**Decomposing the continuous maize penalty**

Maize grown continuously produces lower grain yields compared to maize grown in rotation with another crop, even under high inputs. This phenomenon is commonly referred to as the ‘continuous maize penalty’. In the maize-producing regions of the US, this yield penalty is well-documented, but a lack of mechanistic understanding impedes progress in both applied and basic sciences (e.g. identifying effective management strategies to minimize the penalty, incorporating the effect into crop models). In the present study, we use replicated experimental data to (i) quantify the components of the penalty that are and are not closeable through nitrogen (N) fertilization, (ii) describe variation in those components, and (iii) identify probable mechanisms driving variation. We used nitrogen-response curves for continuous- and rotated-maize systems from 14 sites across Illinois and Iowa conducted between 1999 and 2016, for a total of 179 site-years. All sites were tilled and had sub-surface drainage where geographically appropriate. At optimal rotated-maize N fertilization rates, the mean continuous maize penalty was 1.3 Mg ha-1. An estimated 0.4 Mg ha-1 of that penalty, or 30%, was overcome through application of N above the optimal rate for rotated maize, producing a continuous maize penalty of 0.9 Mg ha-1 even with sufficient N application. Variation in the non-closable maize penalty is due to variation in continuous maize yields, rather than rotated maize yields. Site explained 12% of the total variation in both components with the penalty at more northern sites being less responsive to N fertilization compared to southern sites. Using a causal diagram in combination with literature, statistical models, and a processed-based model (APSIM), we found compromised maize roots following a maize crop could be the strongest driver of the penalty, but to our knowledge there is little data to refute or support this hypothesis. Our study shows that, on average, only a third of the continuous maize penalty at optimal rotated-maize N rates can be overcome through additional N fertilization. Understanding the remaining penalty will require a focus on the structure and functionality of roots in rotated- and continuous-maize systems. This focus would support efforts to manage, breed for, and model the continuous maize penalty, and would represent a major step towards maximizing the efficiency of arable lands.

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. |