# Unraveling causal mechanisms of the continuous maize penalty

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# Abstract

Maize (*Zea mays*) grown continuously on the same land often requires more inputs while also producing lower yields compared to maize grown in rotation with another crop. The lower yields in continuous maize systems, or the ‘continuous maize penalty,’ is well-documented but a mechanistic understanding of the penalty has remained elusive. In the present study, we (1) used 157 site-years of experimental data to quantify site and environmental variation in the continuous maize penalty, (2) synthesized results with existing literature and modelled scenarios to identify probable mechanistic pathways, and (3) provide recommendations for future research. Experimental data consisted of nitrogen (N)-response curves for maize yields from continuous maize and maize-soybean (*Glycine max*) cropping systems from Iowa (7 sites) and Illinois (7 sites) conducted between 1999 and 2016. All sites were tilled and had sub-surface drainage when appropriate. Maximum continuous and rotated maize yields averaged 8.7 and 9.7 Mg ha-1 over the study period, and both increased 213 (SE:36) kg ha-1 yr-1, rendering the continuous maize penalty steady over time at an estimated 1.0 (SE:0.2) Mg ha-1. The penalty ranged from 0-4.8 Mg ha-1, and site contributed to only 12% of the variation. The amount of rainfall two weeks before planting was positively associated with penalty sizes. Applying additional N above the optimal rate for rotated-maize eliminated the penalty in only 6 out of 157 site-years, and was less effective at more northern sites. Using literature, statistical models, and a processed-based model (APSIM), we hypothesize compromised maize roots following a previous maize crop is a strong potential driver of the penalty. To our knowledge there is limited data to refute or support this hypothesis. Additionally, we identify a suite of field measurements that would allow a thorough investigation of the mechanistic underpinnings of the continuous maize penalty including stand counts, residue amounts (total and surface), root front velocity, kernel number and size, and maximum root length and biomass. These focused measurements would support efforts to manage, breed for, and model the continuous maize penalty, representing a major step forward in maximizing the efficient use of arable lands.

# Introduction

Maize grown for two or more consecutive years makes up around 30% of crop acres in the Midwest (NASS 2017, Dave’s paper). However, even with optimal management maize grown continuously yields less than maize rotated with another crop, most commonly soybean. This phenomenon is well-known and is often referred to as the continuous maize yield penalty. Experimental studies report average penalties ranging from 5-30% across the county (Erikson 2008), but even at high nitrogen (N) rates the penalty at a single site can vary from 0% to over 50% depending on the year (CITE). The penalty is the result of a complex interaction between soils, management, and weather (Al Kaisi et al. 2016, others). Several studies have examined factors associated with the continuous maize penalty, but results are either specific to one site (Gentry, Crookston, that crappy one) or are associative and too broad for field-based inference (Seifert). Therefore, despite the penalty being well- documented, the driving causes have remained elusive, rendering the penalty difficult to predict and manage for. Understanding conditions that affect the magnitude of the continuous maize penalty can help producers predict and optimize management to overcome the penalty, and help researchers incorporate the penalty into models to better capture land-use decisions and their effects on both the environment and economic impacts of cropping systems.

Many bio-physical process-based models are available for simulating agricultural systems (SALUS, DAYCENT, APSIM, CropSys, blah blah). The majority of cropping systems models focus on simulating abiotic processes, with the assumption that disease and pests are adequately controlled (CITE). In any given year the continuous maize penalty is likely a function of both biotic and abiotic conditions. However, direct modelling of biotic components would require a substantial increase in the complexity of processed-based models. Pests not only depend on local conditions (soil moisture, air temperature, humidity), but also on complex regional interactions including physical, biological, social, and economic factors (CITE). Incorporating these factors into a single model is not trivial, and would require coordinated efforts to improve data collection and reporting (Donatelli et al., 2017). However, while modelling the biotic factors directly may not be feasible for most cropping system models, incorporating the physical manifestations of biotic effects may be sufficient for certain purposes.

Our goal was to use multi-site, multi-year data coupled with an in-depth literature review and a process-based model (APSIM, CITE) to gain insight into factors contributing to the continuous maize penalty. Specifically, our objectives were to:

(1) use experimental data to quantify site and environmental variation in the continuous maize penalty

(2) synthesized results with existing literature and modelled scenarios to identify probable mechanistic pathways

(3) provide recommendations for future research

# Methods and Materials

## Experimental data

Details about experimental layouts for the sites (Fig. 1) are reported elsewhere (CITE).

Map

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Figure Map of experimental sites

Briefly, treatments consisted of cropping system (continuous maize, maize-soybean rotation with both phases present every year) and maize nitrogen (N) fertilization rate (Table 1). Each site had four replications of each treatment.

Table Experimental site information

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Site ID** | **Latitude, Longitude** | **Nearest town** | **Seasons of data** | **Nitrogen rates (kg ha-1)** | **General management** |
| *Iowa Sites* |  |  |  |  |  |
| IA-1 | 42.93, -95.54 | Sutherland, IA | 17 | 0, 45, 90, 135, 180, 225, **270** |  |
| IA-2 | 42.91, -93.79 | Kanawha, IA | 12 | 0, 45, 90, 135, 180, 225, **270** |  |
| IA-3 | 42.93, -92.57 | Nashua, IA | 12 | 0, 45, 90, 135, 180, 225, **270** |  |
| IA-4 | 42.02, -93.78 | Ames, IA | 18 | 0, 68, 135, 203, **270** |  |
| IA-5 | 41.31, -95.18 | Lewis, IA | 16 | 0, 45, 90, 135, 180, 225, **270** |  |
| IA-6 | 40.97, -93.42 | McNay, IA | 18 | 0, 45, 90, 135, 180, 225, **270** |  |
| IA-7 | 41.19, 91.48 | Crawfordsville, IA | 18 | 0, 45, 90, 135, 180, 225, **270** |  |
| *Illinois Sites* |  |  |  |  |  |
| IL-1 | 41.84, -88.86 | Dekalb, IL | 10 | 0, 51, 101, 152, 203, **253** |  |
| IL-2 | 40.93, 90.73 | Monmouth, IL | 10 | 0, 51, 101, 152, 203, **253** |  |
| IL-3 | 39.80, -90.82 | Orr Center, IL | 10 | 0, 51, 101, 152, 203, **253** |  |
| IL-4 | 40.08, 88.22 | Urbana, IL | 10 | 0, 51, 101, 152, 203, **253** |  |
| IL-5 | 38.95, -88.96 | Brownstown, IL | 8 | 0, 51, 101, 152, 203, **253** |  |
| IL-6 | 37.46, -88.72 | Dixon Springs, IL upland area | 10 | 0, 51, 101, 152, 203, **253** |  |
| IL-7 | 37.42, -88.66 | Dixon Springs, IL lowland area | 10 | 0, 51, 101, 152, 203, **253** |  |

## Modelling

All modelling was done using APSIM v.10 with the SWIM module and custom scripts to simulate water table dynamics (CITE). Soil profiles were built using SSURGO data (CITE) and adjusted using on-site measurements as they were available. All management activities were taken from field logs. The maize phase was simulated using the XX model, and individual maize cultivars were built to reflect maturity groups of each variety used. The soybean phase was simulated using XX. For each site, simulations were run using an X year spin-up of a generic maize/soybean rotation with X kg ha-1 of fertilization, followed by experiment-specific management and weather. All models were run sequentially without a yearly soil reset in order to best represent cropping system legacy effects.

To explore the potential for changes in model parameters to capture the continuous maize penalty, a model was calibrated to the maize-soybean rotation data at each site by adjusting nitrogen mineralization, etc. (Mitch?). The settings for the rotation-calibrated model were then used for the continuous maize system as a baseline for each site. Single parameters were adjusted one at a time using the *apsimx* package (CITE) in R, and the continuous maize model for each site was re-run to calculate the change in model-predicted continuous maize penalty.

To explore the possibility of having parameters change dynamically in response to specified conditions, we built X scripts

## Statistical analyses

All statistical analyses were done using R version 4.0.3 and using the tidyverse collection of packages (CITE). Mixed effect linear models were fit using the *lme4* package (CITE) with means estimated using the *emmeans* package (CITE), and non-linear models were fit using the *nlraa* package (CITE). Other packages are cited upon mention. Assumptions of normally distributed errors and equal variance were explored, and Akaike’s Information Criteria (AIC; XX) were used to identify the best models when appropriate.

To estimate the maximum yields for each site-year’s cropping system a quadratic plateau was fit to each site-year for each system’s maize yields as a function of N fertilization rate (e.g. Figure 2). We chose to use a quadratic plateau because it is a commonly used model for yield-N response curves (CITE), it converged for the most site-years of our data, and it provided the best fit in the majority of cases. The agronomically-optimum-nitrogen-rate (AONR) is the N-rate at which maximum yields are achieved. The difference between the two system’s yields at the rotated AONR is hereafter referred to as the full penalty. Using the quadratic plateau method, we separated the full penalty into two components. The observed penalty is the remaining yield difference after each system is no longer N limited and has reached its maximum yield. The N-compensatable penalty is the amount of yield that can be gained in a continuous maize system by applying more N fertilizer than the rotated AONR value. The N-compensatable penalty was estimated as the difference between the continuous maize yield at the rotated-AONR and the maximum continuous maize yield. There is a large amount of uncertainty in AONR estimations with less than 10 points of data, and we recognize the estimation of the N-compensatable penalty is sensitive to the rotated AONR value and the shape of the continuous maize yield response to maize; we therefore do not interpret the N-penalty as a robust estimation but rather use it only as an indication of whether the N-compensatable and observed penalty are related. The correlation between the two components was assessed using a non-parametric Spearman correlation to account for the large uncertainty in the N-compensatable values (CITE).

If quadratic plateau models did not converge for at least one of the cropping systems in a given site-year, the site-year’s penalty was assumed to be in-estimable. All fits and component estimates are provided in supplementary material. For simplification, the yields at each system’s respective AONR rates are hereafter referred to as the maximum yields.

Chart

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**Figure 2** Conceptual diagram of parsing the full penalty into the amount of penalty that is compensated for through additional nitrogen (N) fertilization and the remaining continuous maize penalty that is observed even at high N inputs. Data is from IA-4 2003, original data (circles) are connected by a dotted line to aid in viewing, statistical model predictions (thick lines) and the estimated agronomically-optimum-nitrogen-rate (AONR) for each system (large diamonds) are estimated from quadratic plateau fits

The percentage of the full penalty that was compensated through additional N fertilization was calculated for each site-year, and the conditional value for each site was estimated using a mixed effects linear model with the percentage as the response variable, site and a year-factor as random intercepts.

Changes in maximum maize yields and the observed penalty over time were assessed using a mixed effect linear model. For the maximum yield analysis, maximum yields were the response variable with a fixed effect of cropping system (rotated, continuous), year as a continuous variable, and their interaction, and a random slope for each site-year and a random intercept for site. Additionally, the relationship within a site was investigated using a site-by-year interaction to ensure the overall effect was not masking different within-site patterns. The significance of the change in penalty over time was estimated by subtracting the maximum continuous maize yields from the maximum rotated maize yields at each site-year and fitting a mixed effect linear model with the penalty as the response variable, year as a fixed effect, and a random slope for each site-year and a random intercept for site.

Overall maximum yields of each system were compared using a mixed effect model with the max-yield as the response variable, cropping system as a fixed effect, and a random intercept for both site and a year factor. We included a year factor because it significantly improved the model fit, and exploratory analysis indicated that the air temperatures of each site were clustered by year. For example, 2012 was a warm year at every site (supplementary material); including a year factor in the statistical model successfully accounted for variation. The mean continuous penalty was estimated using a mixed effects model with site and a year factor as random intercepts. The contributions of site and year-factor to variation in the observed continuous maize penalty were assessed using the *reptR* package (CITE).

To identify soil, weather, and management associations with the continuous maize penalty, we assembled a dataset with various metrics important to maize production in the Midwest (see supplementary material for full list). We performed both a principal component analysis (PCA, cite) and created a correlation matrix to create a set of independent predictors that have less than a XX Pearson’s correlation with each other (see supplementary material for full initial list). The resulting predictor set was used in both stepwise model selection using Bayesian Information Criteria (CITE) using the base R function *step*, and in a partial least squares regression (PLS; cite) to identify predictors associated with the observed penalties. The number of included components in the PLS regression (two components) was determined based on visual inspection of the root-mean-squared-error by component plot. The importance of each predictor was estimated using the varImp function of the *caret* package (CITE), which uses the sums of the absolute regression coefficients weighted proportionally to the reduction in the sums of squares. The robustness of the results was assessed by running each model on a predictor set where one predictor was removed at a time.

Table An ugly version of the table I could include if you think it’s helpful. Could separate it into soil, weather, other. Should add a column with justification for inclusion

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# Results

## Experimental data

Over the duration of the experiments (1999-2016), maximum maize yields increased significantly at a rate of 0.21 Mg ha-1 (SE:0.04), regardless of cropping system (Figure 3). The continuous maize penalty remained steady at 1.02 Mg ha-1 (SE:0.15).

Chart, scatter chart

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**Figure 3** Maximum grain yields for maize grown continuously (pink triangles), in rotation with soybean (blue circles), and the difference between the two (continuous maize penalty, green squares) from 1999-2016.

Results from the quadratic plateau estimations of the N-compensated penalty and observed penalty show N fertilization eliminated the continuous maize penalty in only 6 of the 157 sites years. In 70% of the site-years, the increase in yield with additional N fertilization was less than the remaining observed penalty, with the N-compensated penalty averaging 0.43 Mg ha-1 and the observed penalty averaging 0.93 Mg ha-1, respectively.

Diagram

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Figure (Left) Pyramid plot of each penalty type by site-year, ordered by observed yield penalty; undetermined indicates quadratic plateaus failed to converge (Right) Frequency distributions of the size of the nitrogen-compensatable (yellow) and observed yield penalties (green)

There was no correlation between the size of the N-compensatable and observed yield penalty (supplementary material). Site accounted for 12% of the variation in the observed penalty. The year-factor accounted for an additional 12%, with the site-by-year interaction contributing the remaining 76%. Both of the predictor-selection models (step-wise, PLS) identified the amount of precipitation two weeks before planting and the number of days below -15 deg C between 1-Jan and planting as important. PLS importance scores were highest for the pre-plant precipitation, followed by winter cold days, with both being consistently identified in the leave-one-predictor-out sensitivity analysis. The step-wise regression estimated the penalty increased 37 kg ha-1 (SE: 9.6) for each additional cold day, and increased 9.9 kg ha-1 (SE: 3.0) for each additional mm of precipitation.

On average, N-fertilization compensated for only 39% of the full penalty (Fig. 5).

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Figure Percentage of full penalty overcome through additional nitrogen fertilization above the rotated maize agronoically optimum nitrogen rate; bars are conditional means, line ranges are 95% confidence intervals around the means, dotted line is overall marginal mean

Site and year each accounted for 12% of the variation in the yield penalty, respectively, with the site by year interaction contributing the remaining 76%.

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|  |
| --- |
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| (Left) Variance decomposition site (green), Midwest year (pink), and site-specific year (yellow) contributions to variation in nitrogen- (N) and non-N components of the continuous maize penalty, and (right) lack of co-variation between the two components, with gaps from other factors tending to be larger than N-closable yield gaps |

## Mechanistic Pathways

A survey of literature showed the continuous Maize penalty is most pronounced in the first year of Maize following Maize, and is not related to the number of years of continuous Maize (supplemental material).

Chart, line chart

Description automatically generatedThis indicates considering only the previous year’s crop is sufficient when considering driving factors. In the long-term, growing Maize continuously compared to growing it in rotation with another crop will certainly affect soil characteristics such as organic carbon stocks, topsoil erosion, and weed pressure (CITE). However, these are emergent properties from short-term dynamics, and are therefore not explicitly considered in this exercise.

Based on the experimental data analysis, variation in the CMpen is driven by variation in the continuous maize yields, not in the rotated maize yields. This means there is stronger evidence that the CMpen is the result of yield-suppressing mechanisms in the continuous maize system, rather than yield-enhancing mechanisms in the rotated maize system. Therefore, our efforts focused on understanding mechanisms in the continuous maize system that may limit the system’s expression of yield potential.

Based on an extensive literature review (supplementary material), we identified five general categories of candidate mechanisms for explaining the continuous maize penalty (Table X).

**Table X.** General categories of mechanistic pathways by which growing maize following a maize crop by result in lower grain yields under sufficient nitrogen inputs compared to a maize crop grown following a soybean crop.

|  |  |
| --- | --- |
| **Hypothesis** | **Description** |
| Delayed emergence | The higher amounts of residue in continuous maize systems my result in cooler soil temperatures, which could delay seedling emergence. |
| Seedling death | Planting into soil with high amounts of maize residue may reduce seedling establishment by reducing seed to soil contact, through allelopathic effects, and through the residue creating a physical barrier that lowers seed establishment success. Additionally, higher amounts of residue may lead to cooler and wetter soils which may result increase incidence of seedling disease. |
| Uneven stand establishment | Previous research in no-till has shown more variation in maize plant height leads to lower grain yields. It is possible the previous year’s maize residue could be unevenly distributed throughout the field and result in less uniform emergence and seedling establishment due to factors described above, leading to lower grain yields in continuous maize systems. |
| Decreased early plant growth | More challenging early season conditions may lead to decreased early season plant growth, which would be expressed as a decrease in kernel number. |
| Foliar disease | When left on the soil surface, maize residue harbors innoculants for maize foliar diseases such as XX. Tillage is recommended to reduce inoculant amount (CITE), but it is possible even small amounts of surface residue is sufficient to incudce foliar diseases at a level that significantly affects maize yields. |
| Compromised root growth and/or function | Maize roots from the previous year may support higher levels of soil bacteria harmful to the next year’s maize roots. |
| Insufficient soil water recharge following maize | It is possible the soil water legacy of the previous year’s maize crop limits the amount of water available for the continuous maize system’s subsequent maize crop. |

To test the feasibility of each of these categories, we varied targeted model parameters to simulate each effect (Table X), and ran the models...

|  |  |  |
| --- | --- | --- |
| **Target outcome** | **Parameter** | **APSIM implementation** |
| Compromised root function | Root absorption efficiency | Decreased maize KL(/day) from 0.08 to 0.05 in all soil layers down to 120 cm |
| Compromised root growth | Root front velocity | Decreased root\_depth\_rate at each stage by 50% to 2.5, 4.5, 17, 17, 15, 10 |
| Decreased early plant growth | Decreased potential kernel number | Lowered head\_grain\_no\_max from 770 to 720 |
| Foliar disease-induced decrease in plant function | Decreased radiation use efficiency | Reduced cultivar RUE  from 1.6 to 1.4 for emergence through fi (? Stage 5) |
| Delayed emergence | Time from sowing to emergence | Changed sowing depth from 50 mm to 100 mm |
| Seedling death | Lower plant population | Manually decreased plant population by 1 pl m-2 (X pl ha-1) |

1. **We built a simplified, testable causal diagram. Using a combination of literature, statistical models and APSIM, we tested the feasibility/evidence for pathways.**

|  |
| --- |
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| Pathways with evidence supporting (bold solid arrows) or not supporting (dashed arrows) links between the previous crop (maize, soybean) and the subsequent maize crop yield based on literature, statistical models, and/or APSIM modelling. |

# Discussion

Based on the data available, it is not possible to say whether the maize yield increases are due to weather, increased yield potential of newer varieties, management changes etc. Exploring the drivers of increases in Midwestern maize yields over time has been the subject of multiple investigations (Tollenar et al. 2017, Assefa et al. 2018, Kucharik 2008, Lobell and Burney 2021) and is outside the scope of this study. However, the consistent increase in both rotated and continuous maize yields is, to our knowledge, a novel finding. Conceptually, it indicates the amount of residue in the continuous maize system is not linearly related to the size of the yield penalty.

The N-penalty was not correlated with the previous year’s continuous maize yields, which represent a rough estimation of the amount of residue produced. This suggests the nitrogen ….

The more northern sites’ full penalties being less responsive to N fertilization. Long-term annual rainfall and air temperatures varied with latitude, ranging from 8.1 deg C and 744 mm of rainfall at the lowest latitude (IL-7) to 13.3 deg C and 1075 at the highest (IA-3). Again due to the uncertainty

Within a site year, the experiments use the same maize variety for both the rotated and continuous systems, but continuous-maize specific varieties are available (are they?), meaning the penalty may be smaller in farm fields where varieties are selected with the cropping system in mind (Seifert).