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Contribution of persistent factors to yield gaps in high-yield irrigated maize

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ABSTRACT

Crop yield gap (Yg) can be disaggregated into two components: (i) one that is consistent across years and is, therefore, attributable to persistent factors that limit yields, and (ii) a second that varies from year to year due to inconsistent constraints on yields. Quantifying relative contributions of persistent and non-persistent factors to overall Yg, and identifying their underpinning causes, can help identify sound interventions to narrow current Yg and estimate magnitude of likely impact. The objective of this study was to apply this analytical framework to quantify the contribution of persistent factors to current Yg in high-yield irrigated maize systems in western US Corn Belt and identify some of the underpinning explanatory factors. We used a database containing producer yields collected during 10 years (2004–2013) from *ca.* 3000 irrigated fields in three regions of the state of Nebraska (USA). Yield potential was estimated for each region-year using a crop simulation model and actual weather and management data. Yg was calculated for each field-year as the difference between simulated yield potential and field yield. Two independent sources of field yield data were used: (i) producer-reported yields, and (ii) estimated yields using a combined satellite-crop model approach that does not rely on actual yield data. In each year (hereafter called 'ranking years'), fields were grouped into 'small' and 'large' Yg categories. For a given category, Yg persistence was calculated by comparing mean Yg estimated for ranking years against mean Yg calculated, for the same group of fields, for the rest of the years. Explanatory factors for persistent Yg were assessed. Yg persistence ranged between *ca.* 30% and 50% across regions, with higher persistence in regions with heterogeneous soils. Estimates of Yg size and persistence based on producer-reported yields and satellite-model approach were in reasonable agreement, though the latter approach consistently underestimated Yg size and persistence. Small Yg category exhibited a higher frequency of fields with favorable soils and soybean-maize rotation and greater N fertilizer and irrigation inputs relative to the large Yg category. Remarkably, despite higher applied inputs, efficiencies in the use of N fertilizer, irrigation, and solar radiation were much higher in fields exhibiting small Yg. The framework implemented in this study can be applied to any cropping system for which a reasonable number of field-year yield and management data are available.

1. Introduction

Yield potential (Yp) is defined as the yield of a crop cultivar with nutrient and water non-limiting and pests and diseases effectively controlled (Evans, 1993). In other words, Yp is the yield obtained when crop growth is only limited by solar radiation, temperature, and atmospheric carbon dioxide concentration. The difference between yield potential and actual yield achieved by farmers represents the yield gap (Yg) (van Ittersum et al., 2013). Using a crop simulation model, Grassini et al. (2011a) have estimated a mean Yp of 14.7 Mg ha^{-1} for irrigated maize in Nebraska (western US Corn Belt) based on dominant crop management practices (sowing date, hybrid maturity, and plant population density). This estimate of Yp was substantially lower than the maximum yield potential (MYp) of 17 Mg ha^{-1} estimated from the combination of management practices that resulted in highest Yp for each year. The MYp

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for irrigated maize estimated by Grassini et al. (2011a) compared well with measured yields in contest-winning fields in Nebraska (*ca.* 18.2 Mg ha^{-1}) reported by Duvick and Cassman (1999). For producers, however, MYp is not a realistic yield goal because MYp may be the consequence of a random management × weather interaction and may also require inputs or management practices that are too costly or too risky (Cassman et al., 2003). Still, MYp provides a useful estimate of maximum yield achievable for a given field with the best combination of management practices and inputs in a given year.

Field-to-field variation in Yg can be remarkably high, even within the same region-year. For example, in the study by Grassini et al. (2011a) involving 777 field-year observations in central Nebraska over a 3-year period, Yg of irrigated maize varied from 1.5 to 7 Mg ha^{-1}. Such variation in Yg could be due to different crop management practices, soils, and their interactions with weather (Lobell et al., 2009). Following Lobell et al. (2007), Yg can be disaggregated into two components: one that is consistent across years, hence, it can be attributed to persistent factors (*e.g.*, producer skills, consistently robust management decisions, soil quality), and another component caused by inconsistent yield-limiting factors such as adverse weather, pest outbreaks, and interactions among these factors. Persistent factors can be further classified as manageable and non-manageable factors. Assessing relative contribution of persistent *versus* non-persistent factors to overall Yg can help to determine the likelihood for narrowing Yg in a given cropping system and identify those persistent and manageable factors that can be fine-tuned to narrow Yg in a cost-effective and environmentally sound manner.

Despite the importance of identifying causes for Yg, no attempt has been made to develop a framework that allows to dissect the portion of Yg that is related to persistent *versus* non-persistent factors. Only a few studies have focused on evaluating persistence in actual yields (Lobell et al., 2007, 2010). Indeed, we argue that Yg is a more meaningful parameter, relative to actual yield, to estimate the room for increasing yields in a given region. A major bottleneck for estimating field Yg and persistence is a lack of field-specific high-quality data on yield collected from a large population of fields over a reasonable number of years. Thus, previous studies on persistence have relied mostly on yields estimated from remotely sensed images (Lobell et al., 2007, 2010). Constant advances in remote sensing technology have made satellite-based field-specific data available at high resolution, which allows cost-effective estimation of actual yields and Yg over multiple years and fields (Lobell, 2013). Although promising, accuracy of this approach for estimating Yg and persistence have never been validated using a database for which actual field yield data are available.

To our knowledge, no study to date has attempted to distinguish relative contributions of persistent and non-persistent factors to Yg based on actual yield and crop management data collected from a large population of producer fields over multiple years. The objective of this study was to (i) measure persistence in Yg of irrigated maize fields in Nebraska (western US Corn Belt) using a high-quality on-farm database, (ii) evaluate accuracy of a combined satellite-crop model approach at estimating Yg and their persistence, and (iii) identify explanatory factors responsible for Yg persistence.

2. Materials and methods

2.1. Description of producer self-reported data

Field-specific agronomic data, including yield (at a moisture content of 0.155 g g^{-1} grain), previous crop (maize, soybean), applied nitrogen (N) fertilizer, total irrigation amount, and type of irrigation system are annually collected from producer irrigated fields by the 23 Nebraska Natural Resources Districts (NRDs, http://www.nrdnet.org/). The database used in the present study contained information from producer fields in three regions: Lower Niobrara, Tri-Basin, and Central Platte (Fig. 1). Description of weather and soils for the three regions can be found elsewhere (Grassini et al., 2014). Briefly, the three regions have similar annual total precipitation and reference grass-based evapotranspiration (*ca.* 600 and 1000 mm, respectively) but vary greatly in soil properties, ranging from homogeneous, silt loam soils in Tri-Basin, highly heterogeneous texture of soils in Central Platte, and sandy loam soils in Lower Niobrara (Supplementary Table 1). Crops rely heavily on irrigation: total irrigation amounts averaged 419 mm (Lower Niobrara), 279 mm (Tri-Basin), and 382 mm (Central Platte) across ten years (2004–2013). Mean N fertilizer rate (*ca.* 200 kg N ha^{-1}) was relatively similar across regions (Supplementary Table 1).

Data were subjected to quality control measures and fields with missing or suspicious yield and applied input values were not included in the analysis. Only fields with maize-based crop sequences (continuous maize and soybean-maize rotation) and >8 years of complete information within the 2004–2013 period were used for the subsequent analysis. Also, a small fraction of fields that received manure applications or irrigated with drip irrigation systems (both atypical in Nebraska) were discarded. A total of 3047 fields were selected and digitized using ArcGIS 10.2 (ESRI, Redlands, WA) (Fig. 1). Hence, the database included a total of 27,294 field-year observations (including both irrigated maize and soybean). In the present analysis, we only focused on those fields that had maize sown to produce grain. Accuracy of producer-reported yield and applied input data have been evaluated in previous studies and found to be robust (Grassini et al., 2014; Sadras et al., 2014; Grassini et al., 2015).

Soil and terrain properties, related to soil ability to supply N and water to crops, were obtained for each field from SSUGRO database, including available water holding capacity (AWHC), soil pH, and soil organic matter content (SOM) in the upper 1 m soil depth (Soil Survey Staff, NRCS-USDA, 2015). These soil properties exhibited low co-linearity (Pearson's $r \le 0.50$). A weighted mean for each soil property was calculated based on relative area of each soil component within each field. SAGA wetness index of each field was calculated from raster DEM with a grid size of 100 m^2 (Boehner and Antonic, 2009; Nebraska DNR, 2015). Briefly, SAGA wetness index indicates whether a given field is net importer or exporter of water due to surface runoff: a high SAGA value corresponds to fields typically located in bottomland while a low SAGA value corresponds to fields located on crests and ridges. A summary of soil and terrain properties and applied inputs in each region is provided in Supplementary Table 1.

2.2. Estimation of yield potential and yield gap in irrigated maize fields

Irrigated maize Yp was simulated using Hybrid-Maize model, which has been widely evaluated for its ability to estimate yield in well-managed crops that grew without nutrient limitations and kept free of biotic stresses (Yang et al., 2004; Grassini et al., 2009). For each region-year, irrigated maize Yp values were simulated for different combinations of sowing date (April 15, April 25, May 5, May 10, and May 15), seeding rate (4.9, 6.2, 7.5, 8.6, and 9.9 m^{-2}) and hybrid maturity (95, 100, 105, 110, and 115 days for Lower Niobrara; and 108, 110, 112, 114, and 116 days for Central Platte and Tri-Basin). These ranges were retrieved from survey data collected by previous studies (Grassini et al., 2011a, 2015) and accurately portrayed actual management in each region. Hence, for each region-year, Yp was simulated for 125 combinations of sowing date × seeding rate × maturity. Daily weather data, including all variables needed for simulating Yp, were available from represen-