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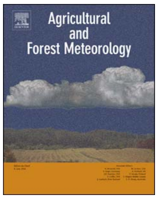

Assessing causes of yield gaps in agricultural areas with diversity in climate and soils

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ABSTRACT

Identification of causes of gaps between yield potential and producer yields has been restricted to small geographic areas. In the present study, we developed a novel approach for identifying causes of yield gaps over large agricultural areas with diversity in climate and soils. This approach was applied to quantify and explain yield gaps in rainfed and irrigated soybean in the North-Central USA (NC USA) region, which accounts for about one third of soybean global production. Survey data on yield and management were collected from 3568 producer fields over two crop seasons and grouped into 10 technology extrapolation domains (TEDs) according to their soil, climate, and water regime. Yield potential was estimated using a combination of crop modeling and boundary functions for water productivity and compared against highest producer yields derived from the yield distribution in each TED-year. Yield gaps were calculated as the difference between yield potential and average producer yield. Explanatory factors for yield gaps were investigated by identifying management practices that were concordantly associated with high- and low-yield fields. Management × TED interactions were then evaluated to elucidate the underlying causes of yield gaps. The chosen spatial TED framework accounted for about half of the regional variation in producer yield within the NC USA region. Across the 10 TEDs, soybean average yield potential ranged from 3.3 to 5.3 Mg ha^{-1} for rainfed fields and from 5.3 to 5.6 Mg ha^{-1} for irrigated fields. Highest producer yields in each TED were similar (± 12%) to the estimated yield potential. Yield gap, calculated as percentage of yield potential, was larger in rainfed (range: 15–28%) than in irrigated (range: 11–16%) soybean. Upscaled to the NC USA region, yield potential was 4.8 Mg ha^{-1} (rainfed) and 5.7 Mg ha^{-1} (irrigated), with a respective yield gap of 22 and 13% of yield potential. Sowing date, tillage, and in-season foliar fungicide and/or insecticide were identified as explanatory causes for yield variation in half or more of the 10 TEDs. However, the degree to which these three factors influenced producer yield varied across TEDs. Analysis of in-season weather helped interpret management × TED interactions. For example, yield increase due to advances in sowing date was greater in TEDs with less water limitation during the pod-setting

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Abbreviations: ETo, grass-reference evapotranspiration; ETc, crop evapotranspiration; HY, high-yield fields; I, irrigated; LY, low-yield fields; MG, cultivar maturity group; M × E, management × environment interaction; NC USA, North-Central United States of America; PAWHC, plant-available water holding capacity in the rootable soil depth; P95, yield potential derived from the 95th percentile of the field yield data distribution; R, rainfed; SD_{P5}, sowing date derived from the 5th percentiles of the sowing date data distribution (i.e., earliest sowing dates); TED, technology extrapolation domain; TED × M, TED × management interaction; Yg, yield gap; Yp, yield potential; Yw, water-limited yield potential

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phase. The present study highlights the strength of combining producer survey data with a spatial framework to measure yield gaps, identify management factors explaining these gaps, and understand the biophysical drivers influencing yield responses to crop management.

1. Introduction

Yield potential (Yp) is the yield of a crop cultivar when grown in an environment to which it is adapted, with non-limiting water and nutrient supplies, and with pests, weeds, and diseases effectively controlled (Evans, 1993; Evans and Fisher, 1999; van Ittersum and Rabbinge, 1997). In these optimal conditions, crop growth is determined by solar radiation, temperature, atmospheric CO_2 concentration, and management practices which influence crop cycle duration and light interception, such as sowing date, cultivar maturity, and plant density. In rainfed systems where water supply from stored soil water at sowing and in-season rainfall is not enough to meet crop water requirement, water-limited yield potential (Yw) is determined by water supply amount and its distribution during the growing season, and by soil properties influencing the crop water balance, such as rootable soil depth, available-water holding capacity, and terrain slope (van Ittersum et al., 2013). Crop simulation models, boundary functions defining maximum yield for a given level of resource availability, and measured yields in highest-yielding farmer's fields have been used to estimate Yp and Yw (Sadras et al., 2015; van Ittersum et al., 2013). The difference between Yp (or Yw in rainfed conditions) and producer average yield is termed the yield gap (Yg). Closing the Yg via a fine-tuning of current management practices provides an opportunity to increase crop production on existing cropland (Cassman et al., 2003; van Ittersum et al., 2013).

The most common approach for assessing the magnitude and causes of Yg in localized areas involves conducting controlled research trials in which researchers experimentally evaluate various input levels or management practices to identify whether a particular input or practice improve yield, and if the degree of yield improvement justifies input costs (Lollato and Edwards, 2015; Salvagiotti et al., 2008; Yang et al., 2004). However, assessing the causes of Yg over large geographic regions has been an elusive goal for three main reasons. First, it is difficult and costly to run field experiments to evaluate each potential factor that might limit producer yields. Second, it is problematic to extrapolate results from these localized experiments to far-flung producer fields, especially if there is lack of an appropriate description of the biophysical environment (*e.g.*, climate, soil) where these experiments are conducted. Finally, even with a large number of site-year experiments, management × environment (M × E) interactions are difficult to interpret without a rational understanding of what the word "environment" means beyond "site" and "year". Consequently, most studies addressing the causes of Yg through on-farm trials have been confined to small geographic areas where field-to-field variation in weather is small (*e.g.*, Kravchenko et al., 2017; Subedi and Ma, 2009; Villamil et al., 2012). Without an objective way to contextualize and extrapolate their findings, it remains uncertain how these local studies can help support more effective research prioritization and impact assessment of technology adoption on crop production and natural resources at local and regional scales.

The present study addresses the aforementioned limitations by proposing a novel, cost-effective approach that combines producer survey data with a robust spatial framework to identify causes of Yg across large geographic areas. We argue that having a database containing yield and management data from producer fields across multiple regions and years, properly contextualized relative to the biophysical environment, can be considered equivalent to running hundreds of field experiments to capture both major management effects and M x E interactions. Such analysis of large-scale producer data can provide a focus as to what treatments are the most promising to

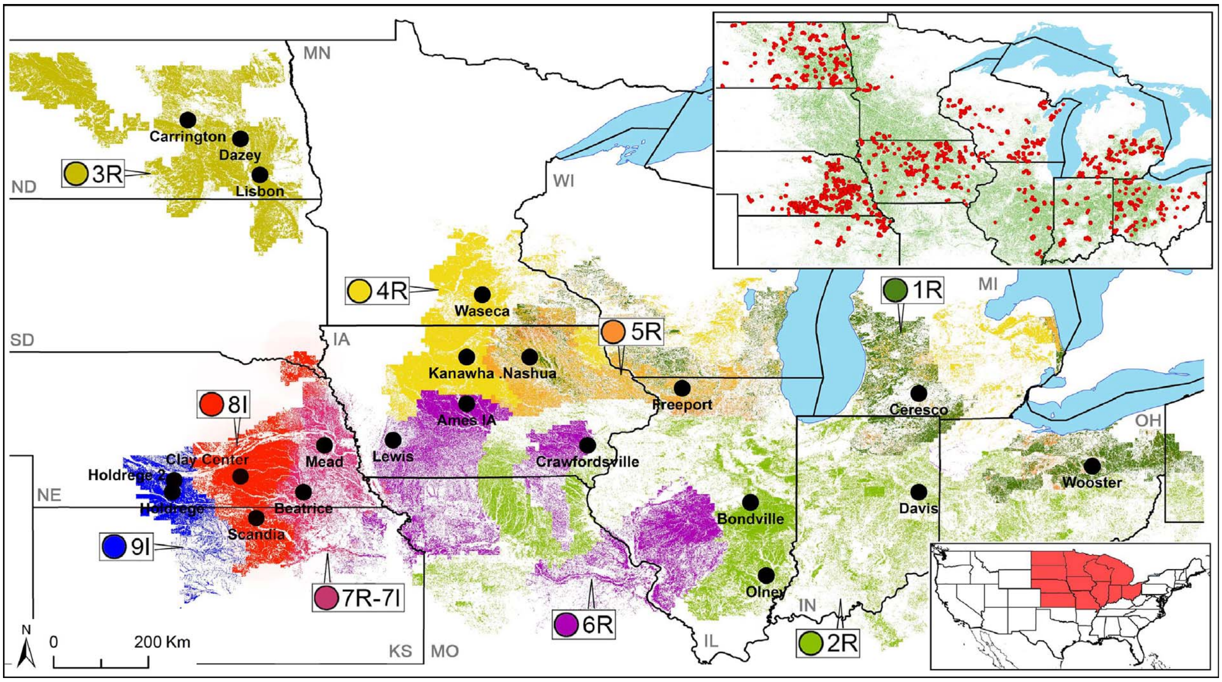

Fig. 1. Map of the North-Central USA (NC USA) region showing nine technology extrapolation domains (TEDs) and meteorological stations (solid circles) selected for the present study. A coding system (from TED 1 to 9) is used to identify each TED (shown with a unique color) and its associated water regime (I: irrigated, R: rainfed). There were actually 10 TED-water regimes (denominated '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 3216 surveyed soybean fields (red dots). Bottom inset: location of NC USA region of 12 states within the conterminous USA. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)