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Drivers of spatial and temporal variation in soybean yield and irrigation requirements in the western US Corn Belt

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ABSTRACT

Both rainfed and irrigated soybean production are important in Nebraska (western US Corn Belt), accounting for a respective 48 and 52% of the state's soybean production of 7 Mt on a respective 55 and 45% share of the state soybean area of 1.9 Mha. To date, no assessment of factors that may account for regional and inter-annual variation in yield and irrigation amount has been performed. To accomplish that objective, we evaluated a database containing on-farm field yields and total irrigation amount used in those fields. These data have been collected annually from *ca.* 1000 soybean fields in six regions of Nebraska during the past eight years. Distributions of farm yield and irrigation amount were analyzed and the impact of selected weather variables and key management factors on these two variables was assessed. For irrigated soybean, attainable yields were estimated from the 95th percentile of the yield distribution, and yield gaps were then calculated as the difference between the attainable yield and average farm yield. The interquartile range for yield and irrigation amount was used as a measure of the management gap between skillfully and sub-optimally managed fields. Distribution of irrigated yield and irrigation amount were skewed, indicating that many producers achieved yields relatively close to the attainable yield, but also that irrigation in excess of the amount needed may have occurred in an important fraction of the total fields. Variation in rainfed yield was strongly related to July–August total rainfall and seasonal water deficit, but, in contrast, no single meteorological factor could consistently explain variation in irrigated yield. In fact, sowing date explained most of the observed inter-annual variation in irrigated yield in all regions. Amount of irrigation applied in each year depended on both rainfall and reference evapotranspiration. Efficiency in use of irrigation water *versus* rainfall to produce seed yield was remarkably similar. Across regions, attainable yield of irrigated soybean in NE averaged 4.7 Mg ha^{-1}, with the yield gap averaging about 16% of the attainable yield. Variation in yield and irrigation amount among fields was more important than variation among years and even regions. Further research is needed to identify the causes for this observed field-to-field variation in yield and irrigation amount within the same year and region.

1. Introduction

The USA produces 84 Mt of soybean [(*Glycine Max* (L.) Merr.] annually, which accounts for about 35% of global soybean production (USDA-NASS; FAOSTAT, 2007-2011). About 85% of the U.S. total is produced in the Corn Belt, where the dominant cropping sequence is the 2-year maize-soybean rotation. Nebraska (NE) ranks fifth among U.S. soybean-producing states with about 6.6 Mt total annual production on a 1.9 Mha harvested with soybean. A unique feature of NE soybean production, compared with other states in the US Corn Belt, is that although only 45% of the state's hectarage is irrigated, it accounts for 52% of state's soybean production. An assured water supply not only enhances yield, but also reduces year-to- year variation, compared with rainfed yields that depend on both total rainfall amount and its distribution during the growing season (Grassini et al., 2014). In NE, 5-year irrigated and rainfed soybean yields average a respective 3.9 and 3.1 Mg ha^{-1} (USDA-NASS). There is, however, considerable spatial and temporal variation in both rainfed and irrigated soybean yields, which could be attributed to weather, soil, and management factors and their interactions. However, there has been no attempt to study the underpinning causes for observed differences

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in rainfed and irrigated soybean yields among regions and years in NE.

NE has the largest share (15%) of irrigated crop area in the United States, a total of 3.5 Mha, of which about 90% is cultivated with maize (65%) and soybean (25%) (USDA-NASS, 2008). Pivot and surface irrigation is used on a respective 80 and 20% of the NE irrigated land. Ground water is the primary water source, with a total of 92,500 active irrigation wells in operation (USDA-NASS, 2011). Because NE irrigated agriculture is not subject to drought-induced fluctuation in crop yields, it has attracted investment in livestock feeding operations, biofuel refineries, and of course, multiple irrigation equipment manufacturers. There is, however, a growing concern about the long-term sustainability of irrigated agriculture in NE due to concerns about groundwater depletion and water quality (Scanlon et al., 2012). Despite these concerns, there is limited published research assessing on-farm irrigation water use, efficiency of irrigation water to produce grain, and underpinning factors that explain differences among years, regions, and farms. Using producer-reported data, Grassini et al. (2011b) showed that irrigated maize in NE achieves a relatively high water productivity, although *ca.* 50% of the fields were likely to be over-irrigated and about 30% of total irrigation water use could be saved by replacing surface irrigation system by central pivots and better irrigation scheduling. This particular study was limited, however, to maize crops grown in a relatively small region in south-central NE and the underlying causes for the observed differences in irrigation amount among regions and years were not investigated.

Yield potential is defined as the yield of a crop cultivar when grown with water and nutrients non-limiting and biotic stress effectively controlled (Evans, 1993; Van Ittersum and Rabbinge, 1997). When grown under optimal conditions, crop growth rate is determined only by solar radiation, temperature, atmospheric CO_2 and genetic traits that govern length of growing period, light interception by the crop canopy, and its conversion to biomass. Average on-farm soybean yield in NE is well below maximum yields >6 Mg ha^{-1} measured in experimental plots or contest-winning fields across the US Corn Belt, which might suggest a large gap between actual and potential yields (Specht et al., 1999). However, no explicit quantification of yield gap has been performed for soybean in the US Corn Belt or other regions of the world. In the case of crop systems where producer yields are already high, and in the case of irrigated crop systems with little or no seasonal water stress, there is relatively close agreement between yield potential estimates based on maximum yields achieved by producers that occupy the upper percentiles of the yield distribution for a specific region-year *versus* estimates based on well-validated crop simulation models with a strong biophysical foundation or measured yields under near-optimal management conditions (Lobell et al., 2009; Van Ittersum et al., 2013). Therefore, for high-yield crop systems, such as irrigated soybean in NE, a meaningful estimate of attainable yields can be determined for each region-year based on the yields attained by the best producers, which can be used, in turn, to estimate the size of the gap between attainable and average producer yields.

Availability of high-quality data on farm yields, inputs, and management practices is required for identifying major sources of spatial and temporal variation in yield, quantification of yield gaps, and alleviation of yield-reducing factors and inefficiencies in the use of agricultural inputs such as irrigation water and nitrogen fertilizer (Van Ittersum et al., 2013). However, on-farm data are usually not available at a temporal and spatial degree of resolution required for a robust assessment of crop-system productivity and input use, even in developed countries with relatively high data availability such as USA. For example, publicly accessible, on-farm yield data in NE are limited to an annual county yield average for irrigated and rainfed crops (USDA-NASS, http://quickstats.nass.usda.gov/). Likewise, despite the continuous public and scientific debate about the use of the US Great Plains aquifer as a source of freshwater for irrigated agriculture, data on irrigation amount are limited to a statewide average value reported every 5 years by the Farm and Ranch Irrigation Survey (USDA-NASS, FRIS, http://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Farm_and_Ranch_Irrigation/index.asp). A single yield and irrigation average value, per region, provides little information about how these two parameters vary amongst the population of farms within a region. That information is needed, however, to reliably discern the factors accounting for spatial and temporal variation in these two parameters as a means to identify ways to improve water use efficiency without decreasing yields or profit.

A number of studies have assessed the sources of on-farm yield variation in sunflower (Mercau et al., 2001; Grassini et al., 2009), wheat (French and Schultz, 1984; Lobell et al., 2002; Calviño and Sadras, 2002; Sadras et al., 2002), rice (Laborte et al., 2012), cassava (Fermont et al., 2009), banana (Wairegi et al., 2010), and maize systems (Calviño et al., 2003a; Tittonell et al., 2008; Grassini et al., 2011a,b). Villamil et al. (2012) investigated sources of field-to-field variation in rainfed soybean yields in Illinois (central US Corn Belt) using on-farm data but just from one growing season. Only the set of studies by Calviño and Sadras (1999) and Calviño et al. (2003b,c) have assessed sources of inter-annual and spatial variation in soybean rainfed yields using on-farm data collected from a large number of years and farms in the Pampas of Argentina (34 to 37° S). This study documented strong associations between soybean yields and sowing date, water availability during the period of pod and grain setting, soil depth, and phosphorous fertilization. No previous study has attempted, however, to investigate sources of variation in yield or irrigation amount and efficiency within a region where both rainfed and irrigated soybean crop fields are often located adjacent to each other, and where sharp gradients of weather and soils co-exist within a relatively small geographic region, as it is the case in NE.

To address the dearth of knowledge about the drivers of observed spatial and temporal variation in soybean yield and irrigation amount in NE, in this paper we analyzed a large database containing on-farm field data collected annually from approximately 1,000 soybean commercial fields in six regions in NE during eight years (2004–2011). The number of years and regions was judged to be a suitable sample of a wide range of weather conditions. At the same time, the time interval (2004–2011) is short enough to justify an assumption of constant technology and, hence, assume that inter-annual variation in average yield is mostly due to weather variability and its associated impact on some key management decisions such as sowing date. Specific objectives of this paper are to (i) provide a quantitative analysis of on-farm soybean yield and total irrigation amount in NE, (ii) identify underpinning weather and management factors that explain spatial and temporal variation in these two parameters, and (iii) estimate irrigation-water use efficiency and yield gaps of irrigated soybean.

2. Materials and methods

2.1. Nebraska Natural Resources Districts data reporting system

State law divides NE into 23 Natural Resources Districts (NRDs, http://www.nrdnet.org/), each serving as a local government entity with authority to establish regulations and incentives to protect and conserve natural resources within the district. Each NRD sets its own priorities and develops its own programs to best serve local needs. Crop producers with fields located in pre-designated reporting areas are required to provide field-specific agronomic