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 mechanistic pathways, and (3) we provide recommendations for future research. We used 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.

**Introduction**

**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.

1. **The continuous maize penalty has not 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. |

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 |

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. |