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Assessing explanatory factors for variation in on-farm irrigation in US maize-soybean systems

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Research Paper

Assessing explanatory factors for variation in on-farm irrigation in US maize-soybean systems

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ABSTRACT

Irrigation exhibits large variation across producer fields, even within same region and year. A knowledge gap exists relative to factors that explain this variation, in part due to lack of availability of high-quality irrigation data from multiple field-years. This study assessed sources of variation in irrigation using a large database collected during 9 years (2005–2013) from *ca.* 1400 maize and soybean producer fields in Nebraska, central USA (total of 12,750 field-year observations). The study area is representative of *ca.* 4.5 million ha of irrigated land sown with maize and soybean. Influence of biophysical (weather, soil, and crop type) and behavioral (producer skills, risk aversion) factors on irrigation was investigated. Field irrigation distributions showed a substantial number of fields received irrigation amounts that were well above average irrigation for same region-year. Variation in irrigation across fields, within the same region, was as large as year-to-year variation. Seasonal water deficit (defined as total reference evapotranspiration minus precipitation), soil available water holding capacity, and crop type explained about half of observed variation in field irrigation, indicating that producers adjusted irrigation depending upon site-year variation in these parameters. However, half of the variation in irrigation remained unexplained, indicating that producer behavior and skills play also an important role. There was evidence of a "neighbor" effect as fields that received large irrigation were surrounded by other fields with similarly large irrigation. Likewise, fields with above- or below-average irrigation in one year remained consistently above and below regional average irrigation, respectively, in other years despite similarity in weather and soil among fields. These findings indicate that irrigation decisions are influenced by both biophysical and behavioral factors, making predictions of field and regional irrigation extremely difficult. This study highlights the value of collecting on-farm irrigation data to understand producer decision-making and find opportunities to improve current water management in irrigated crop systems.

1. Introduction

Irrigated crop systems account for only 20% of arable land, producing *ca.* 40% of global food production (Schultz et al., 2005; Molden, 2007). Irrigation increases and stabilizes crop yields in areas where precipitation is not sufficient to satisfy crop water requirements (Grassini et al., 2014a). However, there is evidence of water withdrawals exceeding recharge and deterioration of water quality in many important irrigated areas of the world (Scanlon et al., 2012; Siebert et al., 2010). Exploring trade-offs in the nexus between food production and water resources is important for identifying pathways for sustainable intensification of irrigated crop systems in order to ensure current and future food production while protecting freshwater resources.

Availability of field-level irrigation data is essential to studies dealing with groundwater dynamics, land surface modelling, and environmental footprint. However, very few studies had access to actual field irrigation data (*e.g.*, Lorite et al., 2004; Grassini et al., 2011, 2014b; O'Keeffe et al., 2016). To our knowledge, there is no open-access source of field irrigation data that includes multiple years and regions, with companion biophysical data (soil, weather, and terrain parameters) that allow proper contextualization and quantitative analysis. To overcome this limitation, previous studies relied on irrigation data aggregated at large spatial scales (country

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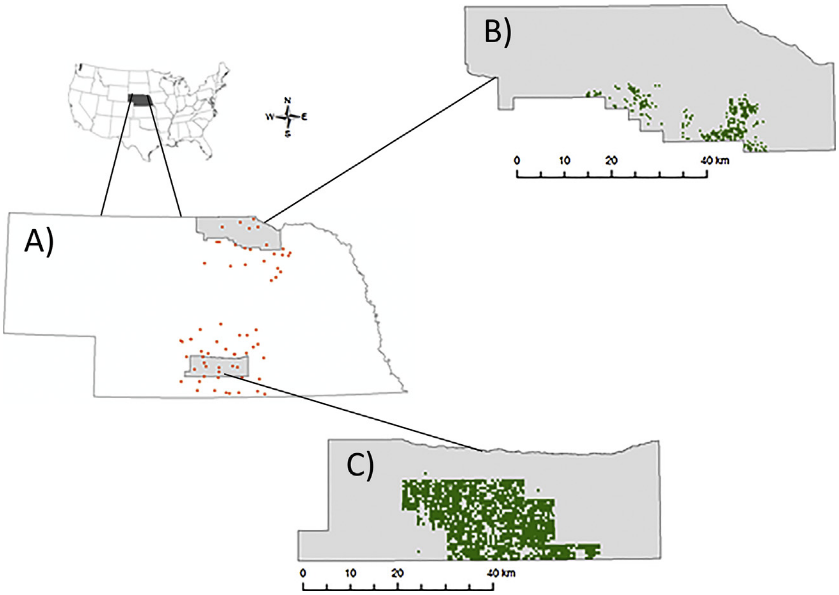

Fig. 1. A) Map showing the two study areas in Nebraska (shaded regions) as well as weather stations (red dots) used for weather interpolation in this study. Green squares indicate field location in north-central (B) and south-central (C) regions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

or state), as those reported through AQUASTAT (http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en) and USDA-FRIS (https://www.agcensus.usda.gov/Publications/2012/Online_Resources/Farm_and_Ranch_Irrigation_Survey/fris13.pdf) databases (*e.g.*, Mullen et al., 2009; Siebert et al., 2010). Other studies attempted to estimate regional irrigation from secondary variables, such as groundwater dynamics, regional water balance, and weather (*e.g.*, Sharma and Irmak, 2012; Döll and Siebert, 2002; Droogers et al., 2010). While useful to detect regional or temporal trends, these sources of irrigation data cannot be used to benchmark water management in producer fields.

Understanding sources of variation in irrigation at field-level is important to identify opportunities for improving current water management. However, as indicated by Lorite et al. (2004), studies assessing the degree of variability in field-level irrigation are lacking. To our knowledge, no previous study explicitly assessed sources of field-to-field variation in irrigation across producer fields in the central US region. In an earlier study in Nebraska, Grassini et al. (2014b) found that field-to-field variation in irrigation was as important as (if not greater) variation across years and regions. And another study (Grassini et al., 2011) found that field-to-field variation in irrigation (coefficient of variation [CV] = 41%) was much larger than variation in yield (CV = 8%) and applied nitrogen fertilizer (CV = 17%). However, as we noted earlier, none of these previous studies looked into the causes for the observed variation in irrigation across producer fields. While field-to-field variation in irrigation may reflect differences in weather across field-years, as well as differences in soil type and topography, it may also reflect differences in producer skills and risk aversion as influenced by socio-economic variables (Andriyas, 2013). No previous study has attempted to dissect the relative contribution of biophysical *versus* behavioral factors to the observed field-to-field variation in irrigation amounts.

Understanding if producer decisions relative to input application (*e.g.*, irrigation, fertilizer) are consistent across years, and to which degree these decisions are influenced by manageable or non-manageable factors (*e.g.*, skill *versus* soil type), can help determine to what extent improvements in input-use efficiency are possible (Lobell et al., 2010; Farmaha et al., 2016). For example, if a producer consistently irrigates more than others in the same region, it implies that there is a persistent factor responsible for such behavior: a non-manageable factor such as soil type or a manageable factor such as irrigation system type or skill. In contrast, if a producer applies more irrigation in one year but a similar or smaller amount in another year, relative to the rest of the population of producers within the same region, it becomes more difficult to understand the factors driving irrigation decisions. To our knowledge, no previous studies have investigated the degree to which producer irrigation decisions are consistent across years.

In the present study, we used a unique database on total annual irrigation collected from *ca.* 1400 maize and soybean fields in Nebraska for 9 years (2005–2013). Our objective was to identify sources of variation in on-farm irrigation, including weather, soil properties, crop type, and producer behavior. Understanding the extent and underlying causes for field-to-field variation in irrigation is essential to benchmark current on-farm water management, identify opportunities for improvement, and better strategize research and extension programs to ensure sustainability of irrigated crop systems.

2. Material and methods

2.1. Study area and producer database

Annual irrigation data (*i.e.*, total amount of irrigation applied during the crop growing season) were available for maize and soybean fields over 9 years (2005–2013) in two regions of Nebraska: north-central (NC) and south-central (SC) (Fig. 1). Fields within these two regions are representative of the high-yield, high-input irrigated maize-soybean systems of the U.S central region, which accounts for *ca.* 4.5 million ha (USDA-NASS, 2014). Detailed description of these irrigated systems can be found elsewhere (Grassini et al., 2011; Farmaha et al., 2016).

Irrigation data were collected by the Tri-Basin (SC fields) and Lower Niobrara (NC fields) Natural Resources Districts (NRDs; https://www.nrdnet.org). The NRD data included field-specific information on sown crop, crop yield, crop rotation, irrigation system type, and total annual nitrogen fertilizer and irrigated water inputs. Previous studies have shown that the NRD producer-reported data aligned well with data reported by other independent sources (Grassini et al., 2014b). Irrigation applied to each field was measured using a flow-meter installed in each irrigation well. Quality control was performed to remove fields containing suspicious (*e.g.*, irrigation values exceeding system capacity over the growing season) or missing data. Fields with missing information in 2 or more years (within the 9-y time period) were also excluded. This study only considered center-pivot irrigated fields, which accounted for *ca.* 75% of SC fields and all NC fields. Likewise, we focused on maize and soybean fields because these two crops accounted for 89% of total irrigated area in Nebraska (USDA-NASS, 2014). The final database used for the study contained a total of 12,750 field-year observations. Within the 9 years of study (2005–2013), there was a wide range of weather conditions, ranging from years with above-average precipitation (*e.g.* 2010) to years with severe drought (*e.g.* 2012).

2.2. Influence of biophysical factors on irrigation

Weather and soil data were retrieved for each individual field-year. Weather data were retrieved from 16 Automated Weather Data Network (AWDN; http://www.hprcc.unl.edu/awdn.php) and 49 National Weather Service (NWS) Cooperative Station Network weather stations located within or near the study areas. Daily precipitation and grass-based reference evapotranspiration (ET_o, Allen et al., 1998) were interpolated from the three weather stations located in closest proximity to each field (on average *ca.* 24 km) using inverse distance weighting (Yang and Torrion, 2014; Franke and Nielson, 1980). For the purpose of interpolating ET_o data, only AWDN stations were used due to lack of all weather variables needed to estimate ET_o in the NWS network stations. However, both AWDN and NWS stations were used for interpolating precipitation in order to increase the spatial coverage of weather stations relative to field locations. This is crucial because of the high spatial variation in precipitation in the western U.S. Corn Belt as reported by Hubbard (1994). For each field-year, seasonal precipitation and ET_o were calculated as the cumulative value for each of these variables from June 1st to August 31st. These dates roughly coincide with the beginning and end of the irrigation season in the western U.S. Corn Belt (Grassini et al., 2014b). Water deficit (WD) was calculated as ET_o minus precipitation (on a seasonal basis) for each field-year case.

For each field, average AWHC for the 0–1 m soil depth was obtained from the Soil Survey Geographic database (SSURGO; http://websoilsurvey.nrcs.usda.gov). AWHC is a measure of how much water the soil can store and make available to plants during rain-free periods. AWHC is defined as the amount of water between soil field capacity and wilting point, in the upper 1 m of soil profile. This depth represents the portion of the crop rooting zone that is typically scouted by crop producers during the crop growing season to make decisions relative to irrigation scheduling. Given the same soil depth, AWHC depends on soil particle size (*i.e.*, soil texture) and soil organic matter. Mean AWHC was calculated for each field by weighting each sub-field soil property unit relative to their proportion within each field. Digital Elevation Model (DEM) data (10-m resolution; http://www.dnr.nebraska.gov/digital-elevation-models) and SAGA GIS software were used to retrieve an average topographic wetness index (TWI) for each field (Conrad et al., 2015; Olaya and Conrad, 2009). TWI indicates likelihood of surface runoff from/to an area based on slope and surrounding area; depression areas have high TWI values while upland areas have low TWI values (Sørensen et al., 2006). To summarize, key weather, soil properties and topography were retrieved for each field-year to understand how these factors may explain field-to-field variation in irrigation.

Analysis of variance was performed using GLM procedure (SAS® software v 9.4, ©2002-2012 SAS Institute Inc., Cary, NC, USA) to determine sources of variation with some selected candidate biophysical factors that were hypothesized as contributors to the observed spatial and temporal variation in irrigation. These factors included weather (precipitation, ET_O, and WD), crop (sown crop and prior crop), and field parameters (AWHC and TWI). Interactions between selected variables were also tested. For example, the WD effect on irrigation could be amplified in fields with low AWHC. To assess the relative contribution of weather, crop, and field parameters at explaining the observed variation in irrigation, the analysis was conducted separately considering (i) only weather, (ii) weather and crop parameters, (iii) weather, crop and field parameters, and (iv) all parameters and their interactions. Using WD, instead of precipitation and ET_o, resulted in slightly higher explanatory power; hence, WD was used in all the analyses. Only interaction terms that were significant at $P \leq 0.05$ were kept in the model. The above analyses were conducted using all field-year observations available for center-pivot irrigated fields. Linear regression analysis was used to assess variation in irrigation in relation to specific variables such as seasonal WD and AWHC.

2.3. Influence of producer behavior on irrigation amounts

Influence of neighboring producers' irrigation decisions on an individual producer's field was analyzed by investigating how irrigation varied in relation with distance from individual fields. To minimize the influence of other sources of field-to-field variation (*e.g.*, weather and soil), only SC fields with almost identical weather, AWHC, and TWI were analyzed to determine the presence of this so-called "neighbor effect". Irrigation data from SC fields were found to be lognormally distributed, and were subsequently logarithmically transformed to obtain z-score values. A z-score was calculated for each field by subtracting mean irrigation from field irrigation and dividing by standard deviation. For each field, the z-score was calculated for all surrounding fields at increasing distance in 1.6 km increments. After the z-score and standard deviation of the z-score were determined, fields were grouped by their local z-score. The mean and standard deviations for each group were then back-calculated to obtain average values. This calculation was performed separately for each year and then averaged across all years included in the study period.

Persistence in irrigation decisions across years was investigated following Farmaha et al. (2016). Because we were interested in analyzing persistence in relation with producer behavior, and not with soil type or irrigation system type, the analysis was constrained to the center-pivot irrigated fields in SC because soil properties were nearly identical among all fields. Two years (2010 and 2012) were chosen in the present study as ranking years to analyze persistence in irrigation amount across all other years during the study period. These two years represent extreme weather conditions, with 2010 and 2012 having above- and below-average seasonal precipitation (415 and 105 mm, respectively). For both 2010 and 2012, fields located in the top and bottom quartiles of the field irrigation distribution were selected, resulting in four categories: 2010 high irrigation, 2012 high irrigation, 2010 low irrigation, and 2012 low irrigation. Relative irrigation (RI) was calculated as follows:

$$RI_{ij} = (I_{ij} - I_j)/I_j \quad (1)$$

where I_{ij} was average irrigation for field category i in year j, and I_j was average regional irrigation in year j. This resulted in RI values for each year. A RI value of zero indicated that average irrigation for a given category was equal to regional average irrigation in that year. In contrast, a RI value of 0.5 meant that average irrigation in that field category was 50% higher than the regional average irrigation for that same year. RI values consistently above or below zero in non-ranking year indicated persistent behavior, meaning that producers applying above or below average irrigation in one year will tend to do the same in the rest of the years. In contrast, if RI

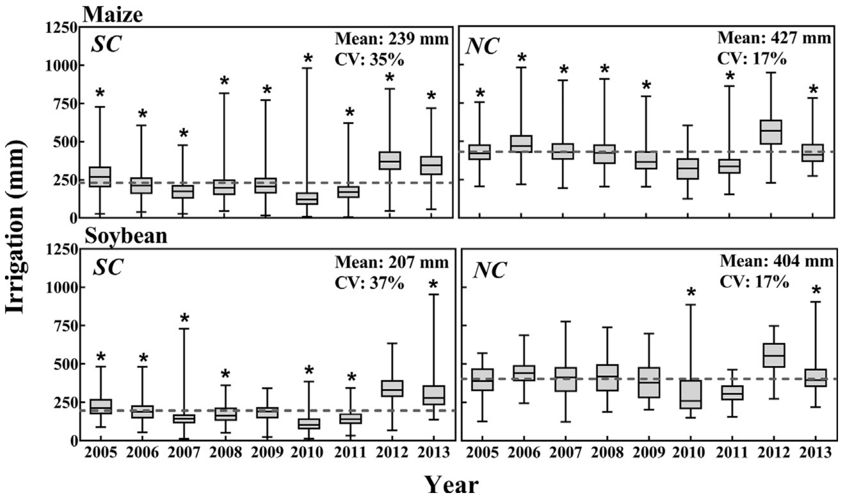

Fig. 2. Distributions of producer field seasonal irrigation from 2005 to 2013 for pivot-irrigated maize (top) and soybean fields (bottom) in south-central (SC) (left) and north-central (NC) (right) regions. Long-term (2005–2013) mean irrigation and year-to-year coefficient of variation are displayed for each region-crop case. Upper and lower boundaries of boxes indicate 75th and 25th percentile, respectively. Vertical bars are maximum and minimum values. Horizontal line within boxes is the median value. Asterisks indicate that irrigation distribution deviates from the normal distribution (D'Agostino-Pearson test, $p < 0.01$).

Table 1

Means of topographic wetness index (TWI) and available water holding capacity (AWHC, 0–1 m of soil) in north-central and south-central fields. Long-term (2005–2013) means of seasonal (June 1st–August 31st) precipitation and grass-based reference evapotranspiration (ET_o) are also shown. Coefficients of variation (CV) are shown in parentheses. CVs correspond to field-to-field variation (TWI and AWHC) and year-to-year variation (precipitation and ET_o).

	TWI[a]	AWHC (mm)[a]	Precipitation (mm)[b]	ET_o (mm)[b]
North-central	7.7 (11%)	104 (34%)	250 (32%)	475 (12%)
South-central	7.4 (7%)	199 (11%)	252 (36%)	475 (10%)

[a] TWI and AWHC were calculated as averages across fields ($n \approx 1400$).

[b] Precipitation and ET_o are 9-year (2005–2013) averages.

Table 2

Analysis of variance for irrigation relative to weather, crop, and field parameters and their interactions. Only center-pivot irrigated fields were considered and data from the two regions (south-central and north-central) were pooled. Separate models were fitted considering only weather (A), weather and crop (B), weather, crop, soil, and topography (C), and all variables and their interactions (D). *F* values and their significance are shown for each model. Overall coefficient of determination (R^2) is also shown.

	A	B	C	D
Weather				
Water deficit (WD)	1028***	1037***	2034***	78***
Crop				
Crop	–	64***	88***	7**
Prior crop	–	4*	5*	5*
Soil & topography				
AWHC	–	–	3079**	893**
TWI	–	–	1	1
Interactions [a]				
WD x crop	–	–	–	4*
WD x AWHC	–	–	–	20***
Model R^2	0.18	0.22	0.52	0.54

Significance at $^{*}p < 0.05$; $^{**}p < 0.01$, $^{***}p < 0.001$.

[a] Other interactions were not significant at $p = 0.05$.

approaches zero in most non-ranking years, it indicated that most producers erratically modify their irrigation decisions year after year. Following Farmaha et al. (2016), persistence was calculated as the ratio between average RI for category *i* (*i.e.*, high- or low-irrigation) across non-ranking years and RI calculated for ranking year *k* (*i.e.*, 2010 or 2012). A high persistence value would imply that irrigation in ranking and non-ranking years consistently deviated from the regional average irrigation across all years and not just in the year in which fields were ranked.

3. Results

3.1. Explanatory factors driving year-to-year and field-to-field variation in irrigation

Average (2005–2013) seasonal precipitation and ET_O were remarkably similar between the two regions (Table 1). However, regions varied markedly relative to soil type, with soils in NC fields having nearly half available water holding capacity (AWHC) relative to SC fields. Coefficient of variation (CV) for AWHC indicate that soils were remarkably similar across SC fields, while soil were more heterogeneous across NC fields. Intermediate TWI values (and their relatively small field-to-field variation) indicate that a large fraction of fields in both regions were located in flat terrain, as expected for center-pivot irrigated fields.

Visual inspection of producer field irrigation distributions indicated large variation in irrigation across regions, year, crops, and fields (Fig. 2). Field-to-field variation in irrigation, within the same crop-region-year, was very large as indicated by CV values ranging from 18% to 58% across crop-region-years cases. Field-to-field variation in irrigation was as large as (if not larger) year-to-year variation (CV range: 17–37%). The majority (70%) of crop-region-year field irrigation distributions deviated from a normal distribution (D'Agostino-Pearson test, $p < 0.01$) and most of them were positively skewed (Fig. 2). In other words, the shape of the irrigation distributions showed a substantial number of fields receiving irrigation amounts that were well above average irrigation for the same region-year.

Availability of irrigation data for a wide range of weather, soil, and management conditions presented a unique opportunity to investigate sources of variation in irrigation. Analysis of variance indicated that weather, soil, and crop type explained an important portion of the observed variation in irrigation across field-years (Table 2). WD alone explained only 18% of observed variation (column A in Table 2). Addition of crop type, soil parameters, and their interactions with WD substantially increased model explanatory power (columns B and C in Table 2). Still, nearly than half (46%) of

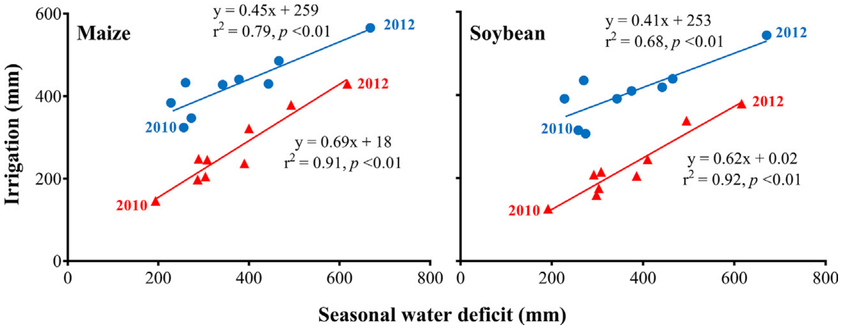

Fig. 3. Irrigation *versus* seasonal water deficit (defined as total grass reference evapotranspiration minus precipitation) for the period between June 1 to August 31 for maize (left) and soybean (right) fields in south-central (SC, triangles) and north-central (NC, circles) regions. Each data point indicates average total irrigation for a crop-region-year combination. Labels indicate years with extremely high (2010) and low (2012) seasonal precipitation amounts (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

field-to-field variation in irrigation remained unexplained by the parameters accounted for in this analysis (Table 2).

Variation in regional average irrigation across years was explained by magnitude of seasonal WD for both crops ($p < 0.01$, $r^2 \geq 0.68$) (Fig. 3). As expected, irrigation amounts were lower than seasonal WD because (i) actual crop ET is significantly lower than ET_0 before canopy closure and during the late reproductive stages (Allen et al., 1998) and (ii) available soil water content at sowing, which is typically near field capacity in Nebraska, also contributes to satisfy crop water requirements (Fig. 3). Indeed, total water supply from sowing to physiological maturity, including stored soil water at sowing plus in-season rainfall and irrigation, exceeded WD in most irrigated fields (data not shown). On average, maize received 15% and 5% higher irrigation than soybean in SC and NC fields, respectively ($p < 0.01$) (Fig. 3). This difference reflected differences in irrigation requirements and management between the two crops (Torrion et al., 2014; Sharma et al., 2015).

Average irrigation in NC fields was consistently higher than in SC fields across the entire range of WD, with an average difference of *ca.* 150 mm between the two regions (Fig. 3). Difference in average irrigation was attributable to the remarkable difference in average AWHC between the two regions (104 *versus* 199 mm) and not due to weather as indicated by similarity in seasonal precipitation and ET_0 (Table 1). Our analysis revealed that irrigation decisions were also influenced by more complex interactions between WD and crop type and AWCH (Table 2, column D). For example, the (150-mm) difference in irrigation between NC and SC fields was disproportionally larger than the difference in AWHC (95 mm) (Fig. 3). We speculate that the inequality (1.6 mm irrigation increase per mm decrease in AWHC) can be explained by (i) producers applying higher seasonal irrigation in NC fields to compensate for lower irrigation efficiency (*i.e.*, how much of the applied irrigation water is captured by crops) in fields with low AWHC, (ii) greater risk-aversion attitude in producers irrigating coarse-textured soils, or (iii) a combination of these two factors.

3.2. Is field-to-field variation in irrigation consistent across years with contrasting weather?

An important question that arose was whether field-to-field variation in producer irrigation was similar across years or, instead, it changed from year to year due to variation in weather. Our analysis indicated that field-to-field irrigation variation (expressed as CV) diminished with increasing magnitude of the seasonal water deficit (Fig. 4). In other words, field-to-field variation in irrigation was largest in the 2010 wet year relative to the 2012 drought year (average CVs: 46% *versus* 25%). This finding suggests that irrigation requirements in a drought year are so high that it becomes less likely for a producer to apply irrigation in excess of crop water requirements because of system capacity constraints, making differences in producer risk behavior less relevant. In contrast, in a wet year, satisfying irrigation water requirements requires fewer irrigation events (and smaller amounts) and differences among producers relative to irrigation scheduling skills and risk aversion become more evident. Field-to-field variation was consistently higher in SC fields relative to NC fields across the entire range of seasonal water deficit (average CVs of 40% and 25%, respectively) (Fig. 4). This finding was consistent with our previous hypothesis since, for the same level of water deficit, irrigation water requirement is higher in NC fields due to lower AWHC relative to SC fields.

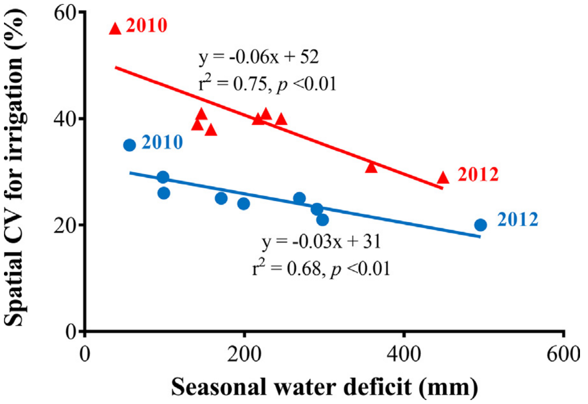

Fig. 4. Field-to-field variation in producer irrigation (quantified with the coefficient of variation, CV) *versus* seasonal water deficit in maize and soybean fields located in the south-central (SC) (red triangles) and north-central (NC) (blue circles) regions. Seasonal water deficit was calculated as the difference between total grass-based reference evapotranspiration and seasonal precipitation for the period between June 1 and Aug 31. Each data point indicates the CV for a given region-year. Labels indicate years with extremely high (2010) and low (2012) seasonal precipitation amounts. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. Producer behavior in relation with irrigation water use

Iterative analysis of irrigation variation with distance from a given field revealed that clustering of irrigation existed within SC fields (Fig. 5). In other words, irrigation decisions made in an individual field also impacted irrigation decision in adjacent fields. As distance increased from a field with high irrigation (651–800 mm), irrigation remained higher than average, with this trend persisting until a distance of about 4 km (*i.e.*, 5 center-pivot irrigated fields in every direction, representing an area equivalent of *ca.* 25 fields). While it is possible that clustering occurred due to management of several fields by a single producer, this is unlikely since,

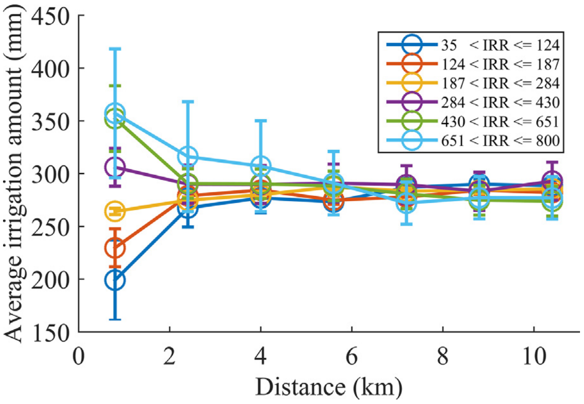

Fig. 5. Relationship between irrigation and distance in maize and soybean fields located in the south-central region. Analysis was performed separately for six ranges of irrigation (IRR), from low-irrigated (35–124 mm) to high-irrigated fields (651–800 mm). Each datapoint represents average irrigation for each irrigation range. Vertical bars indicate ± standard deviation of the mean (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

on average, producers in Nebraska owned 5 irrigated fields. Similarly, fields with low irrigation (35–124 mm) were related to lower than average irrigation in surrounding fields, but only to a distance of about 2 km away. Convergence of lines to regional mean irrigation (between 250 and 300 mm) indicated disappearance of neighbor effect with distance from a given field (Fig. 5). Interestingly, fields with high irrigation affected surrounding fields at a greater distance than low irrigation fields, suggesting that producers applying large irrigation amounts may influence the decisions of neighboring producers to a greater extent relative to the influence of producers applying comparatively smaller amounts over neighboring producers.

Fields in the SC region with above- (high irrigation category) and below-average (low irrigation category) irrigation in ranking years were also the same fields exhibiting respective larger and smaller irrigation amounts in the rest of the years (Fig. 6). High degree of persistence in irrigation decisions across years became clear as average irrigation calculated for each field category did not approach the $y = 0$ line in any of the years. Interestingly, fields with above and below-average irrigation in 2010 had irrigation closer to the regional average in non-ranking years (persistence of *ca.* 40% for both high and low-irrigation field categories) compared to the fields selected in 2012 ranking year (persistence of 73% and 80% for high and low-irrigation field categories, respectively).

4. Discussion

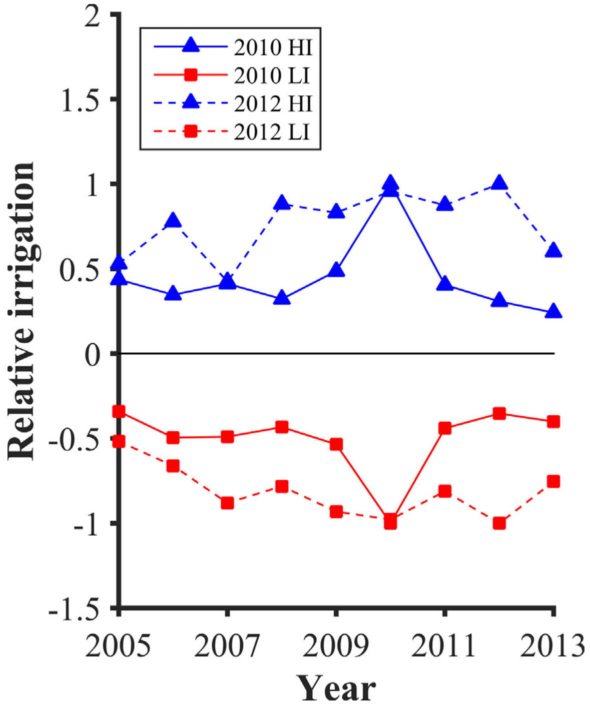

Fig. 6. Relative irrigation for maize and soybean fields in the south-central region classified as high irrigation (HI, blue triangles) and low irrigation (LI, red triangles) according to producer field irrigation distribution in two years: 2010 (solid lines) and 2012 (dashed lines). See Section 2.3 for details on calculation of relative irrigation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Our study analyzed variation in producer irrigation across different years, crops, and soil types using actual irrigation data collected from hundreds of producer fields. The interactive influence of multiple factors, including weather, crop type, soil properties, and producer behavior in relation to irrigation water use highlights how difficult it is to predict field and regional irrigation based on a few biophysical factors. Our findings are consistent with Lorite et al. (2004) who concluded that use of average irrigation values does not capture the variability in water use among farmers or the variation in irrigation strategies among different crops and soil types. For example, our study showed that even at a regional level, average irrigation can vary as much as 200 mm for the same level of seasonal water deficit due to differences in soil type. We argue here that, given the difficulties to predict irrigation accurately from secondary variables, there is an urgent need to increase availability of high-quality, producer field irrigation data. Without accurate irrigation data, future research focusing on the food-water nexus will continue to rely on coarse, fragmented irrigation data, which will in turn, diminish our capacity to inform decision-making and prioritize research and investment in irrigated agriculture and water resources.

Weather, crop type, and soil properties influenced producer field irrigation; however, these factors only accounted for 53% of observed field-to-field variation in producer irrigation. While part of the unexplained variation might be attributable to factors that were not account for in our analysis due to lack of data (*e.g.*, tillage method), producer behavior associated with irrigation management appeared to be an important source of variation. Consistently with this hypothesis, we found that (i) irrigation amounts were higher in the region with sandy soils, even after accounting for differences in AWHC between regions, (ii) field-to-field variation increased with decreasing magnitude of seasonal water deficit (*i.e.*, greater field-to-field variation in wet years), (iii) there was a significant neighbor effect, and (iv) presence of producers that persistently apply greater or lower irrigation relative to the mean average irrigation across fields with almost identical weather and soil type. We also found a high degree of persistence in irrigation amounts over time, indicating that the factor(s) explaining larger irrigation amounts in a group of fields is related with a factor that is persistent over time in contrast to factors that may influence irrigation decisions in a given year but not in others. The implication is that there is a substantial opportunity for improving irrigation water use (*i.e.* grain produced per unit of irrigation) if these factors are identified, allowing research and extension efforts to focus on correcting these management practices in a cost-effective way and properly informing policy and incentives.

The degree of field-to-field variation for irrigation reported here is higher than the reported variation for other agricultural inputs such as nitrogen (N) fertilizer (CV = 17%; Grassini et al., 2011). We speculate that, since most of the N fertilizer is applied in a single dose in the fall or around sowing, producers have limited ability to adjust N input relative to year-specific conditions. Hence, the amount of N fertilizer to be applied depends on producer yield goal, which is generally estimated based on average yield during previous years and exhibits relatively small year-to-year and field-to-field variation in irrigated maize systems (Grassini et al., 2011, 2014a, 2014b). In contrast, producers have more flexibility in relation to irrigation scheduling and, ultimately, producers' decisions on irrigation timing and amount will depend on their understanding of irrigation requirements in a given year, as determined by in-season weather, soil and crop type, and their perception of risk. The 'real-time' nature of irrigation management exposes to a larger degree the differences in skills and risk aversion attitudes among producers, which ultimately results in a high degree of variation in irrigation amounts across fields, even for those with almost identical weather and soil.

Examination of field irrigation distributions indicated that there is an important portion of producers (*ca.* 10–20%) that applied very large irrigation amounts in relation to the rest of producers within the same region-year. This observation has implications relative to the extension model to be used to improve management of water resources for crop production at district, watershed, and state levels. In this case, should extension education prioritize resources to reduce irrigation inputs in the whole population or, instead, focus on those producers within the upper tail of the field irrigation distribution? On the one hand, focusing on fields with highest irrigation offers greater potential payoff in terms of irrigation water savings, especially if the cause for irrigation surplus can be identified and solved. On the other hand, these fields might be managed by producers with very high risk-aversion attitude, who may be less receptive to follow flexible irrigation decisions based, for example, on crop developmental stages or soil water content thresholds. We believe that on-farm data as presented in this study, complemented with data relative to the factors that drive producer irrigation decisions and determine irrigation water requirements, can help answer these kinds of questions as well as prioritize research and extension activities and inform policy and incentive programs. Similarly, access to thousands of irrigation records provides with a unique opportunity to benchmark irrigation management in individual fields. Indeed, we are developing an online database platform to allow producers to compare their field irrigation amounts against the irrigation reported for other fields located within the same climate-soil spatial domain. Such a platform will help producers diagnose current irrigation management and evaluate options to reduce irrigation amount without sacrificing crop yield.

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