Key Management Practices That Explain Soybean Yield Gaps Across the North Central US

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Highlights

- We developed a novel approach that combines producer survey data with a biophysical spatial framework for identifying causes of yield gaps over large agricultural areas with diversity in climate and soils.
- The approach was applied to both rainfed and irrigated soybean in the North Central US region, and it was based on producer survey data on yield and management collected from 3,568 fields over two crop seasons.
- The analysis indicated that the average regional yield potential was 71 bu ac^{-1} (rainfed) and 85 bu ac^{-1} (irrigated), with a respective yield gap of 22% and 13% of maximum yield potential.
- Planting date, tillage, and in-season foliar fungicide and/or insecticide were identified as explanatory causes for yield variation, with planting date the most consistent management factor that influenced soybean yield.

Introduction

To date identification of causes of yield gaps (difference between maximum yield potential and measured yield in producer yields) has been restricted to small geographic areas. In this study, we developed a novel approach that combines producer-reported data and a spatial framework to identify explanatory causes of yield gap over large geographic regions with diversity of climate, soils, and water regimes (rainfed and irrigated). We focused on soybean in the North-Central United States region, which accounts for approximately one third of global soybean production, as a case study to provide a proof of concept on the proposed approach. The specific objectives of this project were to evaluate the proposed approach for its ability to: (1) benchmark producer soybean yields in relation to yield potential of their fields, (2) identify key management practices that explain yield gaps, and (3) explain the drivers for some of the observed (M)anagement × (E)nvironment interactions.

Producer data collection and quality control

Data on soybean yield and management practices were collected over two crop seasons (2014 and 2015) from fields planted to soybean in 10 states in the North Central US region: Illinois (IL), Indiana (IN), Iowa (IA), Kansas (KS),

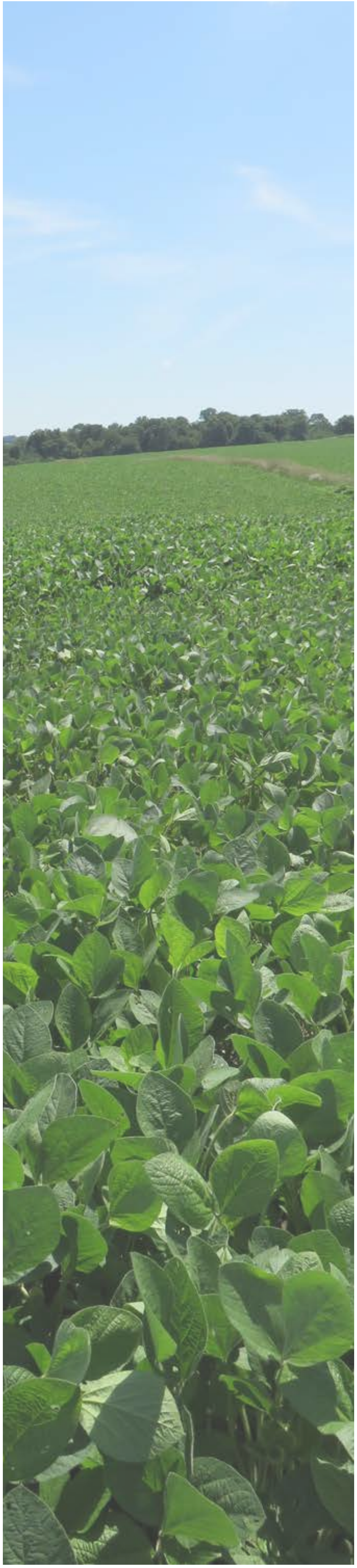
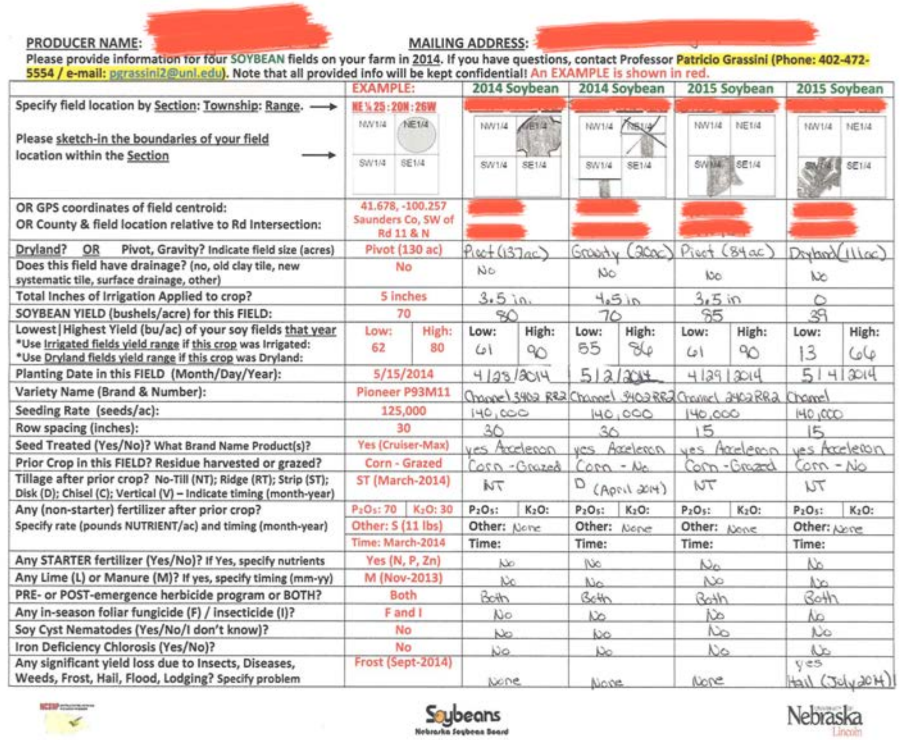


Figure 1. Example of an actual survey form from a Nebraska soybean producer that provides information for three irrigated fields and one rainfed field planted to soybean in 2014 and 2015. This survey form was used to collect information from producer fields across 10 states in the North Central US region. Note that producer name is not shown and field location was hatched in order to keep personal information confidential.



PRODUCER NAME: [redacted] MAILING ADDRESS: [redacted]

Please provide information for four SOYBEAN fields on your farm in 2014. If you have questions, contact Professor Patricio Grassini (Phone: 402-472-5554 / e-mail: pgrassini2@unl.edu). Note that all provided info will be kept confidential! An EXAMPLE is shown in red.

	EXAMPLE:	2014 Soybean	2014 Soybean	2015 Soybean	2015 Soybean
Specify field location by Section: Township: Range. →	NE¼ 25 : 20N : 26W	[redacted]	[redacted]	[redacted]	[redacted]
Please sketch-in the boundaries of your field location within the Section →	NW1/4 NE1/4 SW1/4 SE1/4	NW1/4 NE1/4 SW1/4 SE1/4	NW1/4 NE1/4 SW1/4 SE1/4	NW1/4 NE1/4 SW1/4 SE1/4	NW1/4 NE1/4 SW1/4 SE1/4
OR GPS coordinates of field centroid: OR County & field location relative to Rd Intersection:	41.678, -100.257 Saunders Co, SW of Rd 11 & N	[redacted]	[redacted]	[redacted]	[redacted]
Dryland? OR Pivot, Gravity? Indicate field size (acres)	Pivot (130 ac)	Pivot (137ac)	Gravity (30ac)	Pivot (84ac)	Dryland (11ac)
Does this field have drainage? (no, old clay tile, new systematic tile, surface drainage, other)	No	No	No	No	No
Total Inches of Irrigation Applied to crop?	5 inches	3.5 in.	4.5 in	3.5 in	0
SOYBEAN YIELD (bushels/acre) for this FIELD:	70	80	70	85	39
Lowest|Highest Yield (bu/ac) of your soy fields that year *Use Irrigated fields yield range if this crop was Irrigated: *Use Dryland fields yield range if this crop was Dryland:	Low: 62 High: 80	Low: 61 High: 90	Low: 55 High: 86	Low: 61 High: 90	Low: 13 High: 66
Planting Date in this FIELD (Month/Day/Year):	5/15/2014	4/28/2014	5/2/2014	4/29/2014	5/4/2014
Variety Name (Brand & Number):	Pioneer P93M11	Channel 3402 RR2	Channel 3402RR2	Channel 2402RR2	Channel
Seeding Rate (seeds/ac):	125,000	140,000	140,000	140,000	140,000
Row spacing (inches):	30	30	30	15	15
Seed Treated (Yes/No)? What Brand Name Product(s)?	Yes (Cruiser-Max)	yes Acceleron	yes Acceleron	yes Acceleron	yes Acceleron
Prior Crop in this FIELD? Residue harvested or grazed?	Corn - Grazed	Corn - Grazed	Corn - No	Corn - Grazed	Corn - No
Tillage after prior crop? No-Till (NT); Ridge (RT); Strip (ST); Disk (D); Chisel (C); Vertical (V) – Indicate timing (month-year)	ST (March-2014)	NT	D (April 2014)	NT	NT
Any (non-starter) fertilizer after prior crop? Specify rate (pounds NUTRIENT/ac) and timing (month-year)	P_2O_5: 70 K_2O: 30 Other: S (11 lbs) Time: March-2014	P_2O_5: K_2O: Other: None Time:	P_2O_5: K_2O: Other: None Time:	P_2O_5: K_2O: Other: None Time:	P_2O_5: K_2O: Other: None Time:
Any STARTER fertilizer (Yes/No)? If Yes, specify nutrients	Yes (N, P, Zn)	No	No	No	No
Any Lime (L) or Manure (M)? If yes, specify timing (mm-yy)	M (Nov-2013)	No	No	No	No
PRE- or POST-emergence herbicide program or BOTH?	Both	Both	Both	Both	Both
Any in-season foliar fungicide (F) / insecticide (I)?	F and I	No	No	No	No
Soy Cyst Nematodes (Yes/No/I don't know)?	No	No	No	No	No
Iron Deficiency Chlorosis (Yes/No)?	No	No	No	No	No
Any significant yield loss due to Insects, Diseases, Weeds, Frost, Hail, Flood, Lodging? Specify problem	Frost (Sept-2014)	None	None	None	yes Hail (July 2014)

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Michigan (MI), Minnesota (MN), Ohio (OH), Nebraska (NE), North Dakota (ND), and Wisconsin (WI). Soybean producers provided data via returned surveys distributed by local crop consultants, Extension educators, soybean grower boards, and Natural Resources Districts (Figure 1). Briefly, producers were asked to report the range of average field yield across the fields planted to soybean in each year and water regime and to provide data for a number of fields that portray well that yield range. Requested data also included field location, average field yield, crop management (e.g., planting date, seeding rate, row spacing, cultivar, and tillage method), applied inputs (e.g., irrigation, fertilizer, lime, manure, and pesticides), and incidence of biotic and abiotic factors (e.g., insect pests, diseases, weeds, hail, waterlogging, and frost). Survey data were inputted into a digital database and screened to remove erroneous or missing data entries. We were interested in yield variation as related with management factors; hence, a few fields with extremely low yield due to incidence of unmanageable production site adversities (hail, waterlogging, wind, and frost) were excluded from the analyses. After quality control, the database contained data from a total of 3,216 fields planted to soybean in 2014 and 2015.

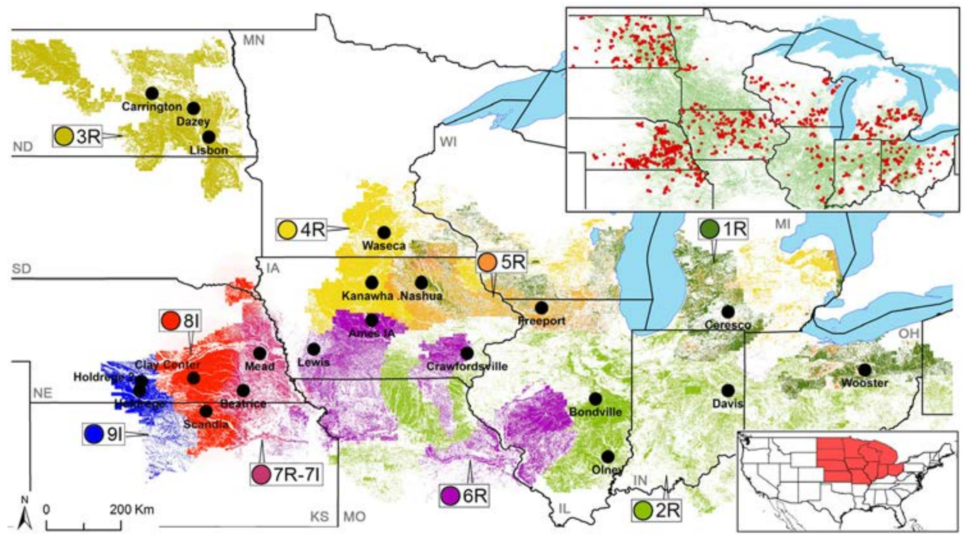
Producer data stratification based on soil-climate conditions

A major challenge with this kind of data is how to cluster producer fields in order to identify management factors that consistently lead to higher yields for a given climate-soil combination. In the present study, surveyed fields were grouped based upon their climate and soil using the spatial framework developed for the central and eastern US by the Global Yield Gap Atlas (http://www.yieldgap.org). This framework delineates regions [hereafter called technology extrapolation domains (TEDs)] based on four biophysical attributes

Figure 2. Map of the North Central US region showing nine technology extrapolation domains (TEDs) and meteorological stations (solid circles) selected for the present study. A coding system (from TED 1 to 9) is used to identify each TED (shown with a unique color) and its associated water regime (I: irrigated, R: rainfed). There were actually 10 TED-water regimes (denominated as just TEDs for simplicity) because rainfed and irrigated fields co-existed in TED 7 (7R and 7I, respectively).

Top inset. Soybean harvested area in year 2015 (green area; USDA-NASS, 2016b) and location of the 3,216 surveyed soybean fields (red dots).

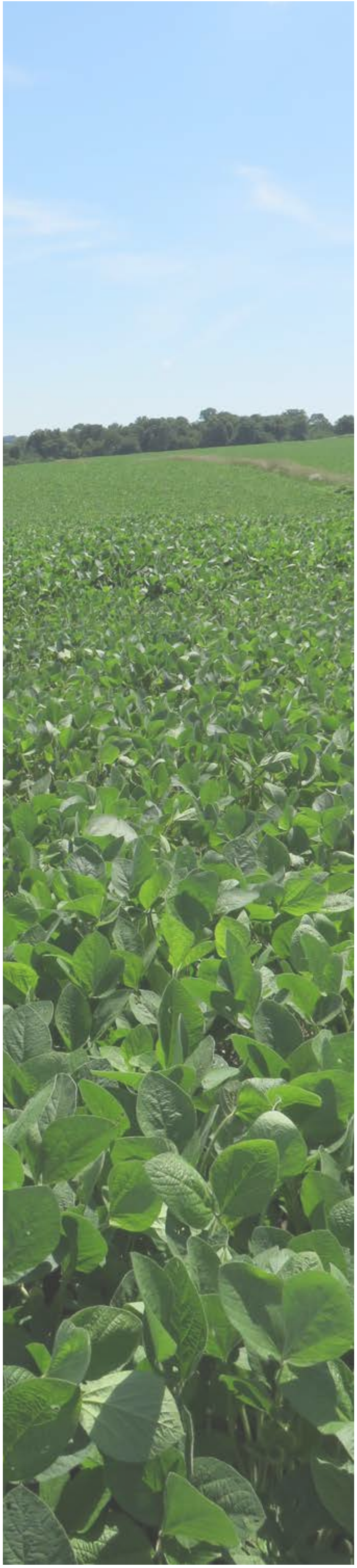
Bottom inset. Location of North Central US region — 12 states within the conterminous US.



that govern crop yield and its inter-annual variability: (1) annual total growing degree-days, which, in large part, determines the length of crop growing season, (2) aridity index, which largely defines the degree of water limitation in rainfed cropping systems, (3) annual temperature seasonality, which differentiates between temperate and tropical climates, and (4) plant-available water holding capacity in the rootable soil depth, which determines the ability of the soil to supply water to support crop growth during rain-free periods. We selected TEDs that portrayed the diversity of climate, soils, and water regimes in the North Central US region (Figure 2). Six TEDs included only rainfed soybean fields (1R, 2R, 3R, 4R, 5R, and 6R) while two TEDs included only irrigated soybean fields (8I and 9I). One TED included both irrigated and rainfed soybean fields (7I and 7R). Because the impact of management factors on yield is influenced by water supply, we separated water regimes (WR; rainfed and irrigated) within the same TED. Hence, a total of 10 TED-WR combinations were eventually used in this study, which are referred hereafter as TEDs for simplicity (total of 10 TEDs). Selected TEDs included 38% of the surveyed fields (total of 1343 fields) and accounted for 25 and 45% of US rainfed and irrigated soybean area, respectively. Each individual TED contained ≥98 (rainfed) and ≥59 (irrigated) surveyed fields, with an average of 137 fields per TED.

Yield potential, average producer yield, and yield gaps

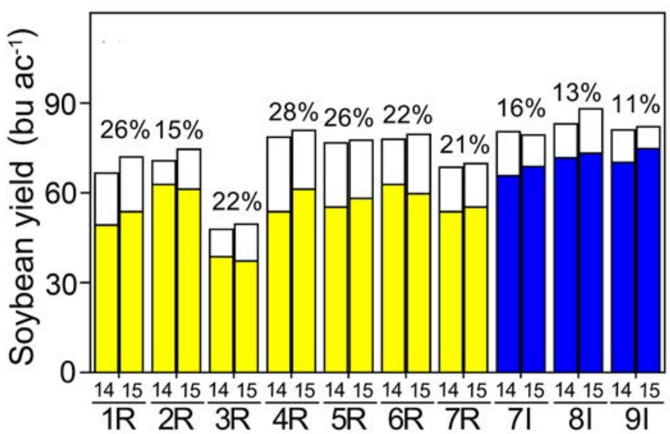
Annual yield potential (Yp, yield potential of irrigated field) and water-limited yield potential (Yw, yield potential of rainfed fields) were estimated using measured daily weather data (including solar radiation, rainfall, and maximum and minimum air temperature) collected at 2–3 meteorological stations located within each TED, preferably in proximity to the areas with the highest density of surveyed fields. Yw and Yp were used as benchmarks for calculating yield



gap for rainfed (TEDs 1R, 2R, 3R, 4R, 5R, 6R, and 7R) and for irrigated TEDs (7I, 8I, and 9I). The yield gap was calculated as the difference between Yp (or Yw) and average producer yield and expressed as percentage of Yp (irrigated) or Yw (rainfed).

Average Yw ranged from 48–80 bu ac^{-1}, while Yp varied from 80–91 bu ac^{-1} across TEDs (Figure 3). TED 3R exhibited the lowest Yw due to lower seasonal precipitation in relation with other TEDs. In contrast, Yp was highest in TED 8I due to non-limiting water supply and high incident solar radiation. Upscaled to the entire North Central US region, Yw and Yp averaged 71 and 85 bu ac^{-1}, respectively. Average producer yield was consistently lower than Yw (or Yp) across all TEDs ($p < 0.01$), and there was a large variation in average annual yield across TEDs, ranging from 39–73 bu ac^{-1}. Yield gap, expressed as percentage of Yp (irrigated) or Yw (rainfed), tended to be larger in rainfed (range: 15–28%) than in irrigated TEDs (range: 11–16%). At the regional level, the rainfed yield gap averaged 22% in contrast to the irrigated yield gap of 13%.

Figure 3. Yield potential for rainfed (Yw) and irrigated (Yp) soybean in each of the 10 TEDs in 2014 (14) and 2015 (15). Solid and empty portions of the bars represent the average producer yield and yield gap, respectively. Values on top of the bars indicate the (2-year) average yield gap, expressed as percentage of Yw (rainfed) or Yp (irrigated).



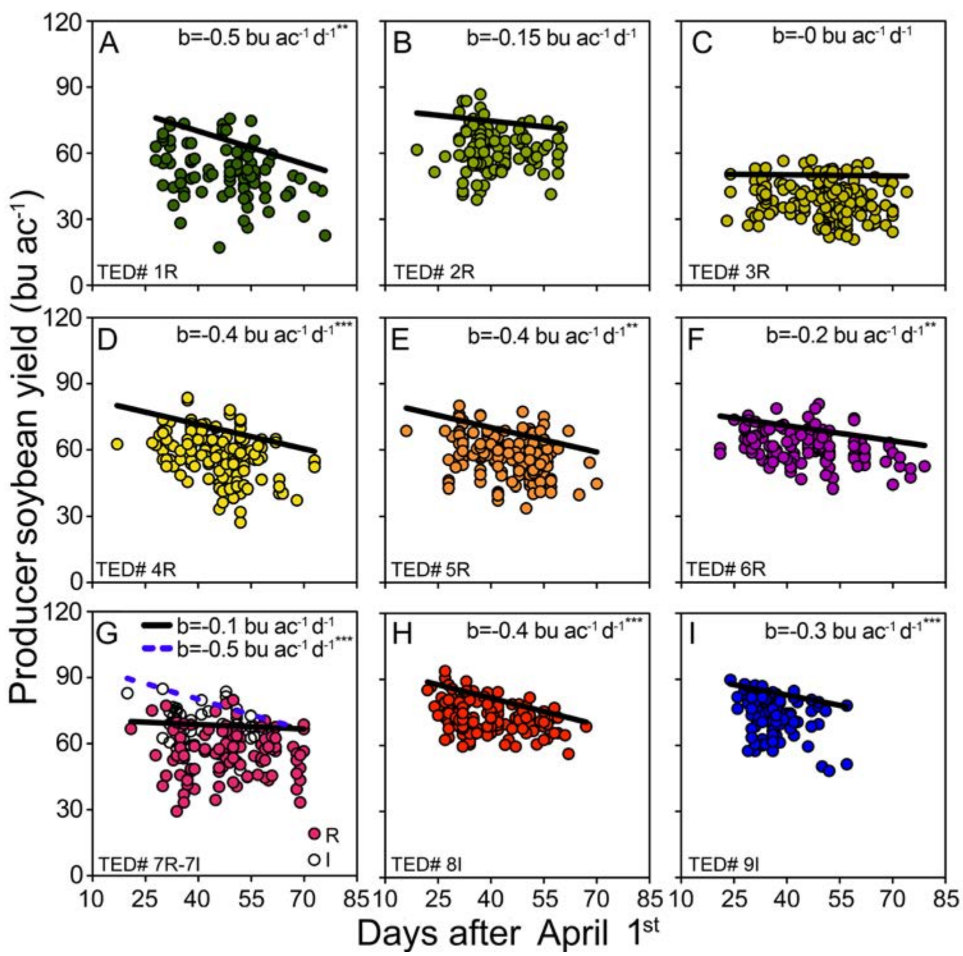
Management practices explaining yield gap between high- and low-yield fields

As a first approach to identify factors explaining yield gap, high-yield (HY) and low-yield (LY) field classes were identified based on their respective presence in the upper and lower terciles (top 1/3 versus bottom 1/3 of fields) of the field yield distribution within each TED. Analysis of management practices allowed identification of candidate factors explaining yield gap in each TED. Differences in planting date, tillage, in-season foliar fungicide and/or insecticide, drainage system, and soybean cultivar maturity group (MG) between high- and low-yield fields were statistically significant in half or more of the 10 TEDs ($p < 0.10$).

Planting date: The main explanatory factor

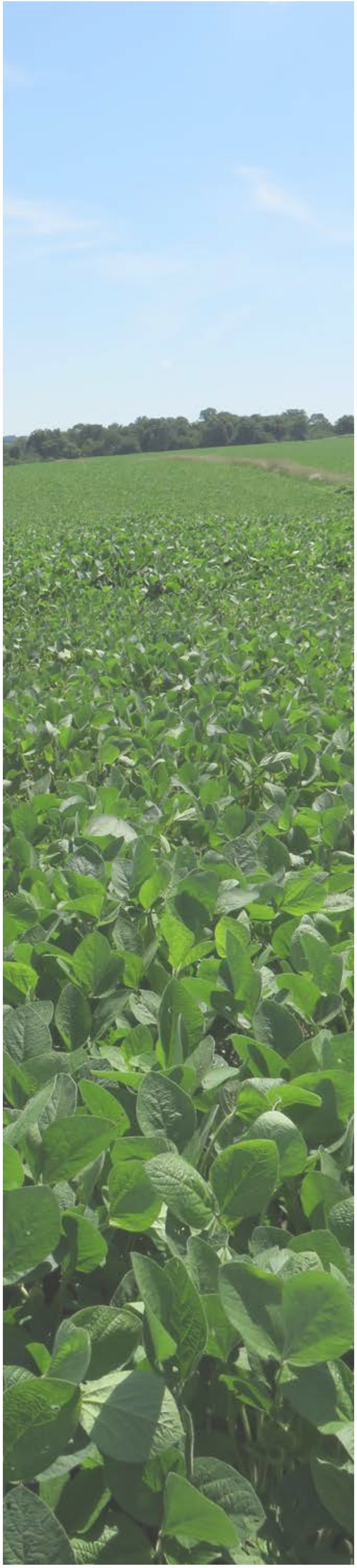
Planting date had the most consistent impact on soybean yield (Figure 4), representing 28% of the total yield gap across TEDs (range: 2–56%). HY fields were sown, on average, 7 days earlier than LY fields in both irrigated and

Figure 4. Producer soybean yield plotted against planting date in 10 technology extrapolation domains (TED) in the NC USA region, including rainfed (A–G) and irrigated (G–I) production areas. Solid line corresponds to the fitted boundary function using quantile regression (percentile 90th). Separate boundaries were derived for rainfed (empty symbols) and irrigated (solid symbols) soybean fields in TED7. Slope of the fitted boundary function (b) is shown, with asterisks indicating significance at $p < 0.1^{*}$, $p < 0.05^{**}$, and $p < 0.01^{***}$ for the null hypothesis of $b = 0$.



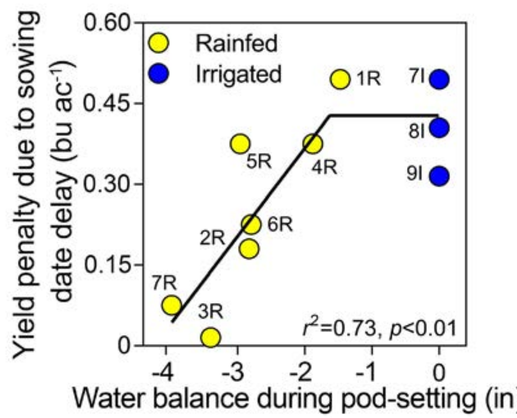
rainfed conditions. There was a strong planting date × TED interaction on yield as indicated by the wide range in yield penalty across TEDs, ranging from 0 to -0.5 bu ac^{-1} day^{-1} (Figure 4).

Assessment of the observed TED x M interactions, in relation to weather dynamics during the growing season, revealed a relationship between yield response to planting date and the degree of water deficit during pod setting (R3–R5) phase (Figure 5). Yield penalty (or response) to planting date was negligible when water balance was <-4 inches, but increased linearly up to nearly -1.6 inches. Yield response to planting date remained relatively unchanged at water balance >-1.6 inches, ranging from 0.3–0.5 bu ac^{-1} day^{-1}. The role of water balance in influencing the yield response to planting date was evident for TED 7, where irrigated and rainfed crops exhibited a six-fold difference (0.5 versus 0.1 bu ac^{-1} day^{-1}, respectively) (Figure 4). In other words, these findings indicated that yield response to planting date diminished as the degree of water limitation in the pod-setting period of the production environment increases. It was notable that yield response to planting date delay exhibited much higher explanatory power with the degree of water deficit during pod setting phase



($r^2 = 0.73$, $p < 0.01$) relative to the other crop phases (early vegetative phase, late vegetative phase, and seed filling) or entire crop season ($r^2 < 0.38$, $p > 0.06$).

Figure 5. Soybean yield penalty due to planting date delay as a function of water balance during the pod-setting (R3–R5) phase across 10 technology extrapolation domains (TEDs) including rainfed (yellow circles) and irrigated (blue circles) production environments (averaged over 2014–2015). Water balance was estimated as the difference between rainfall and simulated non-water limiting crop evapotranspiration and set at zero for irrigated crops. Parameters of the fitted linear-plateau model (solid line) and coefficient of determination (r^2) are shown.

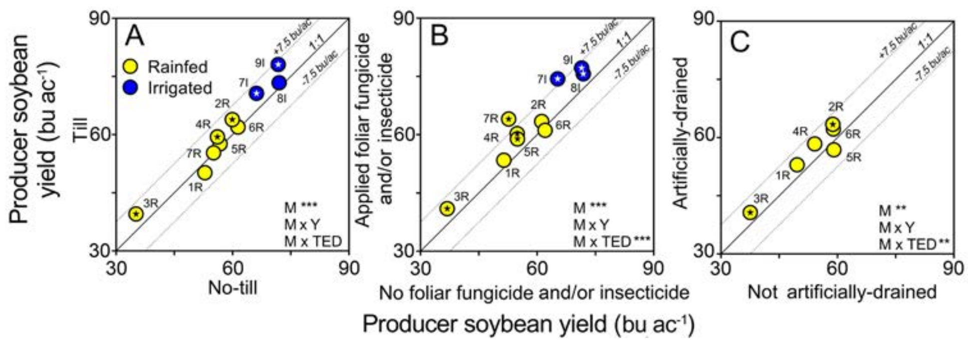


Tillage, fungicide and/or insecticide applications, drainage system, and soybean maturity groups

Similarly to planting date, other management practices also exhibited a significant M x TED interaction (Figure 6). For this analysis, fields were categorized as either no-till or tilled, with the latter including chisel, disk, strip-till, ridge-till, vertical, field cultivator, and moldboard plow. We did not find evidence of no-till fields outperforming yield of tilled fields in every TED; indeed, tilled fields yielded significantly more in half of the TEDs (2.3 bu ac^{-1}; $p = 0.02$) (Figure 6). However, there may still be other functional reasons for producers to adopt no-till despite the observed yield penalty. For example, no-till can help control soil erosion and reduce irrigation water requirements. Indeed we found that, on average, total irrigation was 2.5 inches less in no-till versus tilled fields ($p < 0.01$).

While there was an overall statistically positive impact of foliar fungicide and/or insecticide (4.6 bu ac^{-1}, $p < 0.01$) and artificial drainage (2.7 bu ac^{-1}; $p = 0.05$) on soybean seed yield, the magnitude of these yield differences were not consistent across TEDs and not even significant in some of them (Figure 6). For example, average yield of fields treated with foliar fungicide and/or insecticide was 11.2 bu ac^{-1} higher in relation with untreated fields in TED 7R, but this yield difference was negligible (-0.9 bu ac^{-1}) and not statistically significant in TED 6R. Likewise, artificially drained fields achieved statistically higher yields compared with fields without artificial drainage in only two of six TEDs. Although differences in variety MG between high- and low-yield fields were less than one unit, there was a consistent trend towards shorter MGs in the high-yield field tercile (top 1/3) in all TEDs, except for those located in the northern fringe of the North Central US region (3R and 4R).

Figure 6. Comparison of average producer soybean yield between groups of fields with different management practices across ten technology extrapolation domains (TEDs): (A) tillage (tilled versus no-till), (B) in-season foliar fungicide and/or insecticide (treated versus untreated fields), and (C) artificial drainage (fields with and without artificial drainage system). Star inside symbols indicate statistically significant difference for a given TED (t-test; $p < 0.1$). Asterisks indicate significance of the impact on yield with respect to the specified management factor (M), and its interaction with year ($M \times Y$) or with TED (M x TED) as evaluated using F-test at $p < 0.1$(*), $p < 0.05$(**), and $p < 0.01$(***). Data from the two crop seasons were pooled for the analysis because $M \times Y$ influence on yield was not statistically significant. TEDs 7R, 7I, 8I, and 9I are not included in (C) because of the low number of fields with artificial drainage.



Other management factors with low influence on yield gap

In contrast to the aforementioned variables, there were inconsistent (and generally small) differences between HY and LY fields in relation to row spacing, seeding rate, seed treatment, nutrient (N, P, K) fertilizer application, lime, and manure. Lack of statistically significant differences between management practices need to be interpreted with caution. For example, some practices might influence yield depending upon the level of another management practice [e.g., seed treatment in relation with planting date (Gaspar and Conley, 2015)]. Likewise, the benefit of other practices may only be realized in crop seasons with unfavorable weather, which was not the case in our study [e.g., narrow row spacing, no-till (Taylor, 1980; Wilhelm and Wortmann, 2004)]. Similarly, yield impact of some practices may be masked by other field variables not accounted here. For example, lack of yield differences between fields that received fertilizer application versus those that did not receive fertilizer might reflect producer tendency to apply fertilizer only in fields where soil nutrient status is inadequate as evaluated using soil nutrient tests. It may also reflect that many producers over-fertilized the previous corn crop expecting the subsequent soybean crop to benefit from the residual soil fertility. Finally, there are management practices that exhibited a very narrow range (e.g., MG) or inputs that are applied in amounts well above their optimums. For example, on-farm average soybean seeding rate ranged from 147,000 to 172,000 seeds ac^{-1} across TEDs. These densities are higher than the required plant density for maximum yields (100,000–145000 plants ac^{-1}) (Grassini et al., 2015); hence, our analysis will not fully capture the influence of these management factors on soybean yield.

Final consideration

Beside the identification of yield gap causes, another contribution of the present study is to provide a solid basis to assess what would be the extra crop production, at both local (TED) and regional (North Central US) levels, that would result from complete producer adoption or fine-tuning of a given management practice. For example, the potential extra production derived from earlier soybean planting can be calculated based on the (1) specific yield response to planting date in each TED, (2) the degree to which the current average planting date differs from the optimal one, and (3) soybean harvested area in each TED. For example, a 2-week shift towards early soybean planting in TED 4R, from current average planting on May 17 to a hypothetical, yet realistic, May 3 planting, would result in 5.2 bu ac^{-1} yield increase and 18.5 million bu production increase, leading to a 10% and 0.7% increase in soybean production in TED 4 and North Central US region, respectively. This example illustrates the power of this approach for impact assessment to support policy and investment prioritization and for monitoring the impact of research and Extension programs.

Conclusion

Soybean yield gap and its causes were assessed for the North Central US region using a novel approach that combines a spatial framework and producer self-reported data. The framework applied in this study explained the largest portion of the spatial variation in yield and management practices across the North Central US region. Soybean yield gap in the North Central US were relatively small, averaging 22% (rainfed) and 13% (irrigated) of the estimated yield potential. Planting date was the most consistent factor explaining yield variation within the same TED and year, with magnitude of yield response to planting delay dependent upon degree of water deficit during pod setting phase. Other practices also explained yield variation (tillage, and in-season foliar fungicide and/or insecticide, and artificial drainage), but the degree to which each of these practices influences yield depended upon TED. The combined use of producer data and a robust spatial framework that captured regional variation in weather and soils represents a cost-effective approach to identify causes of yield gap across large geographic regions, which, in turn, can help inform and strategize research and Extension programs at both local and regional levels.

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