

TECHNICAL REPORT

Plant and Environment Interaction

Short-stature maize systems reduce carbon intensity of grain production by an average of 13% compared to commercially relevant tall comparators

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Abstract

The sustainable intensification of crop production provides more output with similar or fewer inputs, and therefore helps to produce food, feed, fiber, and fuel more efficiently. While short-stature maize (*Zea mays* L.) hybrids have been shown to be more climate resilient, with reductions in yield-scaled greenhouse gas production due to reduced crop damage during wind events, other aspects of the climate impact of short-stature maize remain to be quantified. Here we will discuss the use of the greenhouse gases, regulated emissions, and energy use in transportation life cycle assessment model and data inputs from 199 total site-years of grain yield data, 11 site-years of root data, and 10 site-years of stover nitrogen (N) data to determine the carbon (C) footprint of short-stature maize systems for grain production. Short-stature maize hybrids had comparable grain yields to tall comparators under standard management; however, leveraging benefits of the systems, such as in-season access, and higher plant populations improved the yield and efficiency of production. Root volume was increased by 39% for short-stature hybrids compared to tall hybrids. Across a range of agronomic system scenarios, that consider changes in plant density and improved in-season access for split-rate N application, and soil C dynamics, there is a range of greenhouse gas savings of 0.09–0.78 t CO₂e ha⁻¹ year⁻¹ for short-stature maize systems due to improvements in grain yield without increased inputs, reduction in stover N and subsequent N₂O emissions, and increased root dry matter incorporation into soil organic carbon.

Plain Language Summary

Agriculture represents approximately one-fourth to one-third of global greenhouse gas (GHG) emissions. Due to increases in efficiency, the amount of GHG

Abbreviations: CI, carbon intensity; FD-CIC, Feedstock Carbon Intensity Calculator; GHG, greenhouse gas; GREET, greenhouse gases, regulated emissions, and energy use in transportation; LCA, life cycle assessment; RFS, Renewable Fuel Standard; SOC, soil organic carbon; SSM, short-stature maize.

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emissions per unit of output has decreased over previous decades. In other words, the carbon intensity of agricultural production has decreased over time. Maize is the most widely grown and highly produced cereal crop globally. Short-stature maize systems have been shown to provide improvements in water quality and carbon intensity compared to conventional maize systems in Iowa. The purpose of this research was to understand the carbon intensity of short-stature maize production based on grain yield, and carbon and nutrient content of the short-stature hybrids, compared to commercially relevant tall maize hybrids. We show that across a variety of scenarios, short-stature maize systems reduce the carbon intensity of maize production by 3%–28%, with an average of 13% reduction. Short-stature maize systems can provide a more sustainable method of producing maize.

1 | INTRODUCTION

Agriculture is both affected by climate change and a contributor to climate change. Models of the impacts of future climate scenarios project a decrease in global crop yield in cereals of 6%–18% (Zhao et al., 2017). In addition, agriculture also contributes to climate change, accounting for one-fourth to one-third of total greenhouse gas (GHG) emissions (Crippa et al., 2021; Mbow et al., 2019), of which ~70% can be attributed to land use change and waste (Crippa et al., 2021). Agriculture comprises a large proportion of the global landscape, with 46% of global habitable land area used for agriculture (Ritchie & Roser, 2019a). Land area dedicated to cropland increased dramatically between 1700 and 1970s, but the rate of increase in cropland has decreased over the previous decades, while global population has continued to grow (Ritchie & Roser, 2019a). A continued decoupling of population growth and land area for crop production is needed to preserve essential ecosystem services on natural lands while continuing to produce food for a growing and affluent population (Ritchie & Roser, 2019b).

Nitrogen (N) is a major contributor to the GHG emissions in cereal systems, from a combination of the production emissions, the addition of fertilizers, and the release of N₂O from the breakdown of residue (Mbow et al., 2019; Tian et al., 2021). Improvements in the efficiency with which applied N is converted into increased yields have allowed the production of more grain with lower environmental costs (Chen et al., 2014). In US maize (*Zea mays* L.) systems, increases in the efficiency of grain production per unit of applied N (Cassman et al., 2002) have enabled large net energy yields from grain production with relatively small global warming intensity (Grassini & Cassman, 2012).

While there have been impressive gains in the efficiency of cereal production over the previous five decades, developing cropping systems that are resilient to climate change and more efficient in their resource use, including reduction

of both the land use footprint and on-farm waste, is critical to nourishing a growing population while protecting the planet's resources. Crop system improvements come from improving crop yield directly through breeding efforts (Duvick, 1984; Lee & Tollenaar, 2007; Ruiz et al., 2023), climate and agronomic improvements (Rizzo et al., 2022), and more targeted approaches such as improvements in photosynthesis (Zhu et al., 2010). These improvements enable more efficient and productive cropping systems that reduce the need for clearing more nonagricultural land (Mbow et al., 2019; Stevenson et al., 2013). Protecting crops from biotic stresses such as pests and diseases (Lamichhane et al., 2015) and abiotic stresses such as water and nutrient limitation is another avenue for improving the efficiency of cropping systems (Mbow et al., 2019; Mickelbart et al., 2015).

Recent advances in maize cropping systems have further improved the efficiency of production. Biotechnology traits that reduce pest and weed pressure have allowed for increases in crop yield of 22%, while reducing pesticide applications by 39% in maize, soybean (*Glycine max* L.), and cotton (*Gossypium hirsutum* L.) (Klümper & Qaim, 2014; Kovak et al., 2022), while being scalable enough to achieve 92% market penetration within the United States (Dodson, 2024).

Improvements in management practices such as increased plant density have been directly linked to grain yield improvements in maize (Assefa et al., 2018; Saenz et al., 2025; Winans et al., 2021). With increased plant density, however, comes increased risk of plant lodging and concomitant reduction in yield (Barten et al., 2022; Lindsey et al., 2021; Shah et al., 2021). Furthermore, precision fertilization practices, in general, and in-season application of N fertilizer, in particular, are linked with improved yield and N efficiency in maize systems (Davies et al., 2020; Johnston & Bruulsema, 2014). Short-stature maize (SSM) hybrids allow for longer in-season N access, which can ameliorate logistics challenges for in-season N application, leading to improved yield and N efficiency (Kosola et al., 2023; Ordoñez et al., 2024).

Modern maize systems with advanced hybrids and management have been shown to reduce the loss of N to the environment (Dohleman et al., 2024).

SSM is an emerging technology that has been shown to increase yield by 19% and reduce GHG emissions in cases where wind damage occurs (Barten et al., 2022). Improved in-season access has also allowed for split applications of N to produce 0.24 t ha⁻¹ improvements in yield, compared to up-front applications of the same rate, and approximately 10% reduction in total N left on the field due to residue (Kosola et al., 2023). As part of improved cropping systems over time, SSM systems have also reduced yield-scaled nitrate load by 91%, compared to cropping systems prevalent in the 1990s, with 19% reduction in the carbon (C) intensity of grain production (Dohleman et al., 2024).

Model estimates of the carbon intensity (CI) of maize grain production using the greenhouse gases, regulated emissions, and energy use in technologies (GREET) model have been shown to decrease over time (Scully et al., 2021), mostly due to improvements in yield-scaled fertilizer applications and subsequent N₂O emissions, and more efficient fossil fuel use over time (Wang et al., 2011). The GREET model is used as a backbone for policies like the US Renewable Fuel Standard (RFS), California Low Carbon Fuel Standard, and International Civil Aviation Organization methodology for estimating CI of sustainable aviation fuel (Wang et al., 2024). This modeling framework, however, has not taken into consideration the changes to physiology or agronomy of specific maize products. Given the background of SSM hybrids, the research questions for this work are:

1. What is the grain yield of short-stature and tall maize hybrids under various plant density scenarios?
2. What are the changes in the root volume and estimated dry-matter accumulation in SSM hybrids?
3. What is the difference in CI of grain production and soil carbon sequestration in a life cycle assessment of short-stature and tall maize hybrids?

2 | MATERIALS AND METHODS

2.1 | Plant materials

Two SSM technologies are discussed in this analysis, one developed using traditional plant breeding approaches with a native brachytic (*br2*) gene, hereafter called conventionally bred materials (Barten et al., 2022) and the other developed using a biotechnology approach with targeted suppression of gibberellin biosynthetic genes, hereafter called biotechnology-derived materials (Barten et al., 2022; Paciorek et al., 2022). The purpose of this study and analysis was to look across both SSM technologies; locations

Core Ideas

- Historic improvements in maize production have reduced the carbon intensity of maize grain production.
- Short-stature maize systems allow for more efficient grain production and changes in stover and roots.
- Taken together, short-stature maize systems reduce GHG emissions by 13% (range = 3%–28%).

discussed include SSM hybrids developed with either one or both approaches. Hybrids were developed from temperate yellow dent maize lines that are active in Bayer's North America breeding pool. Hybrids from conventionally bred or back-crossed lines were developed utilizing short-stature male and female inbreds with the *br2* mutation, and commercially relevant tall isolines were from the same genetic family and relative maturity. SSM and tall isolate hybrids from the biotechnology-derived lines were developed using Bayer research and development hybrids with and without the *GA20oxidase* transgene. Data for this analysis included only hybrids where short-stature and tall comparators were present at the same locations. To ensure proper genetic comparisons between tall and SSM hybrids, only hybrids from the same genetic family were included in the analysis for the breeding materials.

2.2 | Methods

2.2.1 | Yield data collection

Field sites and cultivation

One hundred ninety-nine site-year field trials within the US Midwest Corn Belt were conducted between 2017 and 2022 to evaluate grain yield for SSM hybrids and tall comparators (Barten et al., 2022; Paciorek et al., 2022). For all trials with the biotechnology-derived hybrids and for 2017–2019 years for the conventionally bred hybrids, studies at each location were conducted using randomized complete block designs within each stature, where a plot was four rows (0.75 m spacing, center 2 harvested) by either 5.3 m or 10.6 m. In 2020–2022 trials for the conventionally bred hybrids, a split-plot design was used with two or three hybrids ($n = 3$). For the conventionally bred hybrids, multiple planting densities were used across site-years (79,000, 89,000, 104,000, or 119,000 plants ha⁻¹). For the biotechnology-derived hybrids, a standard density of 89,000 plants ha⁻¹ was used across all trials. In total, data were collected from 107 site-years for the conventionally bred hybrids and from 92 site-years for the

TABLE 1 Experimental design across years for conventionally bred hybrids.

Year	Locations (#)	Hybrids SSM (#)	Hybrids tall (#)	Densities (#)	Replications (SSM/tall)	Total datapoints per density (SSM)	Total datapoints per density (tall)
2017	5	7	5	2	2/2	70	50
2018	35	9	5	3	4/1	743	222
2019	16	4	12	3	4/4	251	750
2020	13	3	2	4	2/2	266	138
2021	22	6	3	2	3/3	552	278
2022	16	3	3	2	3/3	138	144
Total	107					2008	1582

Abbreviation: SSM, short-stature maize.

TABLE 2 Experimental design across years for biotechnology-derived hybrids.

Year	Locations (#)	Hybrids short (#)	Hybrids tall (#)	Densities (#)	Replications	Total datapoints per density (SSM)	Total datapoints per density (tall)
2019	25	5	5	1	4	500	500
2020	27	19	19	1	3	1385	1331
2021	27	20	20	1	3	1450	1454
2022	13	23	23	1	2	418	399
Total	92					3253	3184

Abbreviation: SSM, short-stature maize.

biotechnology-derived hybrids. Number of locations, hybrids, and replications are shown in Tables 1 and 2. To avoid shading effects, SSM and tall plots were adjacent to each other with buffer rows planted between blocks. Across the 199 locations, management practices, including fertility and crop protection, followed recommendations for obtaining high yields within the region and were applied the same between short-stature and tall hybrids.

Data collection

At all locations, data for plot grain weight, grain moisture, and test weight were collected and normalized to plot yield at 15.5% moisture.

2.2.2 | Root data collection

Locations and materials

Root excavations were conducted at 11 site-years throughout the US Midwest Corn Belt between 2020 and 2023 with a greater number of locations in the western Corn Belt (Figure 1). Two of the locations planted in 2022 had data that were deactivated due to a combination of corn–rootworm damage and the presence of an impenetrable hardpan that limited root growth. An average of 5 (range = 3–8) hybrids were tested at each site-year. Conventionally bred materials used a combination of isogenic and commercial tall hybrids as

comparators in 10 site-years and biotechnology-derived materials used isogenic tall hybrids as comparators at 1 site-year. There were 53 total root volume datapoints collected for SSM hybrids and 61 total root volume datapoints collected for tall hybrids over the 11 site-years.

Root collection methods

Trials were planted at each location under normal agronomic practices for the region. Location, hybrid number, and planting and excavation date are shown in Table 3. Soil root pits were excavated near or after anthesis, at the approximate time of maximum root volume, using a backhoe to a depth of 1–2 m, depending on the depth of the roots at a given location (Figure 2). Once excavated, finer tools were used to remove the soil that was smeared or crushed from the force of the backhoe to provide a more natural view of the root–soil interface (Taylor, 1986). Roots were then traced onto grid paper in 0.3-m depth increments on 2.5-cm grids. Holes were systematically dug horizontally through the *x*–*y* axis, depending on the root density at a given depth to a horizontal interval of 15 cm to estimate the volume of roots in the *z* dimension. The 15-cm interval used was determined by the inter-plant spacing within a row based on planting densities of 79,000 plants ha^{−1} with a row spacing of 76 cm. Root volume was calculated as the product of width, depth, and interplant spacing within each depth increment and summed to determine total root volume.

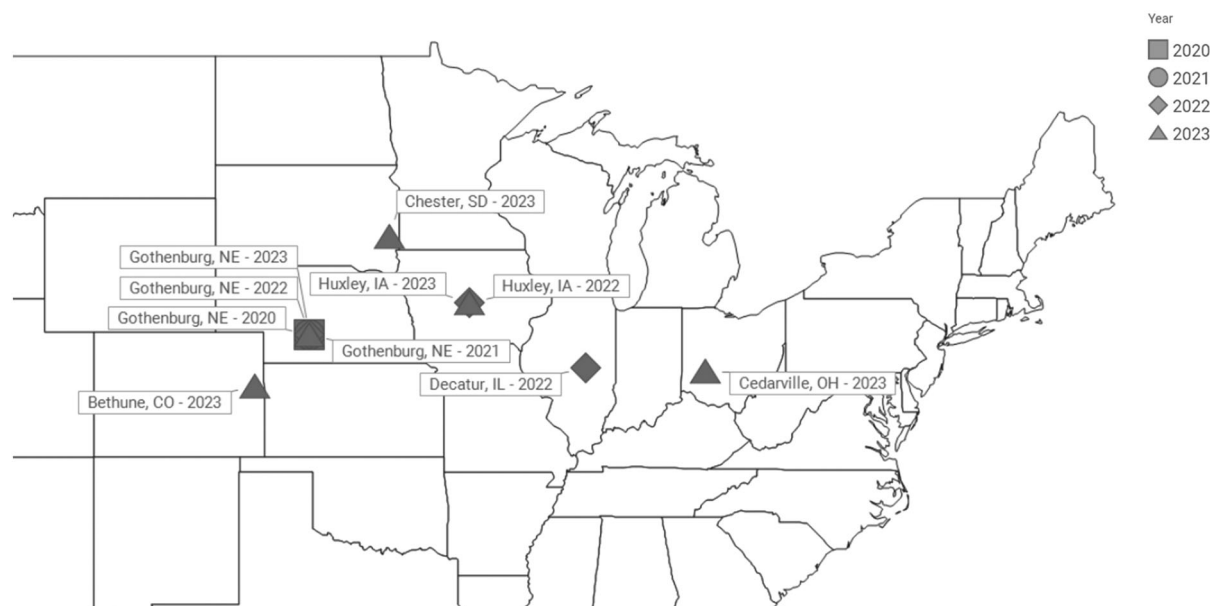


FIGURE 1 Field locations of side-by-side root excavation trials on short-stature maize and tall hybrids. Root excavation was collected between 2020 and 2023 near Gothenburg, NE; in 2022 and 2023 near Huxley, IA; in 2022 near Decatur, IL; and in 2023 near Bethune, CO, Chester, SD, and Cedarville, OH.

TABLE 3 Locations, material, hybrid number, planting and excavation dates for maximum root volume measurements on short-stature and tall maize hybrids.

Year	Location	Material derivation	Hybrid number (short)	Hybrid number (tall)	Planting date	Excavation date
2020	Gothenburg, NE	Breeding	3	7	5/29/2020	8/11/2020
2021	Gothenburg, NE	Breeding	4	8	5/26/2021	7/14/2021
2022	Gothenburg, NE	Breeding	5	5	5/28/2022	8/30/2022
2022	Huxley, IA	Breeding	5	5	5/14/2022	8/16/2022
2022	Decatur, IL	Breeding	5	5	5/14/2022	8/23/2022
2023	Gothenburg, NE	Breeding	5	5	6/13/2023	8/30/2023
2023	Huxley, IA	Breeding	5	5	4/27/2023	8/24/2023
2023	Bethune, CO	Breeding	5	5	6/5/2023	8/6/2023
2023	Cedarville, OH	Breeding	5	5	5/11/2023	8/16/2023
2023	Chester, SD	Breeding	5	5	5/09/2023	8/21/2023
2023	Gothenburg, NE	Biotechnology	6	6	6/13/2023	8/30/2023
Total			53	61		

The difference in root carbon between short-stature and tall maize hybrids was then estimated using literature review of root carbon in maize fields (Table S1) and assuming that the baseline of 1.01 t C ha^{-1} was representative of tall maize hybrids (Amos & Walters, 2006; Hirte et al., 2018; Mathew et al., 2020; Ordoñez et al., 2020; H. Xu et al., 2020). It was further assumed that short-stature and tall hybrids have the same root C concentration, given that there is ~1% genetic variation in maize root C concentration after four decades of breeding and that there is nearly no genetic variation in maize-specific root length within a year of release (Sciaressi et al., 2025).

2.2.3 | Site soil, weather, and management data

Site soil, weather, and management data are shown in Table S2. Soil data for each location were collected from the USDA-NRCS Soil Survey Geographic Database (SSURGO), and weather data were collected from The Weather Channel history on demand (HoD) database, The Weather Channel Hi-res Precipitation database, and the ERA5 database. Site tillage, previous crop, and fertility rate data were provided by on-site cooperators, where applicable.



FIGURE 2 Images of root pit excavation, root measurements, and a tracing of a representative root system in a maize field.

2.2.4 | Statistical analysis

Statistical analysis was conducted on the site means of root volume to compare SSM and tall hybrids using R Statistical Software (Foundation for Statistical Computing). Pairwise *t*-test using each site as a pair was used to evaluate statistical significance and *p* value was calculated. Statistical analysis was conducted on the site means of grain yield to compare SSM and tall hybrids independently for conventionally bred materials and biotechnology-derived materials due to differences in experimental design. Analysis of variance (ANOVA) was conducted across stature and density treatments for the conventionally bred materials, and across stature for biotechnology-derived materials.

2.2.5 | GREET modeling and assumptions

We assessed the carbon footprint by conducting a life cycle assessment (LCA) of short-stature hybrids relative to their tall comparators for maize grain use. The LCA is based on the Argonne National Laboratory Feedstock Carbon Intensity Calculator (FD-CIC) 2023 Dynamic Version (Liu et al., 2023), which is the agricultural sub-module of the GREET model. In its default configuration, FD-CIC is parameterized with US average yield values, average farm energy, and average N rate and nutrient inputs. Each input is then converted into a GHG value based on the intensity of inputs. For fertilizer, for example, the user provides inputs on the type and quantity of product applied (e.g., 60 pounds of ammonia acre⁻¹ and 70 pounds of urea acre⁻¹). The model then calculates the field-level N₂O emissions from nitrogen application (via volatilization, leaching, and denitrification) plus the upstream CO₂ emissions from producing each fertilizer product (e.g., at the ammonia and urea plant). Likewise, the life cycle GHG emissions from diesel fuel use in the tractor and combine are calculated by adding the combustion emissions to the other life cycle components, such as petroleum

extraction and refining. For that, the FD-CIC tool accesses a county-by-county database of soil responses to different management practices. The database contains outputs from a surrogate soil organic carbon (SOC) model based on the Century model for the two dominant soil textures in each county. Also see Figure S1 for the flowchart.

We calculated the life cycle GHG emissions to produce maize grain from short-stature and tall hybrids and parameterized GREET. Hybrid-density combinations were produced with the same nutrient and field energy inputs; therefore, those that exhibited higher yields produced lower GHG emissions per metric ton of grain. GREET via the Carbon Calculator for Land Use Change from Biofuels land use add-on module can also assess emissions from SOC loss and SOC sequestration effects based on dominant soil textures on a county-by-county basis.

In all scenarios, yield-scaled GHG emissions were calculated based on FD-CIC default assumptions for fertility and energy use (Liu et al., 2023), and the average of US Midwest agro-ecological zones was used as a default for soil parameters, given the locations of the trials across the Central Corn Belt. Because of the overestimate of yield derived from small-plot research, short-stature and tall yields were normalized to the 2023 national average yield of 11.2 t ha⁻¹ assuming that tall hybrids at standard density are the baseline prior to incorporation into GREET. The GREET assumptions for N application are based on the range of N rates between 174 and 218 kg ha⁻¹, and within range of the mean applied N rate of 210 kg ha⁻¹ that was utilized in these field trials. Based on the range of yield outcomes across density scenarios, N management practices, and change in root volume, we developed scenarios shown in Table 3. For plant density in the breeding materials, we used two scenarios. In scenario 1, the mean of the 79,000 and 89,000 plants ha⁻¹ yield results provided a normal density as those populations are representative of the region. The mean yield of the 104,000 and 119,000 plants ha⁻¹ yield results provided high density estimates.

Given that SSM reduces the risk of wind damage (Barten et al., 2022), it allows for more frequent planting of higher plant density. Therefore, scenario 1 uses high population yield results for short-stature hybrids and normal population yield results for tall hybrids. Scenario 2 uses the average yield across all densities for short-stature and tall hybrids. Scenario 3 uses the data at the only tested density for the biotechnology-derived material. Scenarios 4, 5, and 6 use the same assumptions as 1, 2, and 3, respectively, except for a split application where 50% of N fertilizer is applied pre-season, and 50% is applied in-season, better enabled by the short-stature hybrids, based on the yield outcomes shown in Kosola et al., 2023. We estimate one extra field pass on 50% of the fields from the added in-season nitrogen application (we assume a fraction of anhydrous N is applied in the fall, as is common practice in maize production in the United States). One extra field pass requires about 0.9 L of additional diesel fuel ha⁻¹ or 30,848 Btu ha⁻¹ (Hanna, 2001). If we assume half the fields require an extra pass, this adds $0.5 \times 30,848$ Btu or 15,419 Btu to each hectare of fuel use. Across all scenarios, the yield-scaled N residue for SSM was 107.7 g bu⁻¹ (Kosola et al., 2023) compared with the 141.6 g bu⁻¹ baseline assumption in GREET. The adjustments in N₂O emissions based on this updated data result in additional GHG reductions of 2.77%. Reduced lodging has been documented for SSM hybrids (Barten et al., 2022) and could also result in a decrease of the planted versus harvested area ratio. Nationally, a consistent 8% of planted area is lost between those planted and harvested (USDA-NASS, 2023). We assume that SSM will reduce this to 4% on the Bayer SSM seeded area (market share of ~33%). For our modeling efforts, this produced an additional 1.33% higher yields on the Bayer SSM planted area due to protection from wind damage (Barten et al., 2022).

There are several major environmental LCA models, including the Argonne National Laboratory's GREET, the Canada-based GHGenius Model, and the European Union-based Ecoinvent and GaBi models. Regardless of origin, each of these LCA models can be modified or updated to allow different parameterizations. However, in general, each of the model's databases tends to be mostly focused on the regions for which it was developed. GREET is supported by the US Department of Energy, updated annually, and contains detailed data on US-specific farm energy use as well as upstream US energy and fertilizer production data that are very relevant for agricultural LCAs (GREET, 2021). GREET is also continuously used by biofuels producers such as the California Air Resources Board and maize ethanol producers to document their CI reductions under regulatory Low Carbon Fuel Standards in California and Oregon and the US EPA RFS, which ensures a high level of review of the GREET model in general and the agricultural interface. We, therefore, chose GREET for the present analysis.

3 | RESULTS

3.1 | Yield results

Across conventionally bred hybrid yield trials, the mean pH of the soils was 6.3, with a range of 5.3–7.5 (Table S2). The mean organic matter was 3.9%, with a range of 0.9%–7%. Growing season mean temperature was 21.9°C, with a range of 19–26°C, and mean growing season precipitation was 532 mm, with a range of 143–1756 mm. The mean N, phosphorus (P), and potassium (K) application rates on trials where data were available were 209, 61, and 63 kg ha⁻¹, respectively.

The mean yield for conventionally bred short-stature hybrids was 14.0 t ha⁻¹ under normal plant population and a significantly higher 15.1 t ha⁻¹ under high population ($p = 0.02$). The mean yield for tall hybrids was 14.5 t ha⁻¹ under normal population and 15.0 t ha⁻¹ under high population (4 Table 5).

Across biotechnology-derived hybrid yield trials, the mean pH of the soils was 6.3, with a range of 5.7–7.9 (Table S2). The mean organic matter was 4.1% with a range of 0.9%–7.5%. Growing season mean temperature was 22.3°C, with a range of 19.5–25.4°C, and mean growing season precipitation was 504 mm, with a range of 251–1756 mm. The mean N, P, and K application rates on trials where data were available were 212, 44, and 49 kg ha⁻¹, respectively.

Across 92 site-years, the mean yield for biotechnology-derived short-stature hybrids was 14.5 t ha⁻¹ and for tall hybrids was 14.3 t ha⁻¹ and was not statistically significant when averaged over all years (Table 6); however, there was a statistically significant difference in 2019.

Average annual grain yields ranged between 12.9 and 17.4 t ha⁻¹ across all years and treatments, with the highest yields under high population for both short-stature and tall hybrids for the conventionally bred material and tall comparators (Table 5). For the biotechnology-derived hybrids, short-stature hybrids and their conventional tall controls showed relatively low variation between years with a range between 13.8 and 14.9 t ha⁻¹ (Table 6).

3.2 | Root volume results

Across root excavation trials, the mean pH of the soils was 6.7, with a range of 6.4–7.5 (Table S2). The mean organic matter was 3.3% with a range of 2.0%–7.0%. Growing season mean temperature was 20.2°C, with a range of 16.4–22.7°C, and mean growing season precipitation was 361 mm, with a range of 197–515 mm. The mean N, P, and K application rates on trials were 233, 63, and 17 kg ha⁻¹, respectively.

The average estimated root volume for tall hybrids was $40,609 \pm 2464$ cm³ and $56,635 \pm 3623$ cm³ for short-stature

TABLE 4 Scenarios for modeling in greenhouse gases, regulated emissions, and energy use in transportation (GREET).

Scenario	Material	Plant density	N management	Root + stover carbon calculations
S1	Conventionally bred	High for SSM Normal for tall	Pre-season application	Not included
S2	Conventionally bred	Average across all densities	Pre-season application	Not included
S3	Biotechnology-derived	Single standard density	Pre-season application	Not included
S4	Conventionally bred	High for SSM Normal for tall	Split application	Not included
S5	Conventionally bred	Average across all densities	Split application	Not included
S6	Biotechnology-derived	Single standard density	Split application	Not included
S7	Conventionally bred	High for SSM Normal for tall	Split application	Included

TABLE 5 Yield of conventionally bred short-stature maize hybrids and tall comparators under normal and high plant populations between 2017 and 2022.

Year	Short—Normal population	Short—High population	Tall—Normal population	Tall—High population
2017	—	17.2	—	17.4
2018	14.7	17.2	16.1	16.3
2019	15.4	15.4	15.7	15.3
2020	13.0	13.1	12.5	13.0
2021	12.9	13.3	13.8	13.7
2022	14.2	14.3	14.3	14.4
Conventionally bred average	14.0 ± 0.4*	15.1 ± 0.7*	14.5 ± 0.6	15.0 ± 0.7

Note: Averages represent means ± standard error of the annual mean.

*Statistically significant difference between high and normal population for short-stature and tall hybrids in the across-year analysis ($p < 0.05$).

TABLE 6 Yield of biotechnology-derived short-stature maize hybrids and isogenic tall comparators under normal plant populations between 2019 and 2022.

Year	Short yield (t ha ⁻¹)	Tall yield (t ha ⁻¹)
2019	14.7*	14.1*
2020	14.0	13.8
2021	14.4	14.8
2022	14.9	14.6
Biotechnology-derived average	14.5 ± 0.4	14.3 ± 0.2

*Statistically significant difference between the average yield for short and tall hybrids within a given year.

hybrids, a difference of 39% ($p < 0.001$). While the absolute values decreased with depth for both short-stature and tall hybrids, there was a higher magnitude percent difference between short-stature and tall hybrids with increasing depth (Figure 3). Across the 11 site-years of data, short-stature hybrids had a larger root volume in all 11 cases (Figure S2).

Root biomass was not collected from the root excavations. Literature review was used to determine the total amount of

root carbon under tall maize hybrids at 1.01 t C ha⁻¹ (Table S2) and calculated for short-stature hybrids based on the 39% difference in root volume at 1.40 t C ha⁻¹, assuming no changes in root [C] or the specific root length. While there is a calculated increase in root biomass, there is a reduction in stover biomass in short-stature hybrids (Kosola et al., 2023). Based on the fraction of root and stover biomass incorporated into SOC (Magdoff & Van Es, 2010; H. Xu et al., 2020), we estimate that an incremental addition of 0.46 t CO₂e ha⁻¹ year⁻¹ would be incorporated into the soil by short-stature hybrids (Table 7).

3.3 | GHG modeling results

Across the modeled scenarios, there was a mean of 0.35 t CO₂e ha⁻¹, with a range of 0.09–0.78 t CO₂e ha⁻¹, savings for SSM, compared to tall hybrids (Figure 4). This corresponds to a 3%–28% reduction compared to the baseline C intensity for maize production in GREET of 2.79 t CO₂e ha⁻¹ year⁻¹. For the breeding materials, there was a savings of 0.32 t CO₂e ha⁻¹ under scenario 1, the agronomic

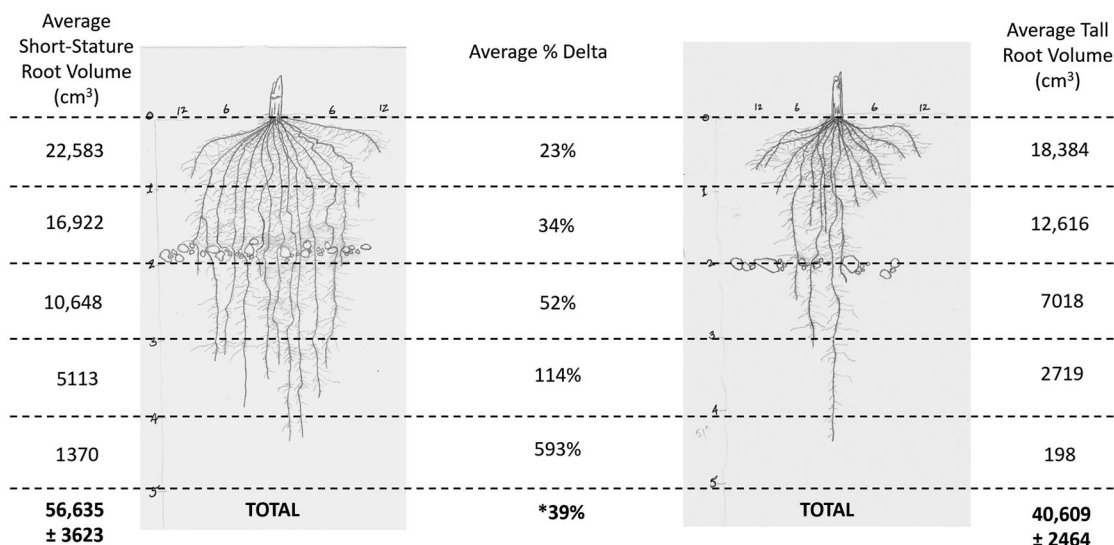


FIGURE 3 Root volume of short-stature (left) and tall (right) maize rooting systems at one-foot (0.3 m) depth increments. Values represent means of 11 site-years of data across the US Corn Belt, and images are tracings of representative plants. *Statistically significant difference in total root volume between short-stature and tall hybrids ($\alpha = 0.05$).

TABLE 7 Root and stover biomass fractions incorporated into soil organic carbon (SOC) for short-stature and tall maize hybrids.

	Short	Tall	Source
Root biomass (t C ha ⁻¹ year ⁻¹)	1.40	1.01	Root excavation data + literature review
Stover biomass (t C ha ⁻¹ year ⁻¹)	4.34	4.76	Kosola et al. (2023)
Root fraction incorporated into SOC (%)	0.5	0.5	Magdoff and Van Es (2010)
Stover fraction incorporated into SOC(%)	0.167	0.167	H. Xu et al. (2020)
Total contribution to SOC (t C ha ⁻¹ year ⁻¹)	1.42	1.30	
Total contribution to SOC (t CO ₂ ha ⁻¹ year ⁻¹)	5.22	4.76	
Incremental addition of short-stature hybrids to SOC (t CO ₂ e ha ⁻¹ year ⁻¹)	0.46		

Note: Bold values represents the total incremental addition based on the difference between the sum for short-stature and tall maize hybrids.

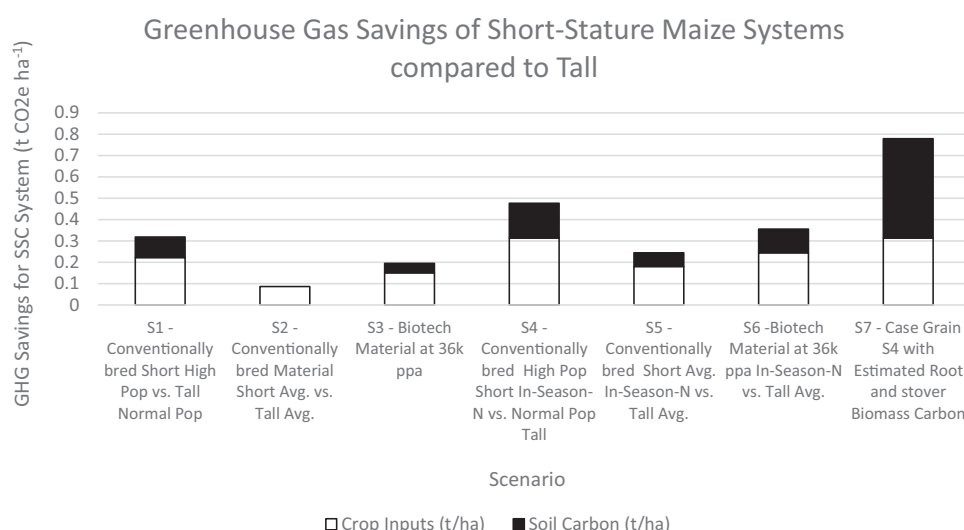


FIGURE 4 Greenhouse gas savings of short-stature maize hybrids compared to tall across different agronomic and physiologic scenarios due to both a more efficient use of crop inputs and an increase in soil carbon.

system, which is recommended commercially with an option for higher planting population for short-stature hybrids due to increased yield potential and reduced risk of lodging. There was savings of 0.1 t CO₂e ha⁻¹ under scenario 2, the yield average across planting populations for the breeding material. For the biotechnology material in scenario 3, there was a savings of 0.20 t CO₂e ha⁻¹ based on the data that were collected under a standard planting density. The in-season N application increased the magnitude of scenarios 1–3 by 0.16 t CO₂e ha⁻¹ through both an increase in yield with in-season N application and a reduction in N₂O emissions due to increased plant uptake, while also accounting for an extra equipment pass. In scenario 7, the changes in root and stover dry matter, along with the reduction in N₂O emissions from lower stover N content resulted in a savings of 0.78 t CO₂e ha⁻¹.

4 | DISCUSSION

Here, we tested the hypothesis that SSM hybrids would have different CI of grain production than tall hybrids under various agronomic systems based on a combination of de-risking of increased plant density, in-season N management, and differential root and stover dry matter accumulation and N content of residue. Data used for modeling were from a minimum of 10 site-years across the US Midwest Corn Belt and a minimum of eight hybrids indicating the strong environmental and genetic inference that can be drawn from its conclusions.

4.1 | Grain yield

The yield and efficiency of maize production systems have increased over time (Cassman et al., 2002) leading to reductions in the global warming intensity and other environmental costs (Chen et al., 2014; Dohleman et al., 2024; Grassini & Cassman, 2012; Northup et al., 2021; C. Xu et al., 2017). Yield results under normal planting densities are similar to previous comparisons of short-stature and tall hybrids (Barten et al., 2022; Kosola et al., 2023). Mean grain yields of 14.0–15.1 t ha⁻¹ are like those seen under non-wind-damaged fields (Barten et al., 2022) and slightly lower than the 15.3–15.9 t ha⁻¹ across N timings (Kosola et al., 2023) potentially because of more locations near the fringes of the US Corn Belt. The statistically significant increase in yield between standard and high population for conventionally bred SSM hybrids could be due to improved lodging tolerance of the short-stature hybrids at high densities, given the propensity of conventional tall hybrids to lodge more frequently at high density (Shah et al., 2021) and the deleterious impact of lodging on yield (Barten et al., 2022; Lindsey et al., 2021). The

statistically significant difference in grain yield in 2019 for the biotechnology-derived materials was likely due to some level of plant lodging in tall hybrids at 12 of the 25 tested locations within that year. Yields were higher than the US average of 10.9 t ha⁻¹ across the tested years (USDA-NASS, 2024). These values are likely inflated due to the nature of small plot trials from commercial research and development pipelines. Importantly, short-stature and tall hybrids were measured side-by-side each site-year, and in the GHG modeling efforts, yield values were normalized to the national average to account for this inflation.

4.2 | Root carbon

To our knowledge, this analysis represents the first peer-reviewed comparison of root architecture between short-stature and tall maize hybrids. While there are a robust number of site-years within this study, a limitation is the assumptions of root dry matter and [C] inferred from the differential root volume. While the assumptions are grounded in literature, an improvement upon this work in future studies should be direct measurement of root [C], specific root length, and root dry matter to determine whether the assumptions built within this modelling effort are validated. The observed increase in estimated root volume in short-stature hybrids is consistent with decreased carbon and N allocation to stalks in short-stature hybrids versus tall (Kosola et al., 2023). Given that leaf N and leaf biomass were similar between short and tall hybrids (Kosola et al., 2023), we would expect similar net carbon assimilation and carbon source availability. The decrease in stalk biomass from V8 to R2 is consistent with decreased carbon demand to support stalk growth; this carbon would be available to support other sinks, including root growth. A consistent increase in root volume over a wide variety of hybrids, and environmental conditions across both breeding and biotechnology materials is compelling, given the high levels of variation in root traits that are driven mostly by environment and residual error, and less so by genetics (Sciarresi et al., 2024; Tucker et al., 2020) and strong genotypic variation in root anatomy based on varying nitrogen stresses (Yang et al., 2019). This finding could reverse a trend of smaller root systems in maize hybrids over time (Rinehart et al., 2024).

Root-system size described previously in semi-dwarf barley (Chloupek et al., 2006) and semi-dwarf wheat (Lupton et al., 1974) varieties has shown more extensive roots at depth, although there are also cases where root dry matter accumulation was not significantly different between semi-dwarf and tall varieties (Siddique et al., 1990), and indications of reduced root dry matter in semi-dwarf wheat (Akman & Bruckner, 2021).

4.3 | Carbon intensity

Here, we show that through both the reduction in the yield-scaled CI of grain production and increases in carbon inputs to the SOC pool, SSM systems reduce the CI of grain production compared to commercially relevant tall maize hybrids by an average of $0.35 \text{ t CO}_2\text{e ha}^{-1} \text{ year}^{-1}$, with a range of $0.09\text{--}0.78 \text{ t CO}_2\text{e ha}^{-1} \text{ year}^{-1}$ across scenarios. The limitations of root C estimates within this analysis impact only scenario 7 within this analysis and provide a higher level of uncertainty for the top end of this range. The average CI reduction represents an average of a 12.6% reduction in the CI of maize production (range across scenarios = 3.1%–28.0%) compared to the GREET baseline assumptions of $2.79 \text{ t CO}_2\text{e ha}^{-1} \text{ year}^{-1}$, based on the national average maize yield of 11 t ha^{-1} and CI of $251 \text{ kg CO}_2\text{e tonne}^{-1}$ of grain produced. This reduction is substantial compared to the Net Ecosystem Exchange of maize–soybean rotation systems that are a net sink of $1.43 \text{ t CO}_2\text{e ha}^{-1} \text{ year}^{-1}$ on average over a 10-year period (Moore et al., 2022). As context, the shift from reduced till to no-till in Champaign County, IL, in the heart of the US Corn Belt, would provide a savings of 11.8% (GREET, 2021). A decarbonization of maize grain production has been proposed that would use three steps: (1) an optimization phase that would lower emissions by 23%, (2) a replacement phase that would reduce emissions by 41%, and (3) a redesign phase that would reduce emissions by 71% (Northup et al., 2021). When the entirety of the density, in-season N, and physiological components of the SSM system are considered, the 28% reduction in scenario 7 is between the optimize and replace phase of decarbonization by reimagining maize grain production described by Northup et al. (2021) with a single technological improvement.

5 | CONCLUSION

A systems-level modeling study was performed with two innovations. First, the first-ever side-by-side comparison of short-stature and tall maize root systems in the field showed a 39% increase in root volume and estimated the C sequestration impact of the larger root system. We also conducted a yield comparison of the SSM and conventional maize systems under varying plant densities. Second, the first life-cycle analysis was conducted to determine the full CI and carbon sequestration potential of SSM system, including grain yield, planting density, in-season N application, and the impacts of large magnitude physiological changes in short-stature hybrids with a range of $0.09\text{--}0.78 \text{ t CO}_2\text{e ha}^{-1} \text{ year}^{-1}$ reduction. Future improvements on this work should include direct measurements of root C, including specific root length, root [C], and root dry matter measurement. If the 36 million ha of land dedicated to maize production in the United States were

shifted to SSM hybrids, then under the average scenario of $0.35 \text{ t CO}_2\text{e ha}^{-1} \text{ year}^{-1}$, the annual carbon emissions of 12.6 million metric tons of CO_2e could be mitigated from maize production in the United States, the equivalent of removing 32.3 billion road miles driven by an average gasoline-powered passenger vehicle (EPA, 2025). This work also shows that comprehensive analysis that includes impact on CI of grain production and soil carbon sequestration is critical to providing a full understanding of the impact of new technologies on the carbon footprint of crop production.

AUTHOR CONTRIBUTIONS

Frank G. Dohleman: Conceptualization; data curation; formal analysis; investigation; methodology; visualization; writing—original draft. **Ty Barten:** Data curation; methodology; writing—review and editing. **Kevin R. Kosola:** Conceptualization; data curation; methodology; writing—review and editing. **Mark Reiman:** Conceptualization; data curation; investigation; writing—review and editing. **Mike Petersen:** Data curation; investigation; methodology; writing—review and editing. **Jeff Tichota:** Data curation; investigation; methodology; writing—review and editing. **Ross Recker:** Conceptualization; data curation; formal analysis; project administration; writing—review and editing. **Devin J. Hammer:** Conceptualization; data curation; formal analysis; project administration; writing—review and editing. **Adam Gold:** Data curation; writing—review and editing. **Brian Olson:** Conceptualization; funding acquisition; supervision; writing—review and editing. **Thomas Orr:** Funding acquisition; project administration; writing—review and editing. **Steffen Mueller:** Conceptualization; data curation; formal analysis; investigation; methodology; software; visualization; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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