# 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 from 1999-2016, 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 13% 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 in continuous maize systems 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, and residual nitrogen at maturity. 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 (CropScape, 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, Genry,others). Several studies have examined factors associated with the continuous maize penalty, but results are either site specific (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. Currently producers are advised to increase N applications in continuous maize systems, but it is unclear how effective and consistent this method is in increasing continuous maize yields. Over-application of N above the agronomically optimum nitrogen rate (AONR) in continuous maize systems carries significantly more risk of nitrate leaching compared to rotated maize systems (Pasley). Furthermore, the percentage of applied N that is released as nitrous oxide emissions, a potent greenhouse gas, may be higher in continuous maize compared to rotated maize (CITE). Given the prevalence of continuous maize in the Midwest, predicting when N application will translate to increased yields in continuous maize systems is therefore vital for protecting water quality and reducing climate impacts of agriculture. Understanding conditions that affect the magnitude of the continuous maize penalty will 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 system 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) synthesize 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 maize nitrogen (N) fertilization rate (Table 1). Each site had three or 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 and custom scripts to simulate water table dynamics (Elnaz paper?). APSIM has been used extensively for Midwestern maize-based systems (CITE), and is appropriately structured for simulating multi-year effects of cropping systems (Basso and Martinez 2020). Soil profiles for the model 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.

### Quadratic plateau models

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

### Mixed effect linear models

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).

### Feature selection models

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 (Chandrashekar2014) 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 2 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

Table

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### Path analysis

Path analysis was done using the *lavaan* package (CITE).

# 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 4 (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 13% of the variation in the observed penalty. The year-factor accounted for an additional 14%, with the site-by-year interaction contributing the remaining 73%.

Chart, scatter chart

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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 model features. 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. No soil characteristics were consistently identified as important features.

On average, N-fertilization compensated for only 39% of the full penalty (Fig. 5). More northern sites had smaller N-compensatable components as a percentage of the full penalty.

Chart, bar chart, histogram

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Figure 5 Percentage of full penalty overcome through additional nitrogen fertilization above the rotated maize agronomically optimum nitrogen rate; bars are conditional means, line ranges are 95% confidence intervals around the means, dotted line is overall marginal mean

## Mechanistic pathways

### Literature

Literature reports mixed results with regards to the time component of the continuous maize penalty. Studies that utilize staggered start dates for assessing the years-in-maize effect, and therefore de-confound years-in-maize with weather, show the penalty does not increase as time in continuous maize increases. To our knowledge, two studies conclude the penalty increases as the number of years in a continuous maize system increases, but one confounds weather with years-in-maize and the other uses satellite imagery and therefore shows an association rather than a causal relationship (Fig. 6).

Chart, line chart

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Figure Summary of literature investigating the relationship between the duration of continuous maize implementation and the continuous maize penalty.

This indicates considering only the previous year’s crop is sufficient when considering driving factors for the continuous maize penalty. 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).

Based on the experimental data analysis, more of the variation in the observed penalty is explained by the continuous maize yields rather that rotated maize yields (supplementary). This suggests it is indeed a yield *penalty* that is manifested through mechanisms present in the continuous maize system, rather than the rotated system driving a yield increase. 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 in the year following a maize crop (Table X).

Table General categories of mechanistic pathways by which growing maize following a maize crop results in lower grain yields under sufficient nitrogen inputs.

|  |  |
| --- | --- |
| **Hypothesis** | **Description** |
| Delayed emergence | The high 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/or 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. |
| 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 inoculants 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 produce localized 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. Additionally, while soil disease is always present, cooler temperatures may result in less microbial competition and higher incidence of root disease. (need to look at Alison’s extension material to get this right) |
| 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. |

### Process-based modelling

The model showed that in our dataset from IL and IA, soil water content was as high or higher before maize planting following a maize crop compared to a soybean crop (supplemental). To assess the feasibility of the remaining categories, we varied targeted model parameters to simulate each effect (Table 4) and ran each site’s calibrated model at that site’s highest experimental nitrogen rate (Table 1).

Table Model parameter adjustments to investigate feasibility of proposed mechanisms for the continuous maize penalty

|  |  |  |  |
| --- | --- | --- | --- |
| **Scenario** | **Target outcome** | **Parameter** | **APSIM implementation** |
| 1 | Seedling death | Lower plant population | Manually decreased plant population by 1 pl m-2 (X pl ha-1) |
| 2 | Delayed emergence | Time from sowing to emergence | Changed sowing depth from 50 mm to 100 mm |
| 3 | Foliar disease-induced decrease in plant function | Decreased radiation use efficiency (RUE) | Reduced cultivar RUE  from 1.6 to 1.4 for emergence through (Stage 5? What is that in corn terms?) |
| 4 | Compromised root growth | Root front velocity (RFV) | Decreased root\_depth\_rate at each stage by 50% to 2.5, 4.5, 17, 17, 15, 10 |
| 5 | Compromised root function | Root absorption efficiency | Decreased maize KL(/day) from 0.08 to 0.05 in all soil layers down to 120 cm |
| 6 | Decreased early plant growth | Decreased potential kernel number | Lowered head\_grain\_no\_max from 770 to 720 |

While results varied by site, delayed emergence (Scenario 2) produced consistently impractical results with regards to the continuous maize penalty, as shown in the results from site IA-3 (Figure 7). Within error, all other scenarios produce feasible effects on continuous maize yields, and combining the effects produces a mean observed penalty comparable to the experimentally observed penalty.

Chart

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Figure Site IA-3 experimentally observed penalties (yellow bars) with 95% confidence intervals (vertical lines) ordered from largest to smallest compared to baseline model parameters (green bars), scenarios (Table 4), and a combination of scenarios excluding delayed emergence (dark blue bars)

The analysis of the experimental data indicated site-by-year interactions are a major contributor to variation in the observed penalty. We therefore implemented scripts to dynamically change parameter values based on surface residue amounts, soil temperature tracking, soil moisture tracking, and XX. However, we found it difficult to assess whether this dynamicism improved model predictions because of the uncertainty around the measured penalty sizes. While the mean observed penalty was 1.0 Mg ha-1, the average standard deviation for the sites where that information was available was 0.7 Mg ha-1. Therefore, while the model indicated most of the scenarios were plausible, the size of the penalty is not known with enough precision to say more.

### Path analysis

To assess the relative strength of each pathway, we first created a simplified directed acyclical graph for path analysis (SmithSEMpaper). To simplify the diagram into a form that was analyzable using available data but still provided value, we used a combination of the modelling and literature review results.

A recent study measured maize plant stand both a continuous- and rotated-maize system over 11 site-years in Iowa and found in tilled systems there was no difference (Licht, unpublished). An 11-year study done in Ohio likewise found no difference in plant population in continuous- and rotated-maize systems (Griffith 1988). We therefore chose to eliminate the reduced plant population from our causal model. To our knowledge there are no studies that report the number or size of maize kernals per ear as a function of cropping system, so we likewise eliminated the reduced potential kernel number. In addition to APSIM’s predictions that delayed germination is an unlikely consistent driver of the penalty, field studies likewise show negligible effects of maize residue on maize plant germination timing versus soybean residue (Kaspar1990, X)

Several studies suggest maize roots are indeed different in maize monocultures compared to rotated systems. A Wisconsin study showing more root length, as well as a higher percentage of necrotic roots in maize monocultures compared to diverse rotations at 0-15 cm depths (Goldstein). Additionally, the author found the monoculture maize had higher soil residual N at harvest compared to the maize-soybean rotation, suggesting that while N was present it may not have been captured by the maize plant due to compromised root function. A study done in Minnesota likewise found monoculture maize had higher root length densities in the top 0-12.5 cm, but had less root length density than maize rotated with soybean below that depth.

# 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. Additionally, none of the statistical models identified the previous year’s continuous maize yields (a proxy for residue amount) as important, and the literature review found no effect of ‘years-in-maize’. While previous studies have found removing residue in continuous maize systems decreases the amount of N required to reach maximum yields (coulter2008, jose, karlen?), many studies still see a significant continuous maize penalty even with complete residue removal (Jose, Karlen, Crookston1989, I think there’s another). Additionally, one study translocated residue from a maize monoculture to a field that was previously soybean before planting a maize crop and saw no effect of the residue on yields (crookston).

The identification of the number of extremely cold days as an important predictor by the statistical model has an unclear interpretation. It may be simply associative, with the true driver being highly correlated with cold winters, may represent disease dynamics, or may indicate less native soil N mineralization due to cold temperatures. It is consistent with the finding that N fertilization was less effective at reducing the full penalty in more northern sites (Figure 5), as long-term annual air temperatures varied strongly by latitude, ranging from 8.1 deg C at the lowest latitude (IL-7) to 13.3 deg C at the highest (IA-3).

Cold and wet soils are highly predictive of soil disease pressure in the Midwest (CITE). The statistical model’s results of the amount of rain two weeks before planting being positively associated with the size of the penalty supports the hypothesis that root diseases play a major role in the penalty, and may render maize monocultures less responsive to N fertilizer.

Our analyses suggest residue amounts may be a smaller driver of the

**Lit for ref for me:**

Dick1985 – bigger penalty in poorly-drained soils in Ohio

Griffin1988 – no diff in plant pop or soil temp at 10 cm depth in Ohio

Goldstein – CC has more necrotic roots and more roots 0-15cm, leaves more N in the soil at harvest,

Nickel – CC has more roots 0-12.5 cm, but less below that.

Livingston2015 – rotating is always economically preferable

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. Again due to the uncertainty