# 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. Continuous and rotated maize yields at high N fertilization (>180 kg ha-1) have both increased 175 (SE:18) kg ha-1 yr-1, rendering the continuous maize penalty steady over time at an estimated 1.4 Mg ha-1. Applying additional N above the optimal rate for rotated-maize eliminated the penalty in only 12 out of 157 site-years, and was less effective at more northern sites. On average, maximum maize yields were 10.3 and 11.7 Mg ha-1 for continuous- and rotated-maize, respectively, corresponding to a 12% continuous maize penalty. Site contributed to only 12% of the variation, and the penalty ranged from 0-4.8 Mg ha-1. The amount of rainfall two weeks before planting was positively associated with penalty sizes. 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 1 Map of experimental sites

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

Table 1 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, XX, XX. Soils were built using SSURGO data (CITE) and adjusted using on-site measurements as they were available. All management activities were taken from field logs. Individual maize cultivars were built to reflect maturity groups of maize. Soybean cultivars XX.

To explore the potential of single changes in 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 rotation-calibrated model was then run for the continuous maize system. The difference between a given year’s modelled rotated maize and continuous maize yields was the current modelled gap. Single parameters were adjusted one at a time, and the continuous maize model 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 effects models were fit using the lme4 package (CITE), non-linear models were fit using the nlraa package (CITE). Other packages are cited upon mention.

Changes in maize yields over time were assessed using a mixed effect linear model. Yield data from plots receiving at least 180 kg ha-1 were set as the response variable with a fixed effect of cropping system (rotated, continuous), year, and their interaction, and a random intercept for site. Additionally, the relationship within a site was investigated using site as a fixed effect 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 continuous maize yields from the rotated maize yields in each site-year at each N rate above 180 kg ha-1 and fitting a mixed effect linear model with the penalty as the response variable, year as a fixed effect, and a random intercept for site. We chose to use all data above 180 kg ha-1 for this statistical model to provide more power to detect trends. In all subsequent estimations of the penalty the quadratic plateau method was used.

To estimate the size of the penalty, 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). It is well-established that at the agronomically-optimum nitrogen rate (AONR) for maize following soybean, continuous maize yields lower (CITE). We refer to this as the full penalty, and it is a combination of an N penalty and the continuous maize penalty. Using the quadratic plateau method, we separated the full penalty into its components. We define the continuous maize penalty as the difference between the rotated maize yields at the rotated-AONR and the continuous maize yields at the continuous-AONR. The N penalty was estimated as the difference between the continuous maize yield at the rotated-AONR and the continuous maize yield at the continuous-AONR; this is the yield that can be gained in a continuous maize system through additional N fertilizer application above the rotated AONR. There is a large amount of uncertainty in AONR estimations with only five points of data, and we fully recognize the estimation of the N-penalty is sensitive to the AONR value; we therefore do not interpret the N-penalty as a robust estimation but rather use it as an indication of whether the N-penalty and observed penalty are related. When quadratic plateau models did not converge for at least one of the cropping systems in that 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.

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Figure Conceptual diagram of parsing 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 is presented (circles) connected by a dotted line to aid in viewing, thick lines represent the quadratic plateau non-linear model predictions, and the agronomically-optimum-nitrogen-rate (AONR) for each system (large diamonds)

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. The mean continuous penalty was estimated using a mixed effects model with site and year as a factor as random intercepts.

The contributions of site and year to variation in both the N-penalty and the continuous maize penalty were assessed using the reptR package (CITE), and the correlation between the two was assessed using a non-parametric Spearman correlation to account for the large uncertainty in the N-penalty values (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 predictors that have less than a XX Pearson’s correlation with each other (see supplementary material? Should I include it?). 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).

# Results and Discussion

## Experimental data analysis

Over the duration of the experiments (1999-2016), maize yields in both rotated and continuous cropping systems increased at a rate of 175(SE:18) kg ha-1. The continuous maize penalty at N rates ≥180 kg ha-1 has not significantly changed over time.

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| (*Left*) Geographic location of the 14 sites included in this dataset, with each site representing 8-18 site-years (size of points) for a total of 179 site-years. (*Right*) Grain yields for maize grown at high nitrogen fertilization rates (≥180 kg ha-1) continuously (pink triangles), in rotation with soybean (blue circles), and the difference between the two (continuous maize penalty, green squares) from 1999-2016. Trends are the same within a site, see supplementary material. |

Exploring the drivers of increases in Midwestern maize yields over time has been the subject of several investigations (Tollenar et al. 2017, Assefa et al. 2018, Kucharik 2008, Lobell and Burney 2021)The consistent increase in both rotated and continuous maize yields is interesting. Within a site year, the experiments use the same maize variety for both the rotated and continuous systems. Based on the data available, it is not possible to say whether these increases are due to weather, increased yield potential of newer varieties, management changes. A recent study showed air pollution (ozone, particulate matter, sulfur dioxide, and nitrogen dioxide) in the Midwest decrease maize yield potential (Lobell and Burney 2021). Pollution has decreased from 1999-2020, with a concomitant increase in maize yields.

The lack of change in the raw amount of yield penalty from growing maize continuously, despite increases

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| (*Top left*) Nitrogen response curves from IA-4 in 2003 with quadratic plateau-estimated agronomically optimum nitrogen rates (AONRs) which are used to estimate the yield gap closable through nitrogen (N) and the yield gap not closable through N (*Bottom left*) The frequency distributions of the size of N- and non-N closable yield gaps (*Right*) Size of each component by site-year, ordered from smallest to largest non-N yield reduction; if quadratic plateaus failed to fit a given site year’s data the components were deemed undeterminable. Quadratic plateau fits for all individual site-years are available in supplementary material. |

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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).

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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...

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| --- | --- | --- |
| **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. |