Maize (Zea mays) grown continuously on the same land often requires more inputs while simultaneously producing lower yields compared to maize grown in rotation with another crop. The consistently lower yield, or the ‘continuous maize penalty,’ is well-documented but a mechanistic understanding has remained elusive. In the present study, (1) we used 157 site-years of experimental data to quantify site and environmental variation in the continuous maize penalty, (2) we synthesized results with existing literature and modelled scenarios to identify probable mechanistic pathways, and (3) we provide recommendations for future research. Experimental data consisted of nitrogen-response curves for maize yields from continuous maize and maize-soybean cropping systems from Iowa (7 sites) and Illinois (7 sites) conducted between 1999 and 2016. All sites were tilled and had sub-surface drainage where geographically appropriate. On average, yields plateaued at 10.3 and 11.7 Mg ha-1 for continuous- and rotated-maize, respectively. The penalty ranged from 0-4.8 Mg ha-1, with a mean value of 1.4 Mg ha-1, corresponding to a 12% penalty. Applying additional N above the optimal rotated-maize N fertilization rates eliminated the penalty in only 12 out of 157 site-years. The penalty at more northern sites was less responsive to N fertilization compared to southern sites, and 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 maize crop is a likely driver of the penalty. To our knowledge there is limited data to refute or support this hypothesis. Our study suggests future research should focus on quantifying structural and functional changes in maize roots in continuous compared to rotational maize cropping systems. This focus 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.

In addition to growth analysis, we recommend a measurement set consisting of stand count, residue amount (total and surface residue), root front velocity, and maximum root length and biomass.

# Introduction

Corn grown for two or more consecutive years is a common land-use in the Midwest (NASS or something). However, even with optimal management corn grown continuously yields less than corn rotated with another crop, most commonly soybean. This phenomenon is well-known and is often referred to as the continuous corn yield penalty. Experimental studies report average penalties ranging from 5-30% across the county (Erikson 2008), but even at recommended nitrogen 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 corn 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, making it difficult to predict and manage. Understanding conditions that affect the magnitude of the continuous corn penalty can (i) help producers optimize management to overcome the penalty, and (ii) help researchers predict the penalty, thus incorporating the penalty into models to better capture land-use decisions and their effects on both the environment and economic impacts of the 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. The CCpen is likely a manifestation 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 gaining insight into the magnitude of these effects.

Our goal was to use multi-site, multi-year data to gain insight into factors contributing to the continuous corn penalty, identify dynamic field conditions that may drive it, and test our hypotheses using a process-based model.

# Methods and Materials

## Experimental data

The experimental layouts for the sites are reported elsewhere. Briefly, treatments consisted of cropping system (continuous maize, maize-soybean rotation with both phases present every year) and nitrogen (N) fertilization rate (Table X).

## Modelling

## Statistical analyses

The significance of YcontM, YrotM, and

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 X). The agronomically-optimum nitrogen rate (AONR) was estimated as the N rate where maize yields plateaued. The difference between the YcontM at the AONRrotM and the YcontM at the AONRcontM was assumed to represent an estimate of the yield gap that was closed through applying additional N fertilizer above the AONRrotM. The remaining yield gap, or the continuous maize penalty, was estimated as the difference between the plateaued YrotM and YcontM. Each site-year therefore had an estimated yield gap closed through N fertilization, and a remaining yield gap. These estimations were done for each site-year (supplemental material).

Chart, line chart

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Plateau yields of each system were compared using a mixed effect model with plateau-yield as the response variable, cropping system as a fixed effect, and a random intercept for both site and year using the lme4 package.

The contributions of site and year to variation in both the yield gap closed through N fertilization and the remaining yield gap were assessed using the reptR package.

Correlations between the yield gap closed through N fertilization and the remaining yield gap were tested using the *cor* function of R.

# 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 X and X Mg ha-1, respectively, rendering the continuous maize penalty steady at X Mg ha-1.

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| Map  Description automatically generated |
| (*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. |

1. **In any given year, the continuous maize penalty is composed of both nitrogen- (closable with additional nitrogen fertilization) and non-nitrogen (not closable) components. The relative contribution of each can be determined from the nitrogen-response curve.**

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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. |

1. **The continuous maize yields are driving the un-closable yield gaps.**

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| (*Top*) The continuous maize yield penalty that is not closable through nitrogen fertilization is not related to rotated maize yields, but is negatively associated with continuous maize yields. (*Bottom*) Conceptual demonstration of continuous maize yields driving yield gap, with accepted hypothesis having bolded colors. |

1. **Site and year explain very little variation in the N- and non N-derived components of the gap, meaning the variation in both components is mainly driven by an interaction between the weather and the site. The two components are not correlated, meaning they have different drivers.**

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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 corn penalty is most pronounced in the first year of corn following corn, and is not related to the number of years of continuous corn (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 corn 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.

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| **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. |