 14-20 kg N/ha) in continuous maize (Figure 2a).

Within the maize-soybean rotation, at N rates above the breakpoint, leaching loads during the soybean seasons (rotated soybean) were higher than those under maize (rotated 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. Estimating the leaching/fertilizer breakpoint is crucial for policy makers and farmers alike given the environmental and financial implications of losing N via leaching at a greater rate above the breakpoint than below.

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 the AONR in maize (our breakpoint was at 66% above the AONR in the maize-soybean rotation and 16% in continuous maize). Our results expand upon this previous finding as Zhou and Butterbach-Bahl [1] 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 influenced by both site and year. Basing our analysis on long-term simulated experiments rather than on data from shorter-term experiments strengthens our confidence in these conclusions.

4.2 Rotation Effect

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.

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 within the 2-crop rotation, soybeans experienced more drainage and leaching than rotated maize (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 (which encompasses annual differences in plant growth, temperature, precipitation, and soil N pool size/composition) explained the variability in the magnitude of the leaching. Therefore, while 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, it 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 year 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. Residual N can be leached from the soil profile or taken up by the plant, resulting in high leaching loads and/or grain yields even in seasons when no N fertilizer is applied. 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 as it is expensive and laborious. 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 demonstrates 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 from Illinois 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.

**Acknowledgments**

This work was supported in part by the Iowa Nutrient Reduction Center, the Foundation for Food and Agricultural Research (#534264), Iowa Crop Improvement Association, Iowa State University Plant Science Institute faculty scholar program, NSF (#1830478), USDA-NIFA Hatch project (IOW10480), and the National Science Foundation under grant No. DGE-1828942. We thank the APSIM Initiative for making the software publicly available and for ensuring software quality. We also thank Drs. Fernando Miguez and Phillip Dixon for their guidance and statistical expertise and Gerasimos G. Danalatos for his assistance via his GIS expertise.

**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.

**References**

1. Zhou M and Butterbach-Bahl K 2014 Assessment of nitrate leaching loss on a yield-scaled basis from maize and wheat cropping systems *Plant soil* **347** 977-91 doi: 10.1007/s11104-013-1876-9
2. Dinnes D L, Karlen K L, Jaynes D B, Kasper T C, Hatfield J L, Colvin T S and Cambardella C A 2002 Nitrogen management strategies to reduce nitrate leaching in tile-drained midwestern soils *Agron. J.* **94** 153-71
3. Moriasi D N, Gowda P H, Arnold J G, Mulla D J, Ale S and Steiner J L 2013 Modeling the impact of nitrogen fertilizer application and tile drain configuration on nitrate leaching using SWAT *Agric. Water Manag.* **130** 36-43
4. King K W, Williams M R and Fausey N R 2016 Effect of crop type and season on nutrient leaching to tile drainage under a corn-soybean rotation *J. Soil Water Conserve.* **71(1)** 56-68, doi: 10.2489/jswc.71.1.56
5. Bailey A, Meyer L, Pettingell N, Macie M and Korstad J 2020 Agricultural Practices Contributing to Aquatic Dead Zones *Ecological and Practical Applications for Sustainable Agriculture* 373-393 (Singapore: Springer)
6. Lord E I and Mitchell R D J 1998 Effect of nitrogen inputs to cereals on nitrate leaching from sandy soils. *Soil Use Manag.* **14** 78-83
7. Pittelkow C M, Clover M W, Hoeft R G, Nafziger E D, Warren J J, Gonizini L C and Greer K D 2017 Tile Drainage Nitrate Losses and Maize Yield Response to Fall and Spring Nitrogen Management *J. Environ. Qual.* **46** 1057-67, doi: 10.2134/jeq2017.03.0109
8. Perego A, Basile A, Bonfante A, de Mascellis R, Terribile F, Brenna S and Acutis M 2012 Nitrate leaching under maize cropping systems in Po Valley (Italy) *Agric. Eco. Env.* **147** 57-65, doi: 10.1016/j.agee.2011.06.014
9. Zhang Y, Want H, Liu S, Lei Q, Liu J, He J, Zhai L, Ren T and Liu H 2015 Identifying critical nitrogen application rate for maize yield and nitrate leaching in a Haplic Luvisol soil using the DNDC model *Sci. Total Environ.* **514** 388-98, doi: 10.1016/j.scitotenv.215.02.022
10. Simmelsgaard S E and Djurhuus J 1998 An empirical model for estimating nitrate leaching as affected by crop type and the long‐term N fertilizer rate *Soil Use Manag*. **14(1)** 37-43
11. Lawlor P A, Helmers M J, Baker J L, Melvin S W and Lemke D W 2008 Nitrogen application rate effect on nitrate-nitrogen concentration and loss in subsurface drainage for a maize-soybean rotation *Trans. ASABE* **51(1)** 83-94
12. Delin S and Stenberg M 2013 Effect of nitrogen fertilization on nitrate leaching in relation to grain yield response on loamy sand in Sweden *Euro. J. Agron.* **52** 291-6
13. Christianson L E and Harmel R D 2015 4R Water Quality impacts: an assessment and synthesis of forty years of drainage nitrogen losses *J. Environ. Qual.* **44** 1852-60, doi: 10. 2134/jeq2015.03.0170
14. Jaynes D B 2015 Maize yield and nitrate loss in subsurface drainage affected by timing of anhydrous ammonia application *Soil Sci. Soc. Am. J.* **79** 1131-41, doi:

10.2136/sssaj2015.01.0033.

1. Martinez-Feria R, Nichols V, Basso B and Archontoulis, S 2019 Can multi-strategy management stabilize nitrate leaching under increasing rainfall? *Environ. Res. Lett.* **14(12)** 124079
2. Poffenbarger H J, Barker D W, Helmers M J, Miguez F E, Olk D C, Sawyer J E, et al. 2017 Maximum soil organic carbon storage in midwest U.S. cropping systems when crops are optimally nitrogen-fertilized *PlosOne,* doi: 10.1371/journal.pone.0172293
3. Morris T F, Murrell T S, Beegle D B, Camberato J J, Ferguson R B, Grove J, et al. 2017 Strength and limitations of nitrogen rate recommendations for maize and opportunities for improvement *Agron. J.* **110(1)** 1-37, doi: 10.2134/agronj2017.02.0112
4. Puntel L A, Sawyer J E, Barker D W, Thorburn P J, Castellano M J and Moore K J 2018 A systems modeling approach to forecast maize economic optimum nitrogen rate *Front. Plant Sci.* **9** 436
5. Johnson G V and Raun W R 1995 Nitrate leaching in continuous winter wheat: use of a soil-plant buffering concept to account for fertilizer nitrogen *J. Prod. Agric.* **8(4)** 443-90, doi: 10.2134/jpa1995.0486
6. Thorburn P J, Biggs J S, Webster A J and Biggs IM 2010 An improved way to determine nitrogen fertilizer requirements of sugarcane crops to meet global environmental challenges *Plant soil* **339** 51-67, doi: 10.1007/s11104-010-0406-2
7. Raymond P A, David M B and Saiers J E 2012 The impact of fertilization and hydrology on nitrate fluxes from Mississippi watersheds *Curr. Opin. Env. Sust.* **4** 212-8, doi: 10.1015/jcosust.2012.04.001
8. Xin J, Yang L, Chen F, Duan Y, Wei G, Zheng X and Li M 2019 The missing nitrogen pieces. a critical review of the distribution, transformation, and budget of nitrogen in the valdose zone-groundwater system *Water Res.* **165** 114977, doi: 10.1016/j.watres.2019.114977
9. Green T R, Kipka H, David O and McMaster G S 2017 Where is the USA maize belt, a how is it changing? *Sci. Total. Environ.,* doi: 10.1016/j.scitotenv.2017.09.325
10. NASS 2020 Acreage USDA
11. Gentry L E, Below F E, David M B, and Bergerou J A 2001 Source of the soybean N credit in maize production. *Plant soil* **236** 175-184
12. Owens L B, Malone R W, Shipitalo M J, Edwards W M and Bonta J V 2000 Lysimeter study of nitrate leaching from a corn-soybean rotation *J. Environ. Qual.* **29** 467-74
13. Hernandez-Ramirez G, Brouder S M, Ruark M D and Turco R F 2011 Nitrate, phosphate, and ammonium loads at subsurface drains: agroecosystems and nitrogen management *J. Environ. Qual.* **40** 1229-40, doi: 10.2134/jeq2010.0195
14. Christianson L E and Harmel R D 2015 The MANAGE drain load database: Review and compilation of more than fifty years of North American drainage nutrient studies *Agric. Water Manag.* **159** 277-89, doi: 10.1016/j.agwat.2015.06.021
15. Daigh A L M, Zhou X, Helmers M J, Pederson C H, Horton R, Jarchow M and Liebman M 2015 Subsurface drainage nitrate and total reactive phosphorus losses in bioenergy-based prairies and maize systems *J. Environ. Qual.* **44** 1638-1646, doi: 10.2134/jeq2015.02.0080
16. Iqbal J, Necpalova M, Archontoulis S V, Anex R P, Bourguignon M, Herzmann D, et al. 2017 Extreme weather-year sequences have nonadditive effects on environmental nitrogen losses *Glob. Change Biol.,* doi: 10.1111/gcb.13866
17. Laan M V D, Annandale J G, Bristow K L, Stirzaker R J, du Preez C C and Thorburn P J 2014 Modelling nitrogen leaching: are we getting the right answer for the right reason? *Agric. Water Manag.* **133** 74-80, doi: 10.1016/j.agwat.2013.10.017
18. Holzworth D P, Huth N I, deVoil P G, Zurcher E J, Herrmann N I, McLean G, et al. 2014 APSIM—Evolution towards a new generation of agricultural systems simulation *Environ. Modell. Soft.* **62,** doi: 10.1016/j.ensoft.2014.07.009
19. Roberts M J, Braun N O, Sinclair T R, Lobell D B and Schlenker W 2017 Comparing and combining process-based crop models and statistical models with some implication for climate change *Environ. Res. Lett.* **12,** doi: 10.1088/1748-9326/aa7f33
20. Basso B, Martinez-Feria R A, Dumont B 2019 Modeling crop rotations: capturing short- and long-term feedbacks for sustainability and soil health *Burleigh Dodds Series in Agricultural Science*
21. Gaydon D S, Wang E, Poulton P L, Ahmad B, Ahmed F, Akhter S, et al. 2017 Evaluation of the APSIM model in cropping systems of Asia *Field Crop. Res.* **204** 52-75
22. Smith C J, Macdonald B C T, Xing H, Denmead O T, Wang E, McLachlan G, Toumi S, Turner D and Chen D 2019 Measurement and APSIM modelling of soil C and N dynamics. *Soil Res.* **58(1)**, doi: 10.1071/SR19021.
23. Archontoulis S V, Castellano M J, Licht M A, Nichols V, Baum M, Huber I, et al. 2020 Predicting crop yields and soil‐plant nitrogen dynamics in the US maize belt *Crop Sci.* **60(2)** 721-38.
24. Pasley H R, Huber I, Castellano M J and Archontoulis S V 2020 Modeling flood-induced stress in soybeans *Front. Plant Sci.* **11(62)**
25. Ebrahimi-Mollabashi E, Huth N I, Holz D P, Ordonez R A, Hatfield J L, Huber I, Castellano, M J and Archontoulis S V 2019 Enhancing APSIM to simulate excessive moisture effects on root growth *Field Crop. Res.* **236**, doi: 10.1016/j.fcr.2019.03.014
26. Randall G W and Iragavarapu T K 1995 Impact of long-term tillage systems for continuous maize on nitrate leaching to tile drainage *J. Environ. Qual.* **24** 360-66
27. Huggins D R, Randall G W and Russelle M P 2001 Subsurface drain losses of water and nitrate following conversion of perennials to row crops *Agron. J.* **93(3)** 477-86
28. Masarik K and Norman J 2014 Long-term drainage and nitrate leaching below well-drained continuous maize agroecosystems and a prairie *J. Environ. Protect.* **5** 240-54, doi: 10.4236/jep.2014.54028
29. Gold A J and Loudon T L 1989 Tillage effects on surface runoff water quality from artificially drained cropland *ASAE.* **32(4)** 1329-34
30. Gentry L E, David M B, Smith-Starks K M and Kovacic D A 2000 Nitrogen fertilizer and herbicide transport from tile drained fields *J. Environ. Qual.* **29** 232-40
31. Kladivko E J, Frankenberger J R, Jaynes D B, Meek D W, Jenkinson B J and Fausey N R 2004 Nitrate leaching to subsurface drains as affected by drain spacing and changes in crop production system *J. Environ. Qual.* **33** 1803-13
32. Kladivko E J, Willoughby G L and Santini J B 2005 Maize growth and yield response to subsurface drain spacing on Clermont silt loam soil *Agron. J.* **97** 1419-28, doi: 10.2134/agonj2005.0090
33. Hofmann B S, Brouder S M and Turco R F 2004 Tile spacing impacts on Zea mays L. yield and drainage water nitrate load *J. Ecol. Engin.* **23** 251-67, doi: 101.1016/j.ecoleng.2004.09.008
34. Archontoulis S V, Miguez F E and Moore K J 2014 A methodology and an optimization tool to calibrate phenology of short-day species included in the APSIM PLANT model: Application to soybean *Environ. Modell. Softw.* **62** 465–477 doi: 10.1016/j.envsoft.2014.04.009
35. Soil Survey Staff, Natural Resources Conservation Service, United Stated Department of Agriculture. Web soil survey. USDA NRCS. http://websoilsurvey.nrcs.usda.gov/app/ (accessed 1 Mar. 2019).
36. Thornton P E, Thornton M M, Mayer B W, Wei Y, Devarakonda R, Vose R S and Cook R B 2018 Daymet: daily surface weather data on a 1-km grid for North America, version 3, ORNL DAAC, Oak Ridge, Tennessee, USA, doi: 10.3334/ORNLDAAC/1328
37. Basche A D, Archontoulis S V, Kaspar T C, Jaynes D B, Parkin T B and Miguez F E.

2016 Simulating long-term impacts of cover crops and climate change on crop production and environmental outcomes in the midwestern United States *Agric. Ecosyst. Environ.***218** 95-106

1. Dietzel R, Liebman M, Ewing R, Helmers M, Horton R, Jarchow M and Archontoulis S 2016 How efficiently do maize‐and soybean‐based cropping systems use water? A systems modeling analysis *Glob. Change Biol.* **22(2)** 666-81
2. Martinez-Feria R A, Dietzel R, Liebman M, Helmers M J and Archontoulis S V 2016 Rye cover crop effects on maize: A system-level analysis *Field Crop. Res.* **196** 145-59
3. Mourtzinis S and Conley S P 2017 Delineating soybean maturity groups across the United States *Agron. J.* **109(4)** 1397-1403, doi: 10.2134/agronj2016.10.0581
4. Baum M E, Archontoulis S V and Licht M A 2018 Planting date, hybrid maturity, and weather effects on maize yield and crop stage *Agron. J.* **111** 303-13, doi: 10.2134/agonj2018.04.0297
5. R Core Team 2019 R: A Language and environment for statistical computing, Vienna, Austria. Available at https://www.R-project.org/
6. Archontoulis S V and Miguez F E 2015 Nonlinear regression models and applications in agricultural research *Agron. J.* **107** 2, doi: 10.2134/agronj2012.0506
7. Wickham H, Averick M, Bryan J, Chang W, McGowan L D A, François R et al. 2019 Welcome to the Tidyverse *J. Open Source Softw.* ***4*(43)** 1686
8. Miguez F 2020 nlraa: Nonlinear Regression for Agricultural Applications. R package version 0.65. https://CRAN.R-project.org/package=nlraa
9. Miguez F, Archontoulis S and Dokoohaki H 2018 Nonlinear regression models and applications. *Applied statistics in agricultural, biological, and environmental sciences*, 401-447.
10. Bozdogan H 1987 Model selection and Akaike's information criterion (AIC): The general theory and its analytical extensions *Psychometrika* **52(3)** 345-370
11. Pinheiro J, Bates D, DebRoy S, Sarkar D, R Core Team (2019). \_nlme: Linear and Nonlinear Mixed Effects Models\_. R package version 3.1-142, <URL: <https://CRAN.R-project.org/package=nlme>>.
12. Lenth R 2019 emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.4.2. <https://CRAN.R-project.org/package=emmeans>
13. Cerrato M E and Blackmer AM 1990 Comparison of models for describing; corn yield response to nitrogen fertilizer *Agron. J.* **82(1)** 138-143
14. Varvel G E and Peterson T A 1990 Residual soil nitrogen as affected by continuous, two-year, and four-year crop rotation systems *Agron. J.* **82** 958-62
15. Zhu Y and Fox R H 2003 Corn-soybean rotation effects on nitrate leaching *Agron. J.* **95** 1028-1033
16. Varvel G E and Peterson T A 1992 Nitrogen fertilizer recovery by soybean in monoculture and rotation systems. *Agron. J.* **84** 215-8
17. Salvagiotti F, Cassman K G, Specht J E, Walters D T, Weiss A and Dobermann A 2008 Nitrogen uptake, fixation and response to fertilizer N in soybeans: A review *Field Crop. Res.* **108** 1-13
18. Sellars S C, Schnitkey G D and Gentry L F 2020 Do Illinois farmers follow university-based nitrogen recommendations? Agricultural & Applied Economics Association Annual Meeting, Kansas City, MO.
19. Roley S S, Tank J L, Tyndall J and Witter J D 2016 How cost-effective are cover crops, wetlands, and two stage ditches for nitrogen removal in the Mississippi River Basin? *Water Resour. Econ.* doi: 10.1016/j.wre.2016.06.003

**Figures**

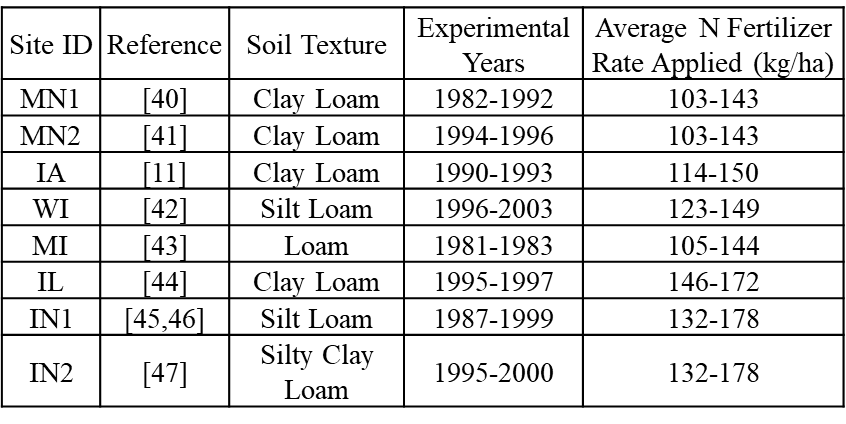


Figure 1: Location, 35-year average annual precipitation (1985-2019), general details of studies modelled in this analysis, and range of average N fertilizer rates applied to maize in each state Data source: USDA ERS 2019.

Chart

Description automatically generated

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 in a 2-year cycle (*Glycine max*)). 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) NO3-N leaching response to N fertilizer. Gray lines in (b) and (c) 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 (orange) and rotated (blue) maize for each site.

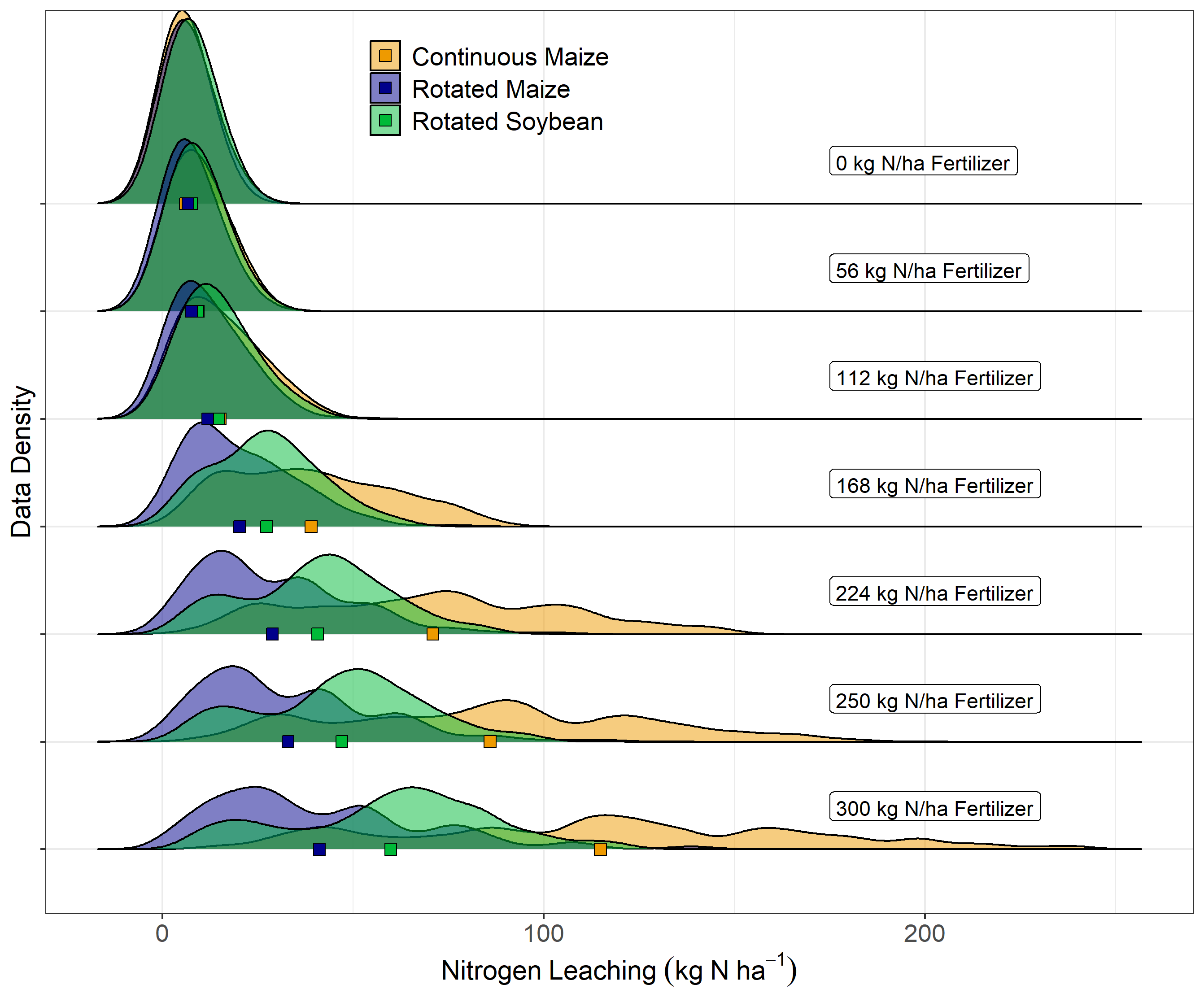


Figure 3: Distribution of NO3-N leaching loads under continuous maize (yellow), rotated maize (maize rotated with soybean in a 2-year cycle) (blue), and rotated soybean (soybean rotated with maize in a 2-year cycle) (green) at different fertilizer N rates with mean values indicated by squares on the x-axes. The height of the peak at a given leaching load (x axis) corresponds to the prevalence of that load across site-years when 0, 56, 112, 168, 224, 250, or 300 kg N/ha (from top to bottom) is applied. For context, the average AONR for continuous maize was 111 kg N/ha and for rotated maize, 70 kg N/ha.