Rotation Impact on On-Farm Yield and Input-Use Efficiency in High-Yield Irrigated Maize–Soybean Systems

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ABSTRACT

Cereal yields tend to be higher in cereal–legume rotations relative to cereal monoculture yields. We investigated the influence of crop rotation on yield and input-use efficiency in high-yield irrigated maize (Zea mays L.)-based cropping systems using producer-reported data from western U.S. Corn Belt (about 11,000 observations). Across regions, average yield of maize grown after soybean (Glycine max (L.) Merr.) (S–M) was 0.2 to 0.6 Mg ha\(^{-1}\) (2–5%) higher, relative to yield of maize grown after maize (M–M). Soybean yield was 5% greater after two consecutive maize crops (M–M–S) than after only 1 yr of maize (S–M–S). Nitrogen fertilizer rate in maize fields was 13 kg N ha\(^{-1}\) (6%) lower in S–M than M–M fields, which, together with higher maize yields in S–M fields, resulted in 11% higher nitrogen partial factor productivity (PPF\(_N\)). Difference in PPF\(_N\) was unrelated with residual soil N–NO\(_3\)\(^-\) from prior crop. Analysis of rotation data indicated that rotation effect persists across a wide range of maize yields, from 6 to 15 Mg ha\(^{-1}\), though magnitude of rotation effect decreases with increasing yield level. Trends toward greater proportion of total maize area in S–M, rather than M–M, accounts for 8% of maize yield gain in U.S. Corn Belt since 1970. Similarity between our findings and previous research highlights the opportunity to quantify impact of management on yield and efficiencies by using producer data as a complement to high-cost multi-year, multi-site field experiments.

Core Ideas

- We assessed rotation effect on on-farm yield and input-use efficiency.
- Analysis was based on a large producer-reported database collected from high-yield irrigated maize–soybean systems.
- There was a consistent positive rotation effect on yield and partial factor productivity for N fertilizer.
- Number of previous maize crops did not affect maize yield in monoculture but soybean yields were higher following multiple maize crops.
- Increasing maize area in rotation relative to monoculture accounts for 8% of the maize yield gain in the U.S. Corn Belt since 1970.

MAIZE AND SOYBEAN have the largest share of the U.S. cropland area, with a total of 36 and 31 Mha sown and annual grain production of 313 and 87 Tg, respectively (USDA–NASS, mean values for 2005–2014). The U.S. Corn Belt and other areas of the central U.S. Great Plains (Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin) account for about 87% of total U.S. maize production and 84% of total U.S. soybean production. The dominant crop sequences in the U.S. Corn Belt in any given 2-yr time frame are S–M and M–M. If 3- or 4-yr periods are considered, there are frequently additional consecutive maize crops prior to a soybean year, when commodity prices and government programs favor maize over soybean. On average, the S–M rotation accounts for about 65% of the area sown with maize and soybean in the U.S. Corn Belt with the remaining area (about 35%) sown with continuous maize (Grassini et al., 2014a). The proportion of land under S–M–S rotation vs. continuous maize has increased over time (USDA–NASS, 1970–2008), though the precise area in a given region year is highly influenced by expected soybean and maize prices and producers’ personal preference for growing one of the two crops.

Numerous field trials have shown that maize grown after soybean gives higher yield than maize after maize (e.g., Crookston et al., 1991; Meese et al., 1991; Porter et al., 1997; Stanger et al., 2008; Sindelar et al., 2015). This yield difference, hereafter called “rotation effect”, is postulated to result from multiple interacting factors (Bullock, 1992), such as beneficial rhizosphere microorganism communities (Turco et al., 1990), reduced pest infestations (Varvel and Peterson, 1990; Katupitiya et al., 1997) in S–M fields, and delayed emergence and difficulties to establish an uniform maize plant density in the M–M no-till fields covered with substantial maize residue, and changes in soil N availability (Green and Blackmer, 1995; Gentry et al., 2001). Other studies have identified factors influencing the magnitude of rotation effect, including weather (Porter et al., 1997; Wolfe and Eckert, 1999), number of consecutive maize crops (Meese et al., 1991; Porter et al., 1997), soil quality (Al-Kaisi et al., 2015), and crop management

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practices (Griffith et al., 1988; Lund et al., 1993; Adviento-Borbe et al., 2007). Most previous studies on rotation effect were conducted on research stations or on-farm field trials conducted for a limited number of site-years, where crops were managed following “recommended” or “best” farm management practices. However, no previous study has provided a more comprehensive assessment of the rotation effect across a broader array of producer-managed fields, and a wide range of weather, soil types, and management practices, where the prime objective of most producers is pursuit of profitability when considering best-practice management options. Likewise, most previous studies on the rotation effect on U.S. maize-based systems have been based on experiments where maize yields were substantially below their yield potential, with only a few studies conducted in high-yield (>10 Mg ha\(^{-1}\)) conditions (e.g., Verma substantially below their yield potential, with only a few studies conducted in high-yield (>10 Mg ha\(^{-1}\)) conditions (e.g., Verma et al., 2005; Adviento-Borbe et al., 2007) and even those were limited to single locations and for a limited number of years.

Aside from conventional field trials as a source of information for estimating rotation effects, one can use an alternative approach based on producer-reported, field-specific data on yield and applied inputs, when such data are available for thousands of fields and several crop seasons to investigate spatial and temporal variation in rotation effect and its underpinning causes. Such an approach provides a much wider range of environments and management interactions to investigate spatial and temporal variation in rotation effects and the underpinning causes. In contrast, most replicated field trials can only capture a few management interactions because the experiments are limited in site-year number and number of management treatment combinations (e.g. tillage method, fertilizer rates, irrigation amounts, etc.) and those might not be intrinsically representative of the actual conditions in major production zones (e.g., research stations are typically located in best soils) and producer management practices. Finally, analyzing the rotation impact in irrigated, high-yield cropping systems, where yields approach yield potential and producers have access to inputs, markets, and extension education, can help distinguish the rotation effect from other factors associated with low-yield environments with high year-to-year weather variability, insufficient N and water supply, and diseases and insect pressure.

In the present study, we assessed the rotation effect on yield and input-use efficiency in high-yield irrigated maize–soybean based systems in the western U.S. Corn Belt, using an exceptionally large dataset that involved thousands of observations over a 9-yr period (2005–2013) with information on crop yield and amounts of applied N fertilizer and irrigation water. These cropping systems achieved very high average yields, ranging from 11.5 to 14 Mg ha\(^{-1}\) across region years. On average, 1882 field observations were evaluated for each year, and the relatively short 9-yr time frame evaluated means that genetic and agronomic technologies were relatively constant over this period. Specific objectives of this study were to: (i) compare maize yield and input-use efficiency between fields where maize was grown after soybean vs. maize after maize, and (ii) identify explanatory factors for spatial and temporal variation in rotation effect magnitude.

**MATERIAL AND METHODS**

**Description of On-Farm Database**

Nebraska (western U.S. Corn Belt) ranks third and fifth among U.S. maize and soybean producing states, respectively, with a respective annual output of 42.8 and 79 Tg (USDA–NASS, 2005–2014). Nebraska has the largest share of U.S. irrigated cropland area (USDA–NASS, 2005–2014), accounting for 61% of irrigated maize and 45% of irrigated soybean harvested area. Producer-reported data are annually collected by the 23 Nebraska Natural Resources Districts (NRDs) (http://www.nrndnet.org/). The database used in the present study contained data from irrigated maize–soybean systems in three regions of Nebraska: Lower Niobrara, Tri-Basin, and Central Platte (Fig. 1). The reporting area within these regions is roughly 1000 km\(^2\) (Lower Niobrara and Tri Basin) and 3000 km\(^2\) (Central Platte).

Detailed description of the database and the three regions is provided elsewhere (Farmaha et al., 2016). Briefly, these regions have similar annual total precipitation and reference evapotranspiration (about 600 and 1000 mm, respectively), but different soil characteristics: homogenous silt-loam soils in Tri-Basin; heterogeneous soils in Central Platte; and sandy-loam soils in Lower Niobrara. Disk is the dominant tillage method in irrigated fields in Lower Niobrara (80% of total fields), whereas no-till or other reduced tillage methods (strip- and ridge-till) dominate in irrigated fields in Tri Basin and Central Platte districts (66% of total fields) (Grassini et al., 2015).

The database includes field-specific crop yield adjusted to a grain moisture content for 15.5% (maize) and 13% (soybean), the previous year’s crop, amount of applied N fertilizer and total applied irrigation, groundwater N–NO\(_3\)\(^{-}\), and residual soil N–NO\(_3\)\(^{-}\) (from top 0.9 m of soil surface) after the previous crop. The database also includes the precise field location. Unfortunately, tillage method for each field-year observation was not available in the NRD database used in the present study. Producer-reported yield and applied input data have been compared with other independently derived datasets and found to be in good agreement (Grassini et al., 2014b, Sadras et al., 2014, Grassini et al., 2015). Data were available from 2004 to 2013, but only those fields for which eight or more years of maize yield had been reported were retained for our analysis. We selected data from eight crop seasons (2005–2013, excluding 2011) for the Lower Niobrara and Tri-Basin districts, and from four crop seasons (2009, 2010, 2012, and 2013) for the Central Platte district. A small number of S–M fields in Central Platte from 2005 to 2008 precluded the use of these years in our study. Likewise, year 2011 was excluded from the analysis for all three regions due to substantial maize harvest losses from late harvest and winter snowfall that would have biased the estimation of rotation effect.

Quality checks were performed on the retained data. For example, crop sequence with soybean after soybean was extremely infrequent, necessitating exclusion of S–S fields from the analysis. Fields sown with popcorn or maize harvested for silage were also excluded from the analysis. In the final database, about 8, 25, and 36% of maize fields in Central Platte, Tri-Basin, and Lower Niobrara were sown after soybean; the rest were sown after maize. Overall, the database contained 11,040 irrigated maize field observations with 8752 of those reflecting a M–M sequence and 2288 reflecting a S–M sequence.
sequence. Further details on field selection and data quality control are provided elsewhere (Farmaha et al., 2016).

For each field observation, data on available water-holding capacity (AWHC), soil organic matter (SOM), and soil pH were retrieved from SSUGRO database for the upper 1-m soil depth (Soil Survey Staff, NRCS-USDA, 2015). The co-linearity among these variables was not significant (Pearson’s $r \leq 0.50$). The SAGA wetness index (SWI) of each field was calculated from raster Digital Elevation Model (DEM) with a grid size of 100 m$^2$ (Böehner and Antonic, 2009). A high SWI value indicates a field that is likely to be a net importer of water from periods of surface runoff, whereas a low SWI value indicates a field that is likely to be net exporter of water during those periods. Daily weather data, including maximum and minimum temperature, solar radiation, and precipitation, were available from automated weather data stations located within each region.

Estimation of Rotation Effect on On-Farm Yield and Input-Use Efficiency

Maize yield, applied inputs (N fertilizer and irrigation water), and input-use efficiencies were compared between the S–M and M–M field groups, where each group included any 2-yr S–M or M–M sequence extractable from any consecutive 2-yr portion of the 8- or 4-yr cropping season dataset. Mean values for each region–year–crop sequence were calculated by averaging reported maize yields, applied inputs, and input-use efficiencies across fields within the same region–year–crop sequence. Following Cassman et al. (2002), PFP$_N$ was calculated as the ratio of grain yield to N fertilizer rate (kg grain kg$^{-1}$ applied N). Irrigation water-use efficiency (IWUE) was calculated as the ratio of grain yield to irrigation amount (kg grain mm$^{-1}$ applied water). Paired $t$ tests were conducted to evaluate significant differences between S–M vs. M–M fields in terms of yield, applied inputs (N fertilizer and irrigation), and input-use efficiencies (PFP$_N$ and IWUE). Linear regression was performed to identify differences in relationships between second year maize yield, residual soil N–NO$_3$ -- applied N fertilizer and irrigation water, PFP$_N$, and IWUE in S–M and M–M fields. Finally, the effect of number of consecutive years of maize (one vs. two) on subsequent crop yields was assessed by comparing final year maize yields in a S–M–M sequence vs. that in a M–M–M sequence. Though the emphasis in this paper is on performance of maize, we provide, for collateral readers’ interest, final year soybean yield in M–M–S vs. S–M–S sequence.

Identification of Sources of Variation for Rotation Effect

A principal component (PC) analysis was performed for each region separately on correlation matrix of soil and terrain properties (AWHC, SOM, pH, and SWI) calculated for each field, using the PRINCOMP procedure available in SAS/STAT software (SAS Institute, 2014). The objective of PC analysis was to generate two or three linear combinations of soil and terrain properties (hereafter called ‘PCs’) that could account for substantial portion(s) of the field-to-field (spatial) variability in soil and terrain properties. In each generated PC, weights were assigned to each property, and that weight ranged from –1 to +1. The sign of weights indicated the directional effect of a given variable relative to the other variables included in the generated PC. As a rule of thumb, if the weight of any given property is $>0.40$, then it was considered to be an important representation of that property in that particular PC (Villamil et al., 2012). Ultimately, each field had a “PC score” calculated from the generated PCs based on field-specific soil and terrain properties. The first generated soil PC $[SPC1 = –0.16 (SWI) + 0.65 (AWHC) + 0.53 (SOM) + 0.52 (pH)]$ explained 44%, and the second PC $[SPC2 = 0.96 (SWI) + 0.03 (AWHC) + 0.28 (SOM)– 0.02 (pH)]$ explained 25%, of field-to-field variation.
positive and high weight for mid-season mean temperature, mid-season accumulated solar radiation, and early-season total precipitation, but had a negative weight for early-season mean temperature.

Analysis of variance was performed using GLM procedure (SAS Institute, 2014) to determine sources of variation with some selected candidate biophysical factors that were hypothesized as contributors to the observed spatial and temporal variation in maize yield and rotation effect. These factors included soil PCs, weather PCs, prior year average maize and soybean yields, N fertilizer rate, and irrigation amount. Interaction of crop sequence with selected variables was also tested. The SPC1 and SPC2 are biophysical indicators of field-to-field variability and WPC1 and WPC2 are indicators of years’ weather variability; hence, we decided to use these factors in the model instead of field and year as individual factors and, similarly, their interactions with crop sequence were included. For example, rotation effect on yield can be amplified in no-tilled maize fields, with heavy residue from prior high-yield maize crop, due to sowing and emergence delays, especially in years with early-season low temperature and high precipitation (Lund et al., 1993). Likewise, applied N fertilizer was also included in the model because maize grown in rotation with soybean typically receives less amount of N fertilizer compared with applied N fertilizer to maize grown after maize (Gentry et al., 2001). The above analysis was conducted separately for each region and for the pooled database using all the data across region-years.

RESULTS

Yield, Applied Inputs, and Input-Use Efficiency across Crop Sequences

The mean second year maize yield difference between M–M and S–M crop sequences revealed an overall rotation effect magnitude of 0.4 Mg ha\(^{-1}\) (Fig. 2a), equivalent to 3% higher maize yield in S–M vs. M–M fields \((P < 0.001)\). Across the entire range of observations, the estimated slope of the fitted linear regression model was unity, thereby leading to

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**Fig. 2.** Comparison of maize yield in (a) maize after soybean (S–M) vs. maize after maize (M–M) irrespective of prior cropping history in both 2-yr subsets, and (b) maize after only 1 yr of maize (S–M–M) vs. maize after two consecutive years of maize (M–M–M). Each data point represents the average yield for a given region-year set of fields. Regional and overall mean magnitudes of the rotation effect, which are shown inside each figure, were tested for statistical significance using paired t tests. Asterisks indicate significance at *P* < 0.05, **P** < 0.01, and † P < 0.10. Parameters of the fitted linear regression (± SE) and coefficient of determination \((r^2)\) are also shown.
the graphed trend being parallel with the 1:1 diagonal line. This result suggests that the rotation effect size was relatively constant at 0.4 Mg ha\(^{-1}\) across yields that ranged from 11.5 to 14.0 Mg ha\(^{-1}\). A positive rotation effect on yield was significant in all regions \(P < 0.10\) but the size of its magnitude was 20% greater in Tri-Basin (0.6 Mg ha\(^{-1}\)) and 60% lesser in Lower Niobrara (0.2 Mg ha\(^{-1}\)) than what was observed in Central Platte (0.5 Mg ha\(^{-1}\)). Still, the effect of region on the magnitude of rotation effect was weak \((P = 0.09)\). Year effect on rotation was not significant \((P = 0.73)\). Putative explanatory factors for differences in rotation effect magnitude across fields are discussed in Spatial and Temporal Variation in Rotation Effect section. It is interesting to note that magnitude of the rotation effect dropped to zero once soybean was no longer the prior year crop (Fig. 2b). Hence, there was no significant difference in maize yields between S–M–M and M–M–M fields for the three regions \((P > 0.18)\). Indeed, all region-year paired observations were within \(\pm 10\%\) of the 1-to-1 line, except for two observations.

Comparison of soybean yields in the final year of a 3-yr rotation in M–M–S vs. S–M–S fields revealed that yields of the former were 0.2 Mg ha\(^{-1}\) (5%) higher \((P < 0.01)\), with the magnitude of this difference smaller (+3%) in Tri-Basin and large (+8%) in Lower Niobrara (Fig. 3). The slope of the fitted linear regression model was significantly different from unity \((P < 0.01)\), which is evident in the graph, based on the non-parallel regression trend and 1:1 diagonal line. Interestingly, the greater yield of a soybean crop when preceded by two prior maize crops seems to decrease from low- to high-yield soybean fields (e.g., 3.0–4.5 Mg ha\(^{-1}\)) (Fig. 3). These results show that the prevailing practice of annually rotating maize and soybean does not give maximum soybean yields.

The second year maize crop in the S–M fields received, on average, 13 kg N ha\(^{-1}\) (6%) less fertilizer N relative to second year maize crop in M–M fields \((P < 0.01)\) (Fig. 4a). This difference was consistent in the three regions and across the entire yield range. Current N fertilizer recommendations for maize take into account empirically defined “N credits” from a previous soybean crop. This is based on earlier research that showed maize grown after soybean has a lower economical optimum N rate than maize grown after maize (Gentry et al., 2001; Shapiro et al., 2003). Therefore, it appears that producers are following this N fertilizer recommendations and doing so does not negatively impact yield of the subsequent maize crop. Greater (3%) maize yields and lower N fertilizer application rates (6%) in S–M fields than in M–M fields resulted in 11% higher PFP\(_N\) in S–M fields than in M–M fields (70 vs. 63 kg kg\(^{-1}\) N, \(P < 0.01\)) (Fig. 4b). Inclusion of groundwater N–NO\(_3^-\) from irrigation water in the calculation of PFP\(_N\) would lead to average PFP\(_N\) of 56 kg kg\(^{-1}\) N in S–M fields and 50 kg kg\(^{-1}\) N in M–M fields. Differences in PFP\(_N\) between S–M and M–M fields were significant in all regions \((P < 0.03)\), but magnitude varied among regions, with smallest difference in PFP\(_N\) in Lower Niobrara (5 kg kg\(^{-1}\) N) and largest in Central Platte (11 kg kg\(^{-1}\) N), which, in turn, was consistent with observed differences in the magnitude of rotation effect across regions (Fig. 2a).

Higher PFP\(_N\) in S–M vs. M–M fields cannot be attributed to differences in residual soil N–NO\(_3^-\) from prior crop. Residual soil N–NO\(_3^-\) after soybean was between \(\pm 15\%\) of residual soil N–NO\(_3^-\) after maize in 70% (19 out of 27) region-year cases (Fig. 5a). Indeed, the difference in residual soil N–NO\(_3^-\) was small (5 kg N ha\(^{-1}\)) and not significantly different after maize vs. after soybean in two of the three regions. Similarly, the difference in residual soil N–NO\(_3^-\) after the harvest of second year maize crop in S–M and M–M fields was nonsignificant in Central Platte and Lower Niobrara \((P > 0.25)\), while the difference was significant \((P = 0.07)\), though small, in Tri-Basin (Fig. 5b).

One would have a priori expected irrigation to be higher in second year in M–M fields relative to S–M fields. Typically, a greater proportion of maize fields are tilled after a prior maize crop, relative to a prior soybean crop, and previous research has shown that larger irrigation amounts are indeed applied in tilled- vs. no-tilled fields (Grassini et al., 2011). Consistent with this expectation, our analysis indicated that, on average, irrigation was slightly though significantly (3%) lower in S–M fields relative to M–M fields \((P = 0.02)\). Difference in IWUE between S–M and M–M fields, due to lower irrigation and higher yield, was significant for two regions and in the pooled analysis \((P < 0.07)\). On average, IWUE was 6% higher in S–M fields relative to M–M fields, with smallest and largest difference in IWUE in Lower Niobrara (3%) and Central Platte (11%), respectively.

**Spatial and Temporal Variation in Rotation Effect**

Variation in soil properties and weather across regions and year explained little of the observed region-year-field variation in rotation effect (Table 1). While the analysis of variance confirmed the effect of the previous crop on yields, which was significant \((P < 0.01)\) for the pooled database and for all
Fig. 4. Comparison of (a) N fertilizer, (b) partial factor productivity for N fertilizer (PFP_{N}), (c) total irrigation, and (d) irrigation water use efficiency (IWUE) in maize after soybean (S–M) (y axis) vs. maize after maize (M–M) (x axis). Each data point represents average applied input or input-use efficiency for a given region-year. Regional and overall differences, which are shown inside each figure, were tested for statistical significance using paired t tests. Asterisks indicate significance at *P < 0.05, **P < 0.01, and † P < 0.10. Parameters of the fitted linear regression (± SE) and coefficient of determination (r²) are also shown.

Fig. 5. Comparison of residual soil N–NO₃⁻ (a) after the harvest of soybean (y axis) vs. after the harvest of maize (x axis) and (b) in maize after soybean (S–M) (y axis) vs. maize after maize fields (M–M) (x axis). Each data point represents the average value for a given region-year. Encircled data point was not included in the regression analysis and calculation of regional means. Mean differences and significance using paired t tests are shown for each region and for the pooled data within each figure. Asterisks indicate significance at *P < 0.05, **P < 0.01, and † P < 0.10.
Table 1. Analysis of variance for maize yield relative to field, year, and management parameters and their interactions. F values and their significance are shown for each region and for the pooled database. Overall R² of the model for each region and for the pooled data is also provided.

<table>
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<tr>
<th>Source</th>
<th>Central Platte</th>
<th>Tri-Basin</th>
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<td>19***</td>
</tr>
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<td>Previous year soybean yield</td>
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<td>4*</td>
<td>266***</td>
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<td>3†</td>
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<tr>
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<td>0.36</td>
<td>0.53</td>
<td>0.58</td>
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</table>

* Significance of F test at P < 0.05.
** Significance of F test at P < 0.01.
† Significance of F test at P < 0.10.
‡ SPC1: soil principal component 1; SPC2: soil principal component 2, WPC1: weather principal component 1, WPC2: weather principal component 2.
§ This effect was non-computable in the model.

regions, interactions between previous crop with soil (SPC1 and SPC2), weather (WPC1 and WPC2), and applied N and water inputs were inconsistent and nonsignificant in most cases (Table 1). For example, previous crop × SPC1 interaction was significant only in Tri-Basin and previous crop × WPC1 interaction was significant in Central Platte and Lower Niobrara (P ≤ 0.05). Given the negligible impact of soil properties and applied N fertilizer and irrigation input on the rotation impact (Table 1), we speculate that the smaller rotation effect in Lower Niobrara relative to Central Platte and Tri-Basin might be associated with greater frequency of fields in the former that are disk-tilled before maize is sown and after a prior maize crop. A rotation × tillage interaction on irrigated maize yield was previously documented by Grassini et al. (2011).

**DISCUSSION**

Across a wide range of irrigated cropping environments, we found that maize yield was consistently higher following soybean than after maize. But the magnitude of the rotation effect in our study was surprisingly small compared to previous reports (Fig. 6). Indeed, when all data from the literature and the present study were pooled, it was possible to derive a generic function for modeling the magnitude of rotation effect with respect to the yield level of the productivity of the environment as estimated by yield. The rotation effect persisted across a wide range of yield level (from 6–15 Mg ha⁻¹), water regimes (i.e., rainfed and irrigated crops), and weather, soil types, and management practices (Fig. 6). The generic function also indicated that rotation effect magnitude decreased from about 1 to 0.2 Mg ha⁻¹ with increasing yield of the production

![Fig. 6. Comparison of maize yield after soybean (S–M) vs. maize yield after maize (M–M) based on data from the present study for irrigated maize (blue triangles, red circles, and black squares) and data reported by previous studies (see the Supplement) for rainfed (green open triangles) and irrigated maize crops (green solid triangles). Green and black stars show average maize yield for rainfed and irrigated crops, including the data from our study. Inset shows the relationship between rotation effect magnitude (calculated as [(yield M–M) − yield S–M)]/100×yield M–M) plotted against the maize yields in M–M fields. Parameters of the fitted linear regression (± SE) and coefficient of determination (r²) are also shown.](image-url)
environment, which is equivalent to a reduction from 15 to 2%, relative to the second year maize yield in the M–M sequence (Fig. 6, inset). These findings are consistent with Porter et al. (1997) who reported a greater rotation effect in low-yield than in high-yield environments.

The fitted generic function between the magnitude of rotation effect size and yield level of the production environment shown in Fig. 6 was used to calculate the proportion of on-farm U.S. yield gain that can be attributed to the increasing proportion of maize grown in a 2-yr M–S rotation. Based on total maize and soybean harvested area data reported for the three major maize producer states (Nebraska, Iowa, and Illinois), it can be inferred that the proportion of maize grown in a 2-yr M–S rotation has increased 1% per year, from approximately 50% (early 1970s) to 80% (mid-2000s) (USDA–NASS, 1970–2008). During the same time period, the annual maize yield gain calculated for the three major maize producing states in the U.S. Corn Belt was remarkably linear at 114 kg ha−1 yr−1. Estimated maize yield gain due to increasing soybean–maize area, at expense of continuous maize, was 9 kg ha−1 yr−1, which represents 8% of the observed U.S. maize yield gain after 1970. The maize yield disadvantage intrinsic in a 2-yr M–M sequence (vs. 2-yr S–M sequence) remained the same even when the maize only sequence goes to a 3-yr M–M–M scenario. In contrast, the number of maize crops influenced the subsequent soybean crop yield, with 5% higher soybean yield in fields with 2 vs. 1 yr of prior maize crops. Crookston et al. (1991) and Porter et al. (1997) reported 6 to 8% increase in soybean yield after two or more years of maize compared with 1 yr of maize in relatively low-yield rainfed environments (soybean and maize yield averaged about 3 and 8.0 Mg ha−1, respectively). In the same studies, Crookston et al. (1991) and Porter et al. (1997) also reported that final year maize yield in S–M–M and M–M–M fields were similar. The present study confirmed these findings and extended them to high-yield irrigated fields. These findings can inform producer decisions on rotating maize with soybean every year or after 2 yr depending on the expected yield difference and grain price ratio between the two crops, and N fertilizer cost.

Our study also found that producers applied 6% less N fertilizer to S–M fields but still achieved a 3% higher maize yield and thereby an 11% higher PEPc relative to M–M fields, despite lack of difference in residual soil N–NO3 from the prior crop, whether maize or soybean. This finding suggests higher indigenous N supply from S–M fields relative to M–M fields, which is consistent with Gentry et al. (2013) who reported higher maize N uptake in non-fertilized experimental plots after prior soybean vs. maize. Decomposition of soybean residue is faster while N immobilization is lower due to lower C/N in soybean vegetative biomass, which increases indigenous N supply in maize fields after a previous soybean crop and offsets the lower N fertilizer input (Green and Blackmer, 1995, Power et al., 1986), also called a “priming effect” of soybean on SOM mineralization (Kuzyakov et al., 2000).

CONCLUSIONS

Key insights from this study focusing on high-yield irrigated maize in the western U.S. Corn Belt are: (i) maize grown after soybean has yield advantage (2–5%) relative to maize grown after maize even at high yield levels (11–14.5 Mg ha−1), (ii) the magnitude of rotation effect size was at the lower end of rotation effects reported in previous studies for (mostly) rainfed environments, (iii) maize grown after soybean received 6% (13 kg N ha−1) less N fertilizer than maize grown after maize but had 11% higher partial factor productivity for N fertilizer, (iv) rotation effect size was smaller in the region with highest proportion of tilled fields, (v) apparent cumulative rotation effect on maize yield lasted only for 1 yr but, in the case of soybean, fields that had two prior maize crops had 3 to 8% higher soybean yield compared to one prior maize crop in 3-yr rotation, and (vi) analysis of the data reported in the literature indicate that rotation effect persists across a wide yield range, but its magnitude decreases with increasing yield of the production environment. Based on these results, we estimated that 8% of the observed maize yield gain between 1970 and 2008 was accounted by the increasingly higher proportion of maize fields in rotation with soybean, relative to continuous maize, over that same period. Similarity between our findings and those reported by others based on long-term experiments (e.g., Crookston et al., 1991, Porter et al., 1997, Sindelar et al., 2015) highlights the opportunity to quantify the impact of management practices on yield and efficiencies of water and fertilizer using producer-reported data as a complement to high-cost multi-year, multi-site field experiments.

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REFERENCES


