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More Crop per Drop: Benchmarking On-Farm Irrigation Water Use for Crop Production.

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MORE CROP PER DROP: BENCHMARKING ON-FARM IRRIGATION WATER
USE FOR CROP PRODUCTION

by

Katherine Elizabeth Boone Gibson

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MORE CROP PER DROP: BENCHMARKING ON-FARM IRRIGATION WATER
USE FOR CROP PRODUCTION

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University of Nebraska, 2016

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Efficient use of irrigation is essential to meet food production needs of growing global populations while ensuring long-term sustainability of freshwater resources. However, lack of on-farm irrigation data constrains understanding of irrigation variation and no framework exists to benchmark irrigation use using actual irrigation data. The following work investigates variation in irrigation using a database of *ca.* 1400 maize and soybean fields over 9 years in Nebraska and presents a framework to benchmark irrigation use using a separate database of *ca.* 1000 maize and soybean fields in Nebraska as proof of concept. "State-of-the-art" crop models estimated yield potential and irrigation water requirements for each field-year observation and were compared against producer-reported yield and irrigation.

Precipitation and ET_o accounted for >68% of observed year-to-year variation in irrigation in maize and soybean fields. Irrigation differed by *ca.*150 mm between regions due to differences in available water holding capacity. Weather and soils explained field-to-field variation in irrigation; however, the majority of field-to-field variation remained unexplained, attributable to producer behavior. Fields with above/below-average irrigation remained consistent across all years, suggesting behavioral components of irrigation variability. Findings illustrate the difficulty of predicting field-scale irrigation due to multiple biophysical and behavioral factors driving irrigation decisions. Increased

availability of high-quality, on-farm irrigation data is needed to inform decision-making related to water resources and irrigated agriculture.

Benchmarking found that 82% of fields reached ≥70% of yield potential. Nearly 75% of maize and *ca.* 40% of soybean fields were irrigated above simulated irrigation requirements, indicating room for improvement in irrigation use. Irrigation surplus increased with decreasing soil water holding capacity. Fields irrigated using high-level technology (*e.g.* soil water sensors) received 95 mm less irrigation than fields where irrigation decisions were not properly informed, with no yield difference between scheduling methods. Half of current irrigation volumes could be potentially reduced in above- or near-average rainfall years if current irrigation surplus is eliminated, but only 10% in drought years. The framework developed can be used to benchmark irrigation use for crop production at different spatial levels (field, region, state), help prioritize extension and research activities, and inform policy and incentive programs.

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Table of Contents

Table of Figures

Table of Tables

List of Equations

Preface

As the world seeks solutions to feed an estimated global population of 9.7 billion people by 2050, irrigated agricultural land and exploitation of groundwater resources in developing countries are expected to increase significantly in the next 30 years with projections estimating a 20 Mha increase in irrigated land from 2005 to 2050 (Alexandratos and Bruinsma, 2012; United Nations; 2015). Global climate change models predict altered precipitation patterns worldwide including prolonged and more severe droughts in some regions, which could portend increased appropriation of groundwater resources with reduced potential for the long-term sustainability of groundwater systems (Kumar, 2012; Scanlon et al., 2012). In view of these challenges, it is essential to find a balance between producing increasing crop yields while managing groundwater resources to ensure long-term sustainability. An important first step of this balance is to understand how crop producers use irrigation water: how much irrigation water is applied, how irrigation varies over time and space, and how well irrigation water is utilized for crop production.

Lack of high-quality, field-scale irrigation data is one of the greatest limitations for studies pertaining to irrigation water usage and its impacts. In the United States, irrigation data are reported by the USDA Farm and Ranch Irrigation Survey in the form of a statewide average value released every five years (https://www.agcensus.usda.gov/Publications/Irrigation_Survey/). Without actual field-scale data, the variability in irrigation is largely unknown and it is impossible to determine how close irrigation amounts are to irrigation requirements. This study makes

use of two unique databases containing on-farm irrigation, yield, and management data collected from irrigated maize and soybean fields to delve into long-standing questions and assumptions about irrigation trends and producer behavior/management related to irrigation and how they relate to crop yields. Throughout this study, Nebraska, USA, was used as a proof of concept for a new framework to analyze spatial and temporal variation in irrigation and benchmark irrigation water use for crop production.

Irrigated agriculture represents a vital part of Nebraska's economy and culture. Nebraska ranks first nationally in number of irrigated hectares, with *ca.* 3.4 Mha of irrigated land (USDA, 2014). Approximately 10.2 billion m^3 of water are pumped from groundwater sources annually to irrigate fields across Nebraska, accounting for 94% of groundwater withdrawals and 84% of total irrigation water for the state (USGS, 2005). Despite intensive use of groundwater for irrigation, the predominant groundwater source in Nebraska (the High Plains Aquifer) has experienced relatively minimal groundwater depletion (Scanlon et al., 2012). Of Nebraska's harvested irrigated cropland, *ca.* 64% and 25% is maize for grain and soybean, respectively, according to most recent U.S. Census of Agriculture estimates from 2012 (USDA-NASS, 2014). About 52% and 48% of total maize and soybean harvested area in Nebraska is irrigated and rainfed, respectively, based on 2012 estimates (USDA-NASS, 2014). Maize and soybean 5-year average yields (2010-2015) in Nebraska are respectively 12.1 and 4.1 Mg ha^{-1} with irrigation and 7.9 and 3.0 Mg ha^{-1} in rainfed conditions, with associated inter-annual coefficient of variations (CV) of 5% and 4% for irrigated maize and soybean, respectively, and 27% and 25% for rainfed maize and soybean yields, respectively (USDA, 2014). Hence, irrigation increases and stabilizes crop production, providing incentives for ethanol

plants, feedlot operations, and machinery and irrigation manufacturers to establish in Nebraska. A 2003 study by the University of Nebraska – Lincoln Bureau of Business Research estimated total economic impact of irrigation to be $3.6 billion USD per year under normal precipitation (Lamphear, 2005). Likewise, another study estimated in 2012 that direct economic losses would be upwards of $7 billion USD if producers in Nebraska were unable to irrigate in a year of severe drought, such as 2012 (Parkinson, 2012).

In Nebraska, a unique system of regional governance oversees the management of natural resources data. Within the state, there are 23 Natural Resources Districts (NRDs; www.nrdnet.org) with watersheds as boundaries. These districts are charged with facilitating programs to conserve water and soil resource quality and quantity, a process which involves collecting pertinent data from crop producers within the NRD. Examples of such data include field-specific applied irrigation and nitrogen fertilizer data required to be reported by producers as part of NRD programs aimed at preventing irrigation overuse and nitrate and pesticide contamination of groundwater. Cooperation between the NRDs and university researchers has resulted in access to databases, varying in reporting area size, containing a wide range of field-specific agronomic data including crop type, sowing date, irrigation system, tillage practice, yield, fertilizer inputs, and irrigation water amount. Research presented in this thesis utilized two databases, the first created by combining data from multiple NRDs over several years and the second the result of data collected via producer surveys created for this study.

The two databases showcased in the following chapters contained a large number of field-year observations along with detailed data on yield and irrigation, all of which allowed a robust analysis of irrigation use and irrigation management practices in

Nebraska. Chapter 1 discusses analysis of a database containing over 1400 maize and soybean fields and 9 years of data to identify sources of spatial and temporal variation in irrigation. Based on the findings in Chapter 1 about the drivers of variation in irrigation in space and time, Chapter 2 presents a comprehensive framework to benchmark and improve on-farm irrigation water use to produce crop yield and proof of concept is provided with a case of study based on a database containing 1000 maize and soybean field-year observations, including three years with contrasting weather. The importance of irrigation in Nebraska and the availability of high-quality producer-reported data make the state an ideal testing ground for new approaches to benchmark irrigation usage. The objectives of this study are to first understand how irrigation varies in time and space, and then to use this information to develop a framework to benchmark current irrigation water use and identify opportunities to improve current irrigation management practices for crop production.

Chapter 1

Understanding the extent and causes of spatial and temporal variation in irrigation

Abstract

Irrigated agriculture accounts for *ca.* 40% global food production and only uses 20% of land allocated to crop production. However, there is a large gap of knowledge relative to the factors that drive variation in irrigation across year, across region, and across fields within the same region and year. Understanding the cause and extent of this variation is necessary to predict and estimate future irrigation use across years, develop tools to aid irrigation decision making, and identify sources of surplus irrigation and opportunities for improvement. This study investigated sources of variation in irrigation using a database collected over 9 years from *ca.* 1400 maize and soybean fields in two distinct regions in Nebraska, USA (total of 12,750 field-year observations). The database contained field-specific data annual irrigation, which was measured using flow meters installed at each irrigation well or estimated by producers. Crop water deficit, calculated as the difference between total precipitation and reference evapotranspiration (ET_o) during the growing season, accounted for >68% of observed year-to-year variation in irrigation in both maize and soybean fields. However, irrigation was markedly different between the two regions (*ca.* 150 mm) due to differences in available water holding capacity between regions. Precipitation, ET_o and soils also explained field-to-field variation in irrigation; however, the majority of field-to-field variation remained unexplained, suggesting that producer behavior in relation to irrigation scheduling may also play an important role. Indeed, our analysis indicated that fields with high irrigation

were surrounded by fields with similarly high irrigation, suggesting the presence of a "neighbor" effect on irrigation decisions. Likewise, our analysis further pointed to a behavioral component since fields with above- or below-average irrigation consistently remained so across all years of the study. Our findings indicate that it is difficult to predict field-scale irrigation due to the presence of multiple factors driving irrigation decisions, including biophysical (crop, precipitation, ET_o, and soil) and behavioral factors. We argue here that, given the difficulties in predicting irrigation accurately from secondary variables, there is an urgent need to increase availability of high-quality, 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.

Keywords: irrigation; soybean; maize; on-farm data

1. Introduction

Irrigation is important to agricultural production worldwide, accounting for *ca.* 40% of global food production and 20% of arable land (Molden, 2007; Schultz et al., 2005). Given the importance of agriculture to produce food for current and future populations and the prevalence of water withdrawals exceeding recharge in many irrigated areas, there is a need to improve use of freshwater resources for agriculture (Godfray et al., 2012; Scanlon et al., 2012; Siebert et al., 2010). However, a dearth of actual producer field irrigation data inhibits the scope and reduces the accuracy of many studies involving irrigation water use in agriculture.

Only a few studies have used reliable, irrigation data from producer fields as the basis for their assessments (Grassini et al., 2014b; O'Keefe 2016). However, the vast majority of previous studies involving use of irrigation water in agriculture have used coarse estimates of irrigation data. Many previous studies have, for example, relied on publically available coarse irrigation data. Irrigation databases, including AQUASTAT (http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en) and USDA Farm and Ranch Irrigation Survey (FRIS,

http://www.agcensus.usda.gov/Publications/2002/FRIS/fris03.pdf) have been used in studies which sought to analyze irrigation on a global or national scale (Mullen et al., 2009; Siebert et al., 2010). These databases provide coarse irrigation data, typically at country or state level, with important gaps relative to geographical and temporal coverage. For example, AQUASTAT does not contain data for North America or Europe and most-recent records may date back decades. Also, while FRIS provides data for the U.S. on a state-level, data on irrigation are only reported every five years. As a result, irrigation data may be biased if weather conditions deviated from normal in the year in which these data were collected. In other studies, irrigation data have been estimated using estimated pumping rates based on publically available groundwater level data (Maupin and Barber, 2005; Mcguire, 2007; Scanlon et al., 2012). However, without actual irrigation data, it is not possible to quantify the exact contribution of irrigation withdrawal on groundwater decline to implement policies for long-term sustainability of both agriculture and groundwater resources. Other studies have estimated irrigation requirements as a proxy to actual irrigation, with the former estimated on meteorological factors or crop and hydrological models (Sharma and Irmak, 2012a; Döll and Siebert,

2002; Droogers et al., 2010; Phillips et al., 2015; and Rohde et al., 2015). Use of estimated irrigation requirements in place of actual irrigation data is problematic for several reasons. Overly simplistic estimations of irrigation based solely on weather variables sometimes do not account for factors influencing the water balance or irrigation water use such as crop type, irrigation system type, and soil properties, make crude assumptions relative to these factors, or rely on coarse soil and weather data (*e.g.*, monthly weather means). Likewise, this approach ignores producer risk perception and associated behavior relative to irrigation scheduling. A common problem of the studies listed above is the total lack of validation of their irrigation estimates against measured irrigation in producer fields.

Understanding the sources of spatial and temporal variation in irrigation at field-level is important to better predict and estimate irrigation use as well as identify sources of irrigation surplus and find opportunities for improvement. To our knowledge, no previous study has attempted to assess sources of field-to-field variation in irrigation across producer fields. In an earlier study in Nebraska, Grassini et al. (2014b) found that the majority of variation in irrigation in soybean fields was due to spatial variation (*i.e.* field-to-field) and that variation was consistent across years. However, this previous study did not look into the causes for the observed temporal and spatial variation in irrigation. Sources of field-to-variation may involve differences in weather across fields and years, as well as differences in soil type and topography between fields. But it may also involve a behavioral component, specifically, the risk perception by producers and how this influences irrigation decisions (Andriyas, 2013).

In the present study, we used a unique database with data on irrigation collected from *ca.* 1,400 maize and soybean fields in Nebraska during 9 years (2005-2013). Our objective was to identify sources of spatial and temporal variation in on-farm irrigation, including weather, soil properties, crop management, and producer behavior. Our hypothesis is that field-specific actual irrigation is determined by multiple, interactive factors and, hence, it cannot be estimated precisely with a few biophysical factors.

2. Methods

2.1 Study area and producer database

Irrigation data were available for irrigated maize and soybean fields over 9 years (2005-2013) in two regions of Nebraska: north-central (NC) and south-central (SC) (Fig. 1.1). While climate varied drastically across years, it was remarkably similar between regions (Table 1.1). However, the two regions varied markedly relative to soil type, with dominant soils in the SC region having nearly two times higher available water holding capacity (AWHC, 0-1 m) than soils in the NC region. Likewise, while soils were remarkably similar across fields in the SC region, soils were highly heterogeneous in the NC region. Finally, topography was similar in fields in both NC and SC regions, as indicated by the similarity in the average topographic wetness index in the two regions (TWI, see description below).
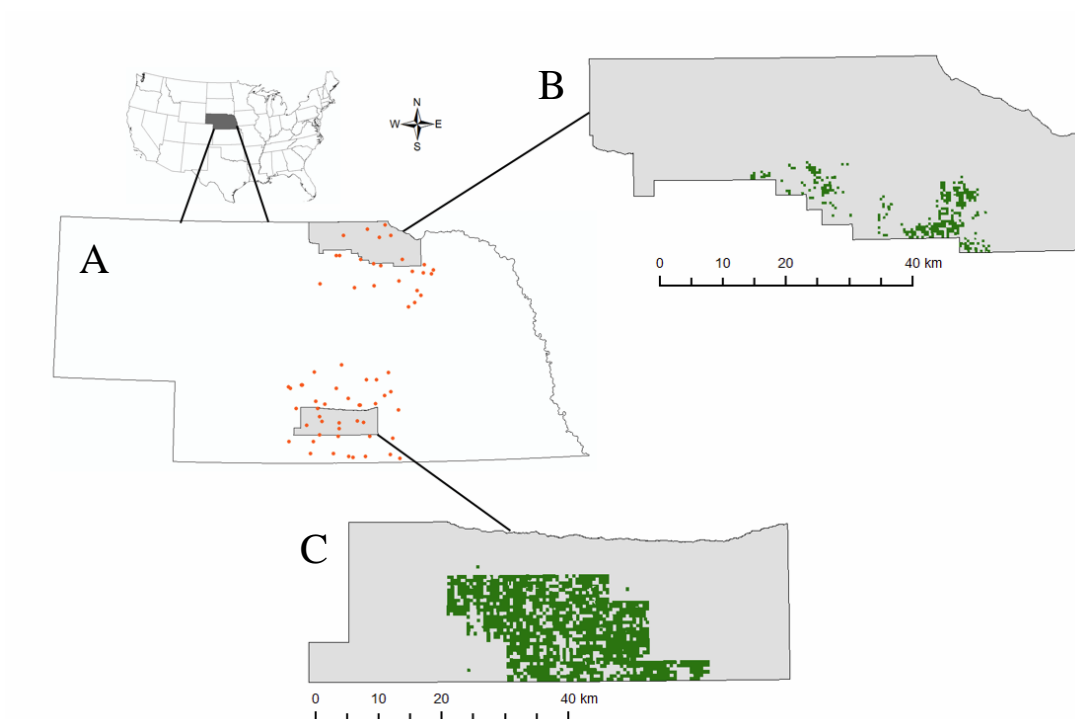
Figure 1.1 A) Map showing the two study areas in Nebraska (shaded regions) as well as meteorological stations (red dots) used for weather interpolation in this study. B) Field locations (green squares) in north-central (NC) region. C) Field locations in south-central region (SC).

The NRD data included field-scale sown crop, yield, fertilizer inputs, crop rotation, irrigation system type, and total irrigation during the crop growing season for the 2005-2013 time period. Irrigation was measured using a flow-meter installed at each irrigation well, although irrigation was estimated by farmers for some fields in NC region based on number of irrigation events and irrigation system flow capacity. Quality control was performed to remove fields containing suspicious (*e.g.*, irrigation values exceeding system capacity over the growing season) or missing data. With the exception of ANOVA for which gravity-irrigated fields were included, this study only considered pivot-irrigated fields, which accounted for *ca.* 75% of fields in SC and all fields in NC. Likewise, we focused on maize and soybean fields because these two crops account for

89% of total irrigated area in Nebraska (USDA-NASS, 2014). The database 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). Availability of irrigation data for a wide range of weather, soil, and management conditions presents a unique new opportunity to investigate sources of spatial and temporal variation and analyze producer behavior in relation to irrigation decisions.

Field-scale weather and soil property data were retrieved for each individual field-year. Precipitation and grass-based reference evapotranspiration (ET_o) were interpolated for each field, using daily weather data from the three weather stations located in closest proximity (on average *ca.* 24 km) to each field, using inverse distance weighting (Yang and Torrion, 2014). 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. For the purpose of interpolating ET_o data, only AWDN stations were used due to lack of all meteorological variables needed to estimate ET_o in the NWS network stations. However, both AWDN and NWS stations were used in the interpolation of precipitation data 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 (1984). For each field-year, seasonal precipitation and ET_o were calculated for each field as the cumulative value for each of these variables from June 1st to August 31st. These dates coincide with the beginning and end of the irrigation season in the maize and soybean crop producing region in the western U.S. Corn Belt (Grassini et al., 2014a).

Available water holding capacity (AWHC) for the 0-1 m soil depth was obtained

for each field from the Soil Survey Geographic database (SSURGO;

http://websoilsurvey.nrcs.usda.gov). AWHC is defined as the amount of water between

soil field capacity and wilting point, in the upper 1 m of soil profile in this case. 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. Mean AWHC was calculated for each field by weighting each sub-field soil

property unit relative to their proportion within each field. SAGA GIS software was used

to obtain topographic wetness index (TWI) for each field (Table 1.1) (Conrad et al.,

2015; Olaya and Conrad, 2009). Topographic wetness index 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.

Table 1.1 Means of topographic wetness index (TWI) and available water holding capacity (AWHC) across north-central and south-central fields. Long-term (2005-2013) means of seasonal (June 1st – August 31st) precipitation and reference evapotranspiration (ET_o) are also shown. Coefficients of variation (CV) are shown in parentheses. CVs correspond to field-to-field variation for TWI and AWHC and year-to-year variation for precipitation and ET_o.

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

2.2 Statistical analysis

Influence of several biophysical and management factors on spatial and temporal variation was evaluated using ANOVA (SAS® software v 9.4, ©2002-2012 SAS Institute Inc., Cary, NC, USA). These factors included crop type, previous crop (*i.e.*, the crop sown in the same field in the prior year), irrigation system type, TWI, AWHC, seasonal precipitation, and seasonal ET_o. Significance of irrigation system type was only evaluated for SC, as NC fields were all pivot-irrigated. Linear regression analysis was used to assess variation in irrigation and its variability in relation with seasonal water deficit (seasonal ET_o minus seasonal precipitation) and AWHC.

2.3 Influence of producer behavior on irrigation amounts

The influence of neighboring producers' irrigation decisions on an individual producer's field was analyzed by investigating irrigation with distance from individual fields. To reduce other sources of field-to-field variation such as soil heterogeneity, only SC fields with almost identical AWHC and TWI were analyzed to determine the presence of this so-called "neighbor effect". Irrigation data within SC 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 (0.8 to 10.5 km), in 1.6 km increments. After the z-score and standard deviation of the z-score were determined, fields were grouped by their local (fields within 0.8 km distance) z-score. The mean and standard deviations for each group were then back-calculated to obtain average values.

This was performed for each year and then averaged across all years included in the study period.

Understanding if producer irrigation decisions are consistent across years can help identify manageable or non-manageable factors influencing irrigation and determine to what extent improvement in irrigation usage is possible. This methodology has been followed by Lobell et al. (2010) and Farmaha et al. (2016) to detect sources of yield variation in relation to management factors. If a producer consistently irrigates more than others in the same region, it implies that there is a persistent factor responsible, 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.

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 pivot-irrigated fields in the SC region because soil properties were nearly identical among all fields. Following Farmaha et al. (2016), 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. Both years represent extreme weather years, 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 irrigation distribution were selected, resulting in four categories: 2010 high irrigation (HI), 2012 HI, 2010 lower irrigation (LI), and 2012 LI.

A relative fraction of irrigation was calculated for each field falling in the HI and LI categories in 2010 and 2012 as follows:

$$\text{RIF} = \frac{I_F - \overline{I}_R}{\overline{I}_R} \qquad \text{(Eq. 1)}$$

where RIF was relative irrigation fraction, I_F was field irrigation and $\overline{I}_R$ was average regional irrigation. Relative fraction of irrigation was then calculated for each of these fields in the non-ranking years (2005, 2006, 2007, 2008, 2009, 2011, 2013), and averaged across those non-ranking years. A relative irrigation fraction of zero in a non-ranking year indicated that average field irrigation was equal to regional irrigation amount in that year. A relative irrigation fraction of 0.5, for example, meant that average irrigation for fields in that non-ranking year was 50% higher than the regional average irrigation for that year. If relative irrigation fraction was consistently above or below zero, it would indicate persistent behavior, meaning that the HI producers tend to always apply more irrigation than other producers while LI producers tend to always apply less irrigation. In contrast, if irrigation fraction approached zero, it indicated that most farmers erratically modify their irrigation decisions year after year. As a measure of the degree of persistence, percentage of persistence was calculated as:

$$\text{Persistence \%} = \frac{\overline{RIF}_N}{\overline{RIF}_R} \times 100\% \qquad \text{(Eq. 2)}$$

where $\overline{RIF}_N$ was the average relative irrigation fraction in a non-ranking year and $\overline{RIF}_R$ was the average relative irrigation fraction in a ranking year. Percentage of persistence was computed for HI and LI fields. A high persistence value implied that irrigation in

ranking and non-ranking years was consistently above or below the regional average

irrigation across all years and not just in the year in which the fields were ranked.

3. Results

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

Visual inspection of producer irrigation distributions clearly showed important

variation in irrigation across regions, year, and crops (Fig. 1.2). Remarkably, field-to-

field variation in irrigation, within the same region-year, was very large as indicated by

CV values ranging from 18% to 58% across region-years cases. The majority (70%) of

site-year irrigation distributions shown in Fig. 1.2, deviated from a normal distribution

(D'Agostino-Pearson test, $p<0.01$) and most of them were skewed towards high irrigation

values. In other words, the shape of the irrigation distributions clearly indicated that,

within a given region-year, a substantial number of fields received irrigation amounts that

were well above the average irrigation for the same region-year.
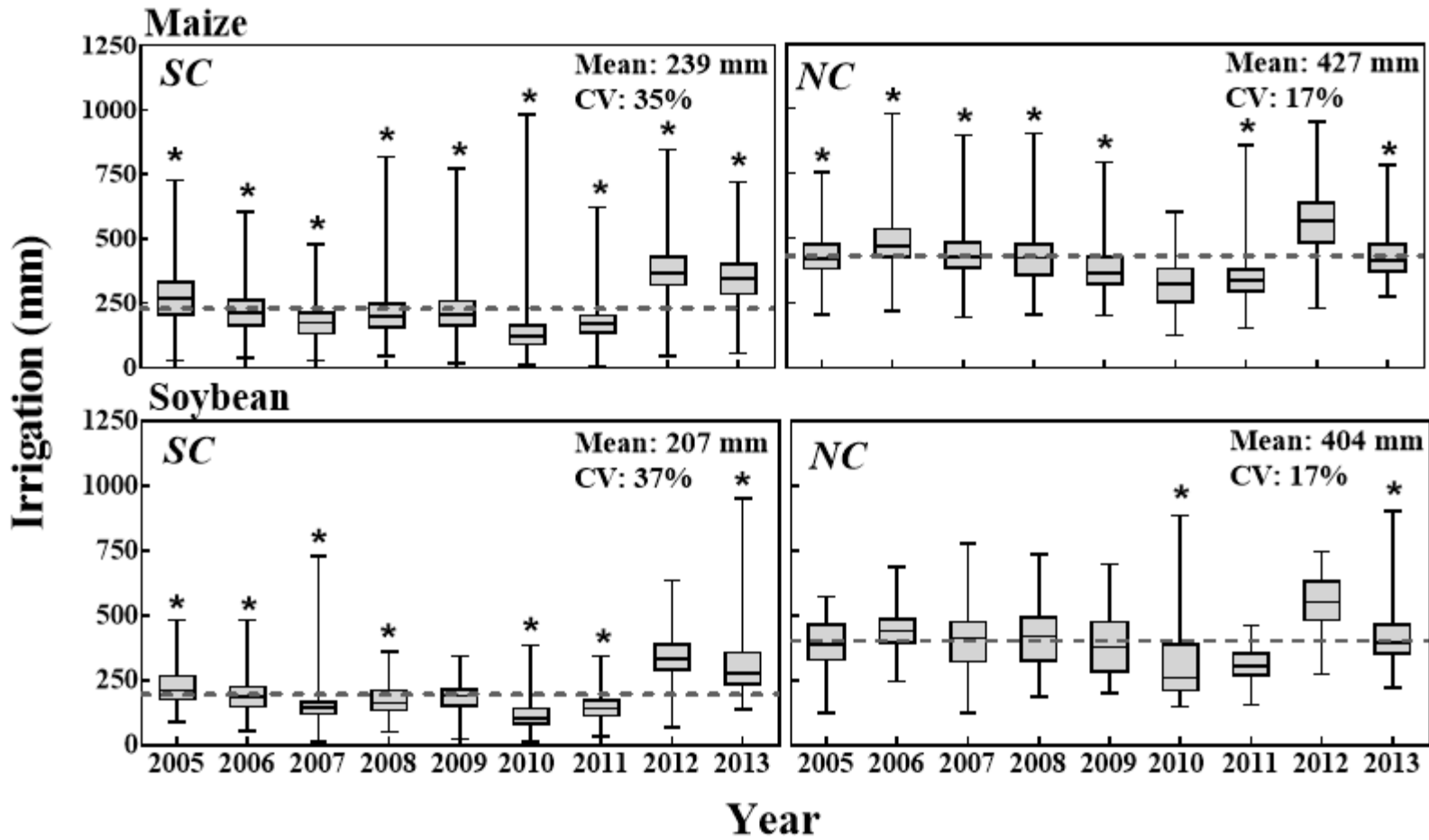
Figure 1.2 Distributions of producer field seasonal irrigation from 2005-2013 for pivot-irrigated maize and soybean fields in north-central (NC) and south-central (SC) regions. Long-term (9 year) mean irrigation and year-to-year coefficient of variation are displayed for each region and crop. Upper and lower boundaries of boxes indicate 75th and 25th percentile, respectively. Horizontal line within boxes is the median value. Whiskers (error bars) are maximum and minimum values. Asterisks indicate that irrigation distribution deviates from the normal distribution (D'Agostino-Pearson test, $p<0.01$).

Analysis of variation indicated that weather, soil, and crop type explained an important portion of the variation in producer irrigation across fields (Table 1.2). Precipitation and AWHC appeared to be major sources of variation, explaining 26% and 51%, respectively, of the observed variation in irrigation across fields after excluding the error ($p<0.01$). Other factors, such as crop type, irrigation system type, and ET_o, had a significant influence on irrigation ($p<0.01$), but their explanatory power was smaller relative to the aforementioned factors (<15%). Remarkably, more than half (55%) of the field-to-field variation in irrigation remained unexplained by the factors accounted for in this analysis (Table 1.2).

Table 1.2 Analysis of factors influencing temporal and spatial variation in producer field irrigation.

Source	Temporal				Spatial			
	F-value	df [a]	Sum of squares	% SS†	F-value	df [a]	Sum of squares†	% SS†
MODEL	413*	4	32939167	22%	611	8	68515445	45%
Crop	42*	2	1687444	8%	63*	1	879876	1%
Prior crop	–	–	–	–	2	1	28985	0%
Irrigation system	–	–	–	–	653*	1	9149452	15%
TWI [b]	–	–	–	–	3	1	41897	0%
AWHC [c]	–	–	–	–	2243*	1	31439791	51%
Precipitation	767*	1	15297782	75%	1169*	1	16389809	26%
ET_o [d]	171*	1	3403535	17%	301*	1	4216767	7%
ERROR		5986	119397760			5979	83798737	
TOTAL		5990	152336927			5987	152314182	

*Significant to $p<0.001$
[a] df: degrees of freedom
[b] TWI: Topographic wetness index
[c] AWHC: Available water holding capacity
[d] ET_o: Grass-reference evapotranspiration
†Model % sum of squares (SS) calculated relative to total SS; parameter % calculated relative to model SS

While soil AWHC had a greater impact on spatial variation in irrigation than precipitation and ET_o, precipitation in particular contributed significantly to temporal variation in irrigation, accounting for 75% of observed variation in irrigation across years (Table 1.2). Variation in regional average irrigation across years was explained by the magnitude of seasonal water deficit for both crops ($p<0.01$, $r^2>0.68$) (Fig. 1.3). Seasonal water deficit had more explanatory power relative to rainfall ($r^2>0.60$) and ET_o ($r^2> 0.55$) alone at explaining year-to-year variation in irrigation. On average, maize fields received 15% and 5% higher irrigation than soybean fields in SC and NC fields ($p<0.01$) (Fig. 1.3). While this difference reflects differences in irrigation requirements between the two crops (Sharma and Irmak, 2015b), this difference is probably amplified by producer tendency to apply more irrigation in maize fields (see Chapter 2). Crop influence on producer irrigation was consistent across years as indicated by the lack of a significant crop $\times$ year interaction on irrigation ($p=0.81$). While irrigation amounts do not appear to compensate for water deficit in Fig. 1.3, this is because irrigation, when combined with initial soil moisture which is not accounted for in these analyses, would likely exceed or equal water deficit.
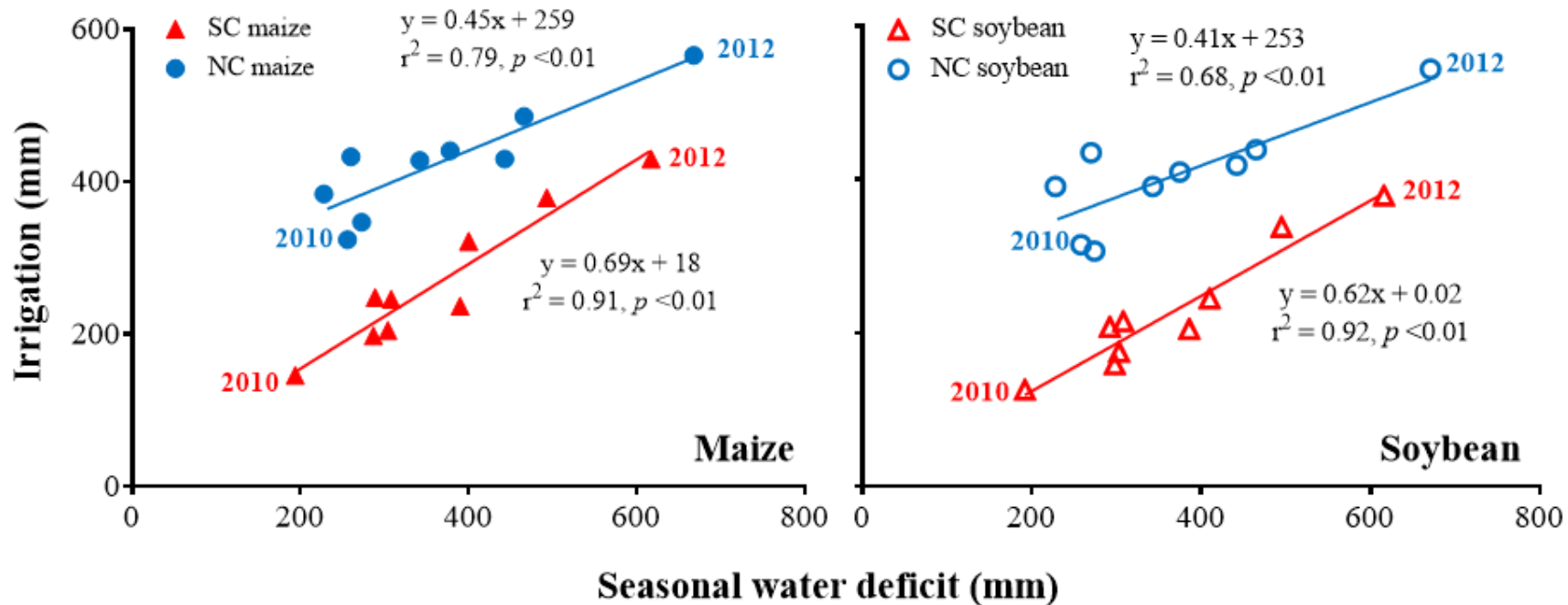
Figure 1.3 Irrigation *versus* seasonal water deficit (defined as grass referenced evapotranspiration – precipitation, from June 1st to August 31st) for south-central (SC) (red triangles) and north-central (NC) (blue circles) regions. Each data point indicates the average seasonal irrigation for a region-year. Years with extremely high (2010) and low (2012) seasonal precipitation amounts are indicated.

Average irrigation in producer fields located in the NC region was consistently higher than irrigation in SC fields across the entire range of crop water deficit, with an average difference of *ca.* 170 mm between the two regions (Fig. 1.3). This difference in average irrigation is likely attributable to the substantial difference in soil AWHC between the two regions (104 *versus* 199 mm in NC and SC, respectively) and not due to weather differences as indicated by the similarity in seasonal precipitation and ET_o (Table 1.1). However, the difference in irrigation between the NC and SC region (150 mm) was not directly proportional to the difference in AWHC (95 mm). This pattern was consistent irrespective of weather conditions. 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, (iii) a combination of these two factors.

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

A question is whether field-to-field variation in producer irrigation is similar across years or, instead, it changes 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 crop water deficit (Fig. 1.4). 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 more unlikely for a producer to apply irrigation in excess of crop water requirements, 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 perception become more evident. Field-to-field variation was consistently higher in SC fields relative to NC fields across the entire range of crop water deficit (average CVs of 40% and 25%, respectively) (Fig. 1.4).
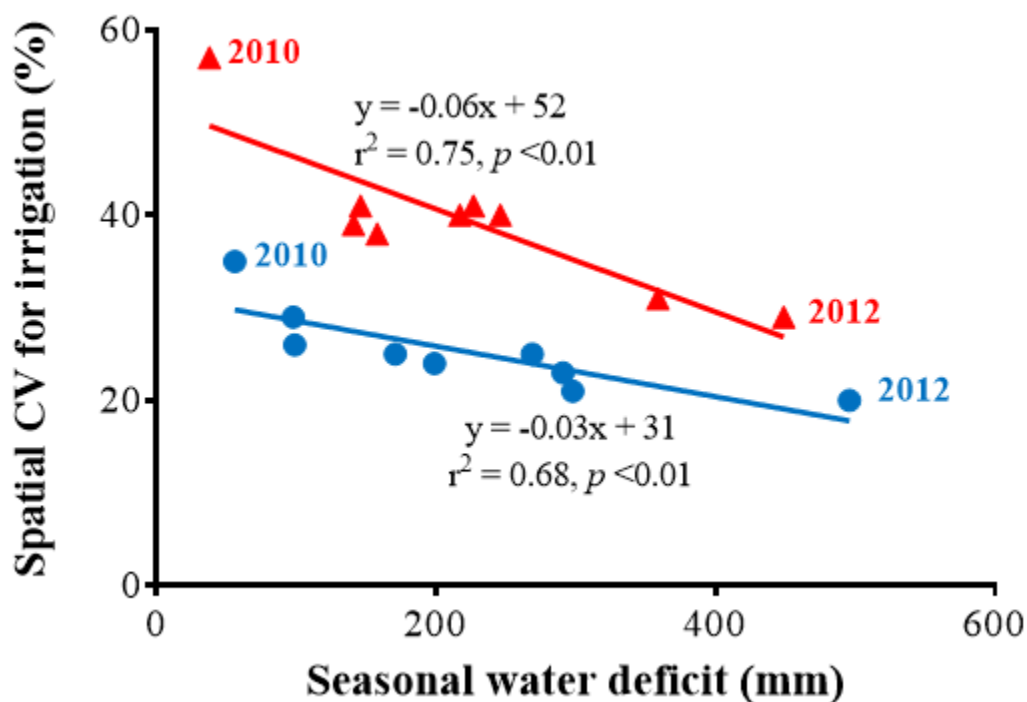
Figure 1.4 Field-to-field variation in producer irrigation (calculated with the coefficient of variation, CV) *versus* seasonal water deficit for fields located in the south-central (red triangles) and north-central (blue circles) regions. Seasonal water deficit was calculated as the difference between seasonal reference evapotranspiration and seasonal precipitation. Each data point indicates the CV for a given region-year. Years with extremely high (2010) and low (2012) seasonal precipitation amounts are indicated.

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 fields in the SC region (Fig. 1.5). 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. 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. 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.
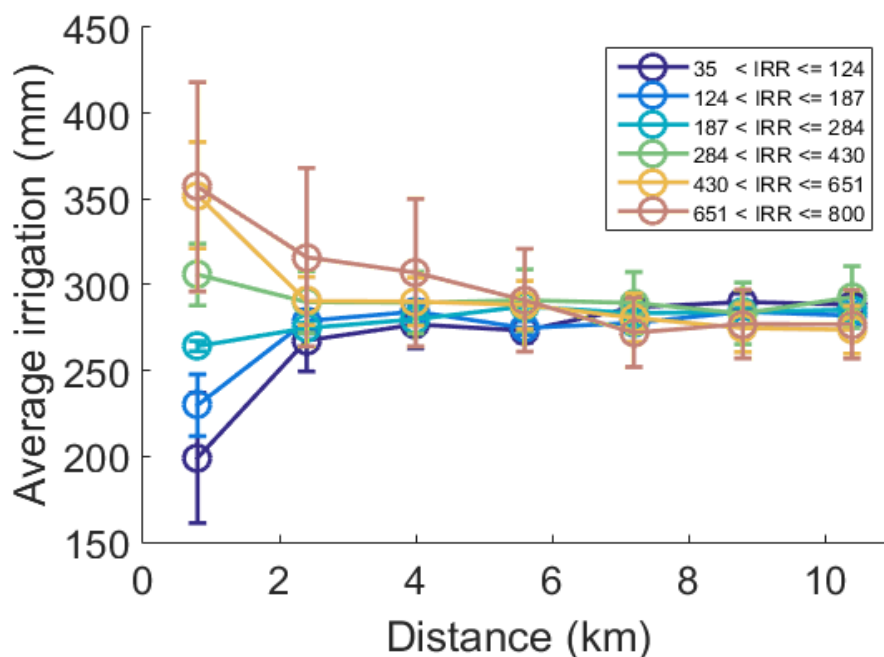
Figure 1.5 Relationship between average irrigation and distance for all fields grouped by irrigation in the south-central (SC) region. Analysis was conducted separately for six ranges of irrigation (IRR), from low irrigated fields (35-124 mm) to high irrigated fields (651-800 mm). Bars indicate ± standard deviation.

Fields in the SC fields with above- (HI category) and below-average (LI category) irrigation in ranking years were also the same fields exhibiting respective larger and smaller irrigation amounts in the rest of the years. The degree of persistence in SC can be seen in Fig. 1.6, wherein the lines of fit for all HI and LI groups do not cross or even approach the y=0 line. Fields with above- and below-average irrigation in 2010 had irrigation closer to regional average irrigation in non-ranking years (persistence of *ca.* 40% for both HI and LI fields) compared to those fields in 2012, for which irrigation was more consistently well above- or below-average in all other years (73% and 80% persistence, respectively). This illustrates the influence of the ranking year such that identifying fields with above- or below-average irrigation in a wet year (*e.g.* 2010) is not as representative of irrigation water use across years with near- or below-average rainfall.
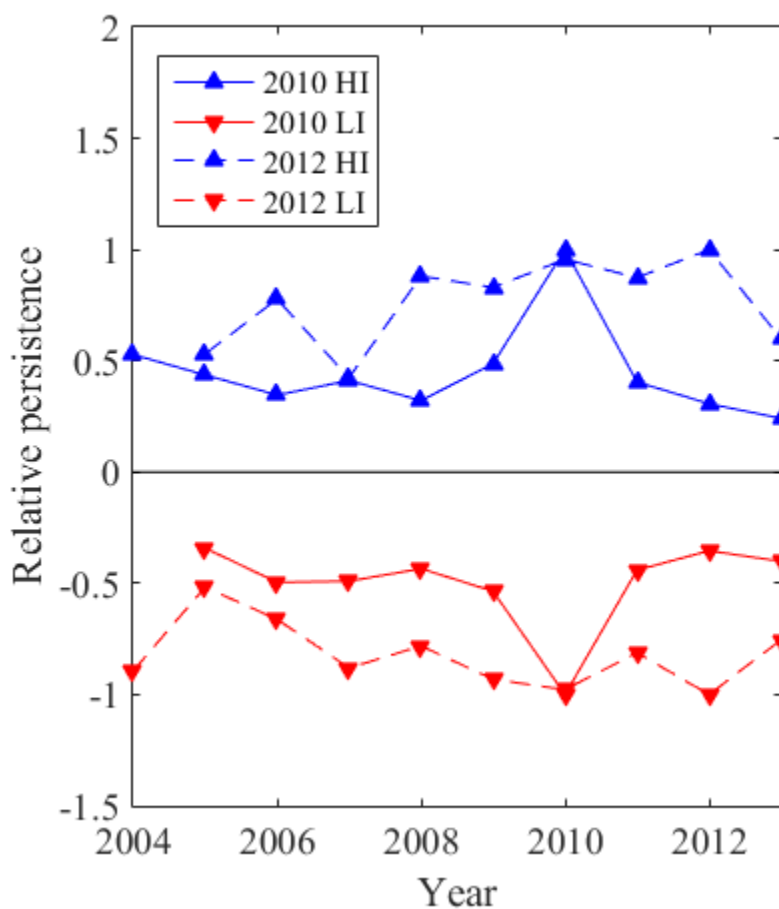
Figure 1.6 Relative persistence of producer irrigation in fields in the south-central region. Blue and red lines indicate average irrigation for fields that were classified as high irrigation (HI) and low irrigation (LI), respectively, according to the producer field irrigation distribution in 2010 (solid lines) and 2012 (dashed lines). See Section 2.3 for details on calculation of relative persistence.

4. Discussion

This is the first study to analyze variation of 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 as performed by previous studies. For example, our study shows 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 (Appendix explores potential impact of irrigation on groundwater dynamics).

Weather, crop type, and soil properties influenced producer field irrigation; however, these factors only accounted for *ca.* 50% of observed field-to-field variation in producer irrigation. We hypothesize here that most of the remaining variation is attributable to producer behavior, specifically, skill and risk perception associated with irrigation water use. 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 increases with decreasing magnitude of crop 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.

The neighbor effect illustrated in the present study is consistent with data from the 2013 USDA Farm and Ranch Irrigation Survey, which reports that 3% of reporting producers in Nebraska begin irrigating when their neighbors do so (USDA, 2014). The tendency of producers to rely on their neighbor to make irrigation decisions opens a new dimension for extension education to develop methods to remove uncertainty that

producers have associated with irrigation decisions, specifically, in relation to irrigation occurring early and late in the crop growing season. For example, extension educations directed towards helping producers recognize key crop developmental stages can help improve synchronization between irrigation decisions in relation to crop water requirements (Torrion et al., 2014). This study also found a high degree of persistence in irrigation amounts over time, which indicates 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 other factors that may influence irrigation decisions in a given year but not in others (Table 1.3). The implication is that there is substantial opportunity for improving irrigation water use (*i.e.* increasing grain produced per unit of irrigation water) if these factors are identified and research and extension can then focus efforts on correcting these management practices in a cost-effective way and properly informing policy and incentives.

Table 1.3 Conceptual framework categorizing explanatory factors for variation in irrigation in producer fields into persistent/non persistent and manageable/non-manageable.

Factor	Persistent	Non-persistent	Manageable	Non-manageable
Soil & topography	X			X
Crop type		X	X	
Tillage*		X	X	
Weather		X		X
Risk aversion	X		X	
Irrigation scheduling method*	X		X	
Irrigation system type	X		X	
Fuel & grain price*		X		X

*Possible factor influencing irrigation but not included in the present study

Field-to-field variation in irrigation, within the same region-year, typically exhibits CVs > 20%. The degree of variation for irrigation reported here is much higher than the reported variation for other agricultural inputs such as nitrogen (N) fertilizer (CV=17%; Grassini et al., 2011a) 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. Since irrigated yields typically exhibit small year-to-year and field-to-field variation (Grassini et al., 2011a), producer yield goals and N fertilizer rates also vary little among fields. 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. While the 'real-time' nature of irrigation water use gives producers more flexibility to adjust irrigation input in relation to crop water requirements, it also exposes bigger differences in skills and risk aversion attitudes among producers, which, ultimately, results in a high degree of variation in irrigation amounts, even for the same weather, soil, and crop type.

Examination of field irrigation distribution indicated that there is an important portion of producers (*ca.* 10-20%) that apply very large irrigation amounts in relation to the rest of producer 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 source of irrigation surplus can be corrected by improving producer irrigation water use skills. On the other hand, these fields might be managed by producers with very high risk-aversion attitude, who may be more resistant to adopt 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, can help answer these kinds of questions as well as prioritize research and extension activities and inform policy and incentive programs that focus on the food-water nexus.

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Chapter 2

Developing a framework to benchmark irrigation water use for crop production

Abstract

Irrigation is the major use of global freshwater resources and in many areas of the world, irrigation withdrawal is greater than recharge, threatening long-term sustainability of groundwater resources. Efficient use of freshwater resources is necessary to balance food production and use of water resources; however, no framework exists to benchmark on-farm irrigation water use relative to crop yield. This study presents a framework to benchmark irrigation water use. We provide proof of concept on the utility of this framework with a case of study based on an extensive database of *ca.* 1000 maize and soybean fields in Nebraska, USA, including 3 years of contrasting weather conditions. The database includes producer field irrigation, yield, and management and associated field-specific weather and soil properties. "State-of-the-art" crop models and irrigation decision making tools were used to estimate yield potential and irrigation water requirements for each field-year observation and these estimates were compared against producer-reported yield and irrigation. Field irrigation was upscaled to regional scale to estimate potential irrigation water savings for a scenario in which actual irrigation matches estimated irrigation crop water requirements in all producer fields. A majority of all fields (82%) achieved yields close to yield potential (70% or greater). However *ca.* 75% of maize fields and *ca.* 40% of soybean fields received irrigation amounts well above the simulated irrigation requirements, indicating room for improvement in irrigation water use. Magnitude of this irrigation surplus (actual irrigation – simulated

irrigation requirements) increased with decreasing soil water holding capacity. Irrigation scheduling method had a substantial impact on the magnitude of irrigation surplus: producer fields where irrigation was scheduled based on soil water sensors or irrigation decision tools received, on average, 95 mm less irrigation than fields where irrigation decisions were not properly informed, with no yield difference between the two groups of fields. Upscaling of potential water saving derived from eliminating current irrigation surplus indicated that 50% of current irrigation volume could be reduced in years with above- or near-average rainfall, but only 10% in extreme drought years. The framework developed in this study can be used to benchmark irrigation water use for crop production at different spatial levels (field, region, state), help prioritize extension and research activities, and inform policy and incentive programs.

Keywords: irrigation; water use; soybean; maize; on-farm data; yield

1. Introduction

Irrigated agriculture accounts for 40% of global food crop production, even when it only occupies 20% of global cropland area (Molden, 2007). Water resources will become more limited in the future due to effects of climate change and competition for freshwater resources for residential and industrial uses, threatening the sustainability of irrigated cropping systems (Kumar, 2012; Scanlon et al., 2012). The multitude of studies that have looked at irrigation water use for crop production can be roughly be classified into two categories: (i) experiments examining the yield response to different levels of irrigation water inputs, across different irrigation schedules, fertilizer application, etc. (*e.g.*, Kang et al., 2000; Zwart and Bastiaanssen, 2004) and (ii) studies aimed at

estimating irrigation crop water requirements at regional and global levels following top-down approaches (*e.g.* de Rosnay et al., 2003; Döll and Siebert, 2002; Sharma and Irmak, 2012b) However, none of these previous studies have attempted to determine the how effectively irrigation water is utilized to produce yield in producer fields. Indeed, to date, no conceptual framework exists to benchmark on-farm irrigation water use for crop production, which could potentially help diagnose current crop and irrigation water use of irrigation and identify opportunities for improving irrigation water use at field, watershed, and regional levels.

Benchmarking is defined as the act of measuring performance relative to an expected or target response. It is an established method to evaluate output-input response and track progress in many disciplines (Malano et al., 2004). It also provides a gauge of current behavior and the means to track long-term changes in behavior, as well as effectiveness of new technology or management practices. Within the realm of agricultural production, benchmarking and the use of efficiency frontiers are commonly used to assess efficient management of inputs. For example, Hochman et al. (2014) presented a framework to benchmark the efficiency of numerous cropping systems in Australia in which relative output (yield) was analyzed in relation to the relative input (nitrogen fertilizer) to create an input-yield production frontier. The concept of benchmarking has also been applied to determine the attainable yield given a certain level of water supply and diagnose current yields in relation to attainable water-limited productivity. For example, Grassini et al. (2011b, 2015) applied boundary functions to the relationship between yield and seasonal water supply to determine yield gaps of maize and soybean fields in the western U.S. Corn Belt. Stemming from a lack of data,

the cause and extent of irrigation surplus have not been accurately quantified and no basis exists to identify means to improve irrigation water use based on actual on-farm irrigation. A flexible framework, applicable for any crop, management, and location, is needed to benchmark irrigation water use. And, no less importantly, a robust spatial framework is needed to upscale results at field level to larger spatial scales such as district, watershed, state, and country.

The objective of this study is to develop a framework to benchmark irrigation water use for crop production. Subsequently, proof-of-concept is provided by diagnosing and identifying opportunities for improvement in irrigation water use in irrigated producer fields in Nebraska, a region that accounts for 2.1 Mha and 0.84 Mha of maize and soybean production under irrigation, respectively (USDA-NASS, 2014). Finally, results from the case study are upscaled from field to region and state following a bottom up approach to determine the potential for irrigation water savings without reduction in crop production. Having previously explored factors impacting irrigation in previous work (Chapter 1), the framework to benchmark irrigation water use here was created with the knowledge that specific field-level factors must be accounted for with regard to their impact on irrigation requirements for a particular field-year. While benchmarking irrigation water use for crop production can be a multifaceted analyses related to business, financial, and environmental management, the study presented here focused on biophysical aspects of crop irrigation and its broad implications for water use at different spatial scales.

2. Methods

The conceptual benchmarking framework presented here is intended to be generic and robust such that it can be applied to any cropping system given availability of required data. Data inputs are publically available field-scale agricultural data, the source of which could be surveyed producer data or data collected from local and governmental agencies. The framework utilizes validated crop simulation models to benchmark each field relative to its field-specific potential yield and irrigation requirements, defined here as crop water demand to achieve potential yield. To accomplish this, the framework utilizes validated crop simulation models. Specific input parameters for modeling yield potential and irrigation requirements may vary depending on the model being implemented, however, yield data and field-scale irrigation data are essential to this framework's process. Previous analysis of the extent and sources of variation in irrigation (Chapter 1) illustrated the influence of crop type, weather and soil on irrigation. Based on these previous findings, the framework as presented here would ideally utilize crop models which could account for the management and biophysical variables found to impact irrigation, most importantly field-specific soil texture (correlated to available water holding capacity, AWHC) and weather (precipitation, grass-referenced evapotranspiration, ET_o) (Chapter 1). Major assumptions of the benchmarking framework include: field-scale data are quality-controlled and consist of a sufficient number for fields for robust statistical analyses, and crop model simulation results have been validated with on-farm data or field experiments.

Relative yield (RY) and relative in-season water supply (RWS) are used to evaluate irrigation water use. Relative values are used so that fields across different

regions and years can be compared fairly, on the basis of how closely each field's yield and irrigation usage are in relation to its field-specific potential yield and irrigation requirements. RY in this framework is calculated as follows:

$$RY = \frac{Y_A}{Y_P} \qquad \text{(Eq. 3)}$$

where RY is relative yield, Y_A is actual, producer reported yield, and Y_P is field-specific simulated potential yield. Therefore, a RY of 1.0 indicates that actual yield is equal to the simulated yield potential based on field-year specific weather, soil, and management.

Because field locations may correspond with a wide range of precipitation zones, relative irrigation values (*i.e.* ratio of producer-reported applied irrigation *versus* simulated irrigation requirement) in this framework cannot be compared without skewing results in favor of those fields that received comparatively less seasonal rainfall. For example, hypothetical *Field A* received 100 mm of irrigation, was estimated to require 50 mm, and received 400 mm of seasonal rainfall. Hypothetical *Field B*, on the other hand, received 350 mm of irrigation, had an estimated requirement of 300 mm, and received 100 mm of seasonal rainfall. Both fields received 50 mm more irrigation than required but relative irrigation would be 2.0 for *Field A* and 1.2 for *Field B*. Hence, for this framework, relative seasonal water supply is calculated for each field as follows:

$$RWS = \frac{I_A + P_S}{I_R + P_S} \qquad \text{(Eq. 4)}$$

where RWS is relative in-season water supply, I_A is actual, producer total irrigation, P_S is total precipitation between sowing and physiological maturity, and I_R is field-specific

simulated irrigation requirement. A RWS of 1.0 indicates the point at which irrigation

applied is equal to simulated irrigation requirement. The difference between in-season

water supply (actual minus simulated) is equivalent to irrigation surplus because in-

season rainfall is identical in both terms. Initial soil moisture was not included in Eq. 4 as

it is accounted for in crop model simulations and is typically near field capacity in most

region-years.

A boundary function for the relationship between RY and RWS was fit to the

data, separately by crop type. The boundary function in this framework represents an

efficiency frontier to delineate the maximum RY for a given RWS. The breakpoint of the

model indicates the relative water supply at which yield potential was not responsive to

further increase in water availability (Fig. 2.1).

For the purpose of diagnosing irrigation surplus and identifying areas for future

improvement, fields were grouped into four categories (A, B, C, D) based on their RY

and RWS (Fig. 2.1). Category A corresponded to fields with RWS above the breakpoint

and below 1.05, and RY above *y*, with *y* representing average regional yield gap (i.e.,

actual water supply close to the simulated in-season water supply and small yield gap).

Category B fields had the same range of RWS as category A but RYs below *y* (*i.e.*

similar actual and simulated water supply but large gap). Fields with RWS above 1.05

were denoted as category C or category D fields (*i.e.*, field with an apparent irrigation

surplus), where category C had RY above *y* and D, below *y*. The threshold of 1.05 for

RWS was chosen for this framework instead of 1.0 (*i.e.* the point at which irrigation

applied was equal to simulated irrigation requirement) to allow a margin of one

additional irrigation event (*ca.* 25 mm) before a field would be classified as having irrigation surplus.
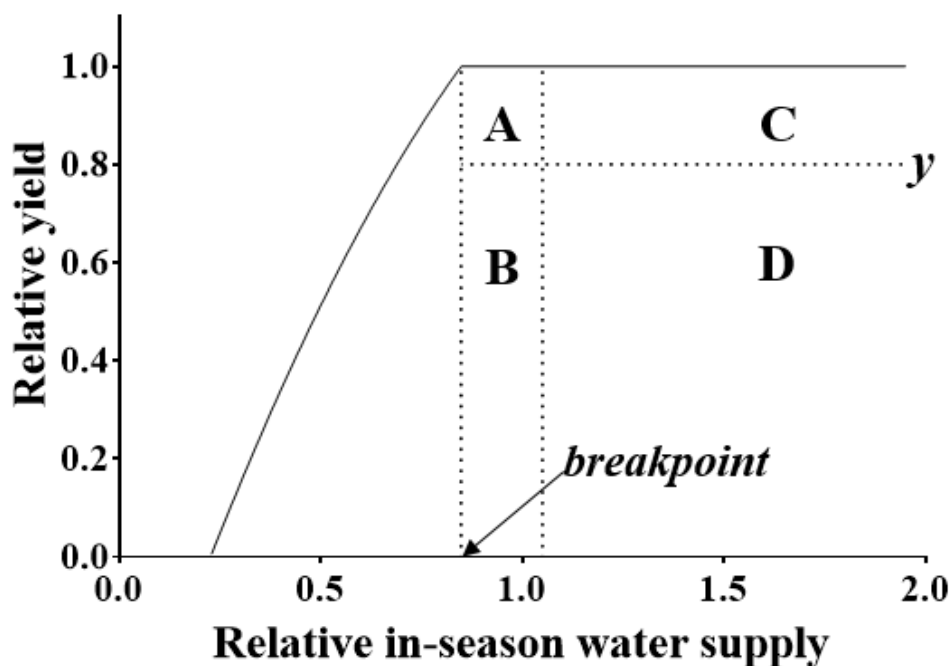
Figure 2.1 Conceptual diagram showing four management categories: A) near-optimal water supply, near potential yield; B) near-optimal water supply, below potential yield; C) surplus water supply, near potential yield; and D) surplus water supply, below potential yield. Regional yield gap represented by *y*.

2.1 Description of study area and data sources

In the US, Nebraska ranks 3rd and 5th nationally amongst maize and soybean producing states, respectively (USDA-NASS, 2015). Both crops are largely irrigated in Nebraska, with 59% of maize and 49% of soybean land area irrigated. Between the 1960s and 2010s, irrigated maize and soybean areas in Nebraska increased by 3x and *ca.* 350x respectively, with the total irrigated area for both crops summing up to 3.0 Mha (Fig. 2.2). Given the importance of irrigated agriculture, combined with availability of

producer field data and weather and soil databases, Nebraska is prime testing ground for

applying this novel framework to benchmark irrigation usage.
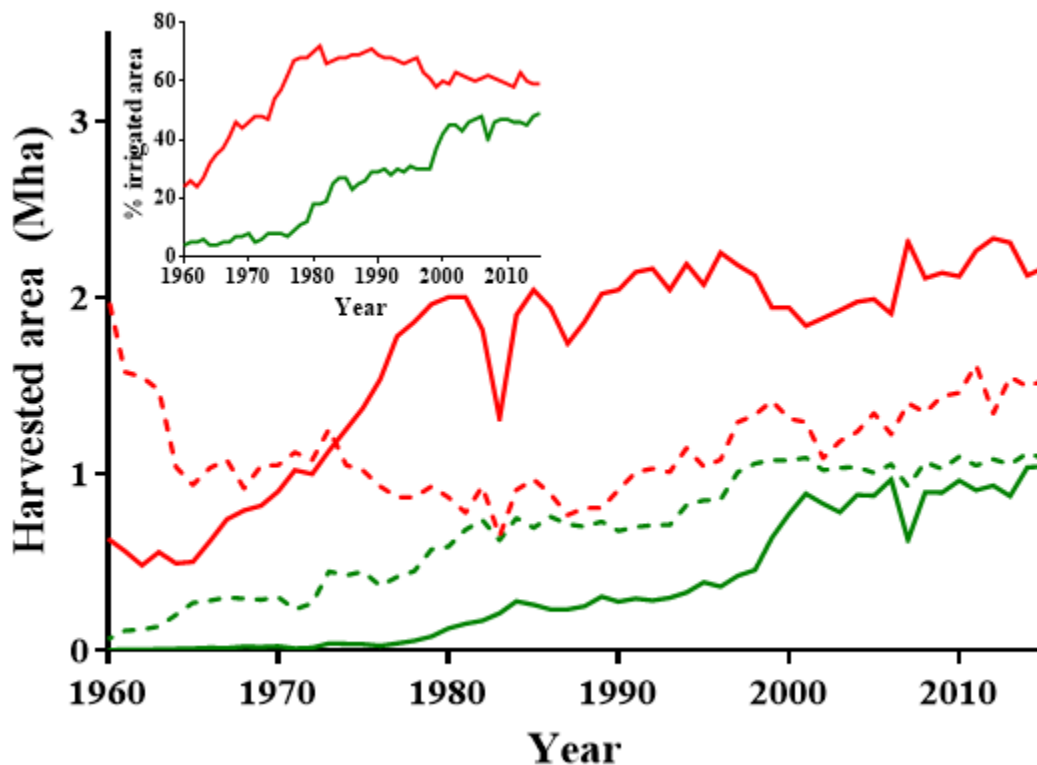
Figure 2.2 Trends in irrigated (solid lines) and rainfed (dashed lines) maize (red) and soybean (green) harvested area in Nebraska from 1960 to 2015. Inset: irrigated area as a percent of total harvested area for maize (red) and soybean (green). Source: USDA-NASS, 2015.

An original database containing yield, applied inputs, and management

information from 534 irrigated maize (n=241) and soybean (n=293) fields collected over

three years (2010-2012) was utilized to benchmark irrigation water use in Nebraska.

Locations of fields ranged from northeast Nebraska ("region 1") to east ("region 2"),

southeast ("region 3"), and south-central Nebraska ("region 4") (Fig. 2.3).

Data provided by producers included: crop type, crop yield, total irrigation

(metered or producer-estimated), fertilizer and pesticide inputs, crop management

(sowing date, seeding rate, irrigation system, irrigation scheduling method, tillage, seed variety and maturity group), and incidence of biotic and abiotic yield-reducing factors such as hail, frost, flooding, etc. Quality control was performed to remove fields containing suspicious (*e.g.*, irrigation values exceeding system capacity over the growing season, unusual cultivar maturities or sowing dates, etc.) or missing data, resulting in 534 fields for analysis. While the database included both surface- and pivot-irrigated fields, only pivot-irrigated fields were analyzed in this study because surface irrigated fields account for a small percentage of irrigated area statewide ($< 15\%$) and this area continues to decline over time as surface irrigation systems are converted to more efficient pivot systems (USDA, 2014).
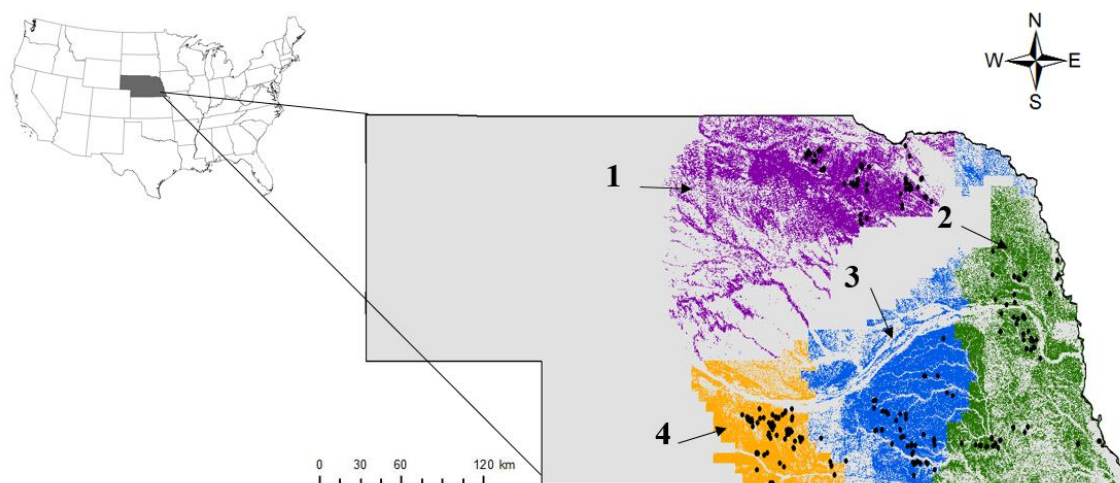
Figure 2.3 Map indicating surveyed field locations (black points) in Nebraska. Regions overlapping surveyed field areas are shown as: region 1 (purple), region 2 (green), region 3 (blue), and region 4 (yellow). Inset shows Nebraska's location within the conterminous U.S.

The study encompassed three years with contrasting weather conditions: 2010 (above-average precipitation and below-average evapotranspiration), 2011 (near-average precipitation and evapotranspiration), and 2012 (below-average precipitation and above-

average evapotranspiration) (Fig. 2.4). Actual irrigation data exhibited significant

variation among regions, crops, and years ($p<0.01$) (Fig. 2.5). Across regions-crops,

variation in irrigation ranged from 13% to 69% (CV), with mean irrigation ranging from

118 to 329 mm. Within the same region, average maize irrigation was significantly

higher than soybean for all regions ($p<0.01$), corroborating data presented in Chapter 1.
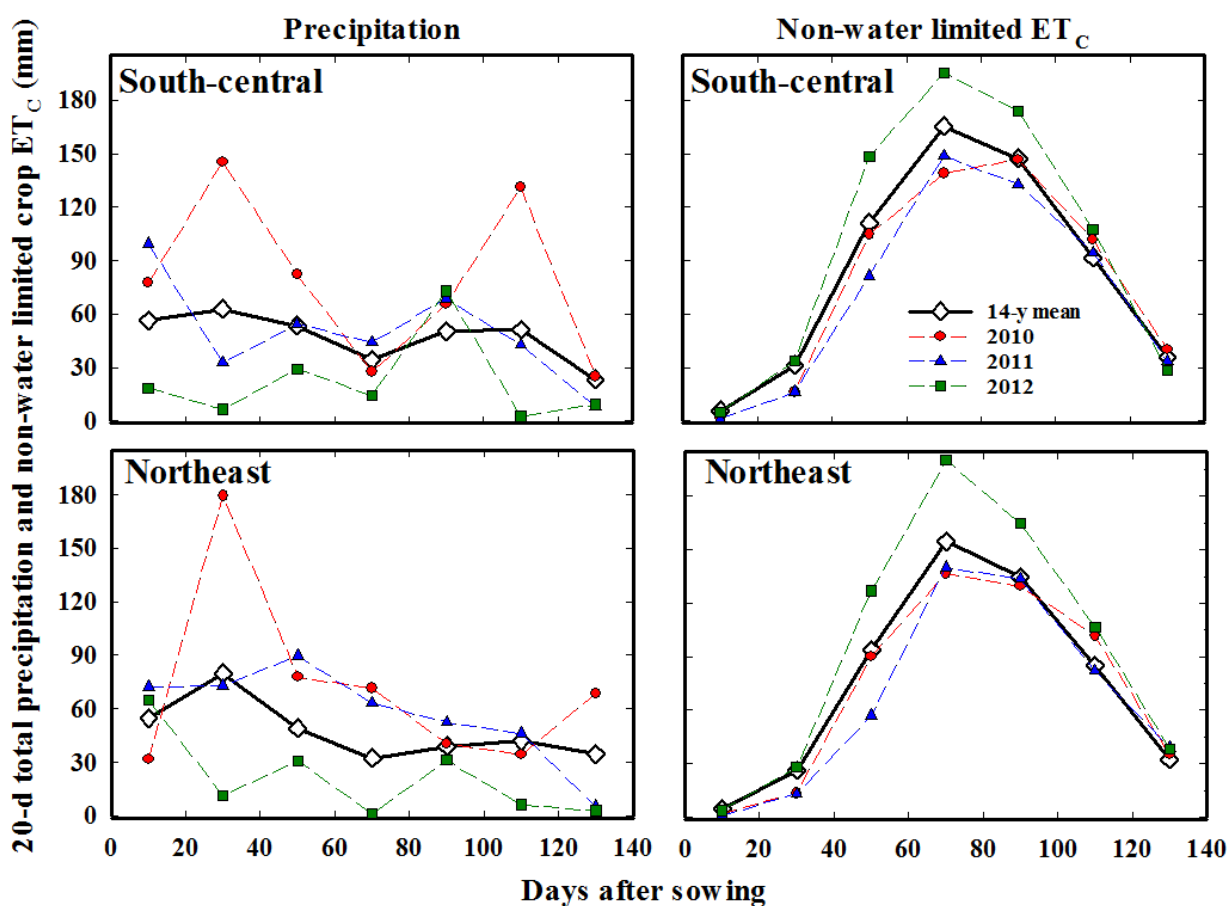
Figure 2.4 Precipitation and non-water limited crop evapotranspiration (ET$_c$) shown as 20-day cumulative totals, from day of sowing until 130 days after sowing, for 2010 (red), 2011 (blue), and 2012 (green), for two locations: Holdrege, NE (south-central region) O'Neill, NE (north-central region). Black line represents long-term (1999-2012) means. SoySim model was used to simulate non-water limited ET$_c$ using regional-average sowing date and maturity group.
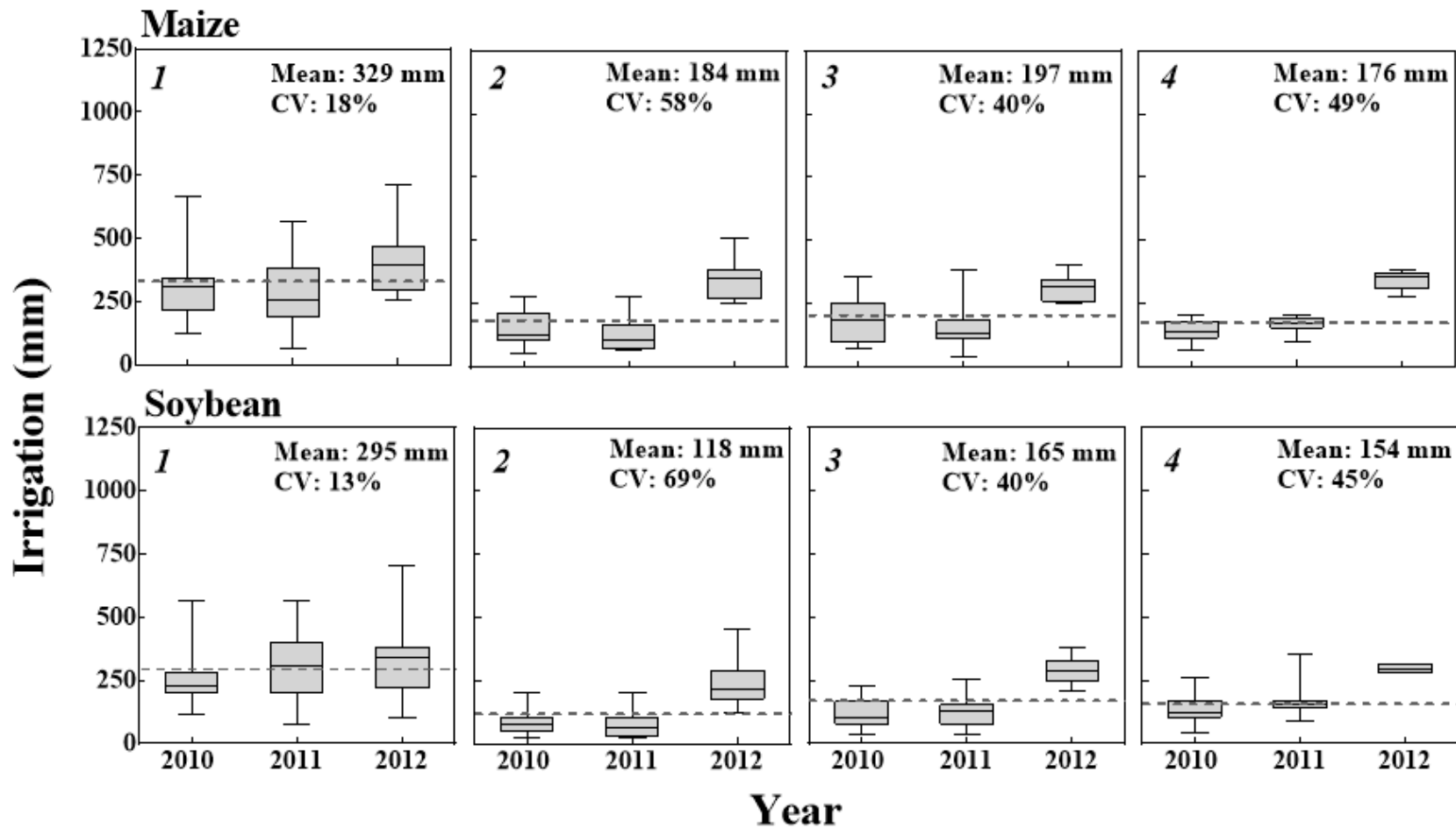
Figure 2.5 Annual irrigation from 2010-2012 for pivot-irrigated maize and soybean fields in regions 1-4. Mean irrigation for the 3 years and year-to-year coefficient of variation are displayed for each region and crop. Upper and lower boundaries of boxes indicate 75th and 25th percentile, respectively. Horizontal line within boxes is the median value. Whiskers (error bars) are maximum and minimum values.

2.2 Estimation of field-scale irrigation requirements and yield potential

Three separate crop models were used to estimate yield potential and irrigation water requirements: Hybrid-Maize (Yang et al., 2013, 2004), SoySim (Setiyono et al., 2010), and SoyWater (http://hprcc-agron0.unl.edu/soywater/). Previous studies have evaluated these models relative to their ability to reproduce yield and water requirements (Grassini et al., 2009; Setiyono et al., 2010; and Torrion et al., 2011. Both Hybrid-Maize and SoySim models simulate crop yield potential, assuming no limitations by nutrient and water supply and no incidence of weeds, insect pests, and pathogens.

Irrigation requirements estimated using Hybrid-Maize and SoyWater reflect the best possible irrigation schedule to avoid crop water stress and minimize total irrigation amount. Soil water dynamics are simulated in Hybrid-Maize and SoyWater using a "tipping bucket mechanism" in which water in excess of AWHC is assumed to be lost by percolation to the soil layer below the crop rooting profile. Both models simulate soil water balance based on estimated crop water requirement, precipitation, and AWHC in the prior day, accounting for losses from soil evaporation and crop transpiration. In SoyWater, irrigation is triggered when soil water content ≤ 65% AWHC while in Hybrid-Maize model, irrigation is triggered when crop water uptake does not meet potential crop evapotranspiration. Results were almost identical when the two approaches to trigger irrigation were used separately for estimating irrigation water requirements (<2% difference). As this study uses model estimations, it is important to recognize that there are uncertainties associated with model simulations stemming from errors in parameters and spatial variability of soil and weather, however, the validated models used in this

study represent the most robust means to estimate irrigation water requirements and potential yield for the given data.

Yield potential and irrigation requirement were simulated for each field-year case using field-specific input variables, including daily weather data (precipitation, maximum and minimum temperature, solar radiation, wind speed, relative humidity, reference evapotranspiration [ET_o]), crop management (sowing date, cultivar maturity, and plant density) and soil and terrain properties (soil depth, texture, bulk density, soil surface residue cover, and field slope). Field-scale estimates of precipitation and reference evapotranspiration (ET_o), as well as additional daily weather variables including maximum and minimum temperature, solar radiation, wind speed, and relative humidity, were interpolated for each field using inverse distance weighting of daily weather data from the three nearest weather stations (Yang and Torrion, 2014; Franke and Nielson, 1980). Soil water content was set at 50% of soil AWHC at the at the start of the fallow period, which occurred approximately 8 months before sowing and right after harvest of prior crop. Following this approach, the models simulated soil water recharge during the non-growing season. Rooting depth was set at 1.5 m for all fields, except for some fields in the region where soil texture was sandy (sand content>90%) below 1.2 m depth, for which soil depth used for the simulations of yield potential and irrigation requirements was 1.2 m. Percentage of soil residue cover was estimated for each field based on reported tillage practice following Shelton et. al 2005.

2.3 Efficiency frontier to benchmark irrigation water use in maize and soybean irrigated fields in Nebraska

Following calculation of RY and RWS, a small number of fields (7%) with RY>1.0 were constrained such that RY = 1.0. Causes for fields with RY>1.0 include incorrect yield reporting by producers, model error, or incorrect inputs of specific model parameters. Actual yields for maize fields ranged from 3.1-17.6 Mg ha^{-1}, averaging 13.2 Mg ha^{-1}, while soybean field actual yields ranged from 1.3-5.7 Mg ha^{-1}, with average yield of 4.3 Mg ha^{-1}. Actual irrigation ranged from 0-711 mm with average of 223 mm for maize fields, and 0-706 mm with average irrigation of 187 mm for soybean fields. A quadratic-plateau model was used to derive a boundary function for the relationship between RY and RWS, for maize and soybean, separately. It was determined that additional data points were necessary to properly fit the boundary function to the maize data; hence, 28 fields were chosen (seven per region of the study area: regions 1-4), representing a range of management variables, soil types, and precipitation regimes. For each field, 10 different deficit irrigation regimes (0 to 75% of full irrigation requirements at 5 % increments) were simulated to estimate irrigation and corresponding yield potentials. Simulation of deficit irrigation regimes was conducted by first simulating full irrigation for each of the 28 fields given field-specific weather, management, and soil, and reducing the irrigation amounts progressively for each simulated treatment. Resulting 280 simulated irrigation-yield observations were combined with the 534 actual observations and a boundary function was fitted for the pooled data. Quadratic-plateau was used as it provided the best fit for the maize subset data (r^2 =0.99) and soybean data (r^2=0.98). The simulated observations were not used for any subsequent analysis.

2.4 Analysis and diagnosis of irrigation water use and irrigation surplus

A threshold of 0.80 for RY was used in this proof of concept of the benchmarking framework to distinguish between fields with large and small yield gaps (*i.e.*, difference between potential and actual yield) based on the average yield gap reported for irrigated maize and soybean in the U.S. Corn Belt (Grassini et al., 2011b, 2015). For the purpose of analysis, fields that exhibited RWS <0.75 were excluded because potential yield was no longer obtainable below this water supply. For maize fields, RWS at the breakpoint was 0.85 while breakpoint for soybean fields was 0.78 for maize and soybean, respectively. These breakpoints represent the RWS at which yield potential does not respond to further increase in water supply and were utilized to create the low RWS boundary for field categories A and B. As noted in section 2.1, upper range of RWS for categories A and B (also the lowest RWS for categories C and D) was established as 1.05 to allow a margin of one additional irrigation event relative to irrigation requirements. Explanatory factors that can reveal differences in irrigation surplus among fields were investigated by comparing management and soil properties between categories A and B *versus* C and D (*i.e.*, fields with surplus water supply *versus* those with near-optimal water supply). Analysis of explanatory factors for gaps between actual and potential yield was beyond the scope of the study and this kind of analysis has been reported by previous studies (Grassini et al., 2011b, 2015). For our analysis of factors explaining field-to-field variation in magnitude of irrigation surplus, fields with extremely low yields or irrigation amounts due to un-manageable factors such as flooding, hail, or frost were excluded. Two-tail Student's t-tests were used to evaluate differences in means between categories AB and CD for factors including relative maturity, AWHC, plant density, sowing date,

nitrogen fertilizer rate, etc. Wilcoxon test was used when distributions deviated from normality ($p<0.05$, Kolmogorov–Smirnov test). Tukey comparison test was utilized to determine significant differences between categories being compared (*e.g.* between AWHC groups).

Soil properties, including available water holding capacity (AWHC) and topographic wetness index (TWI) were also included in this analysis. TWI was derived for each field using SAGA software (Conrad et al., 2015; Olaya and Conrad, 2009). Topographic wetness index 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). Soil available water capacity (AWHC) for the upper 1 m of soil was derived for each field from the Soil Survey Geographic database (SSURGO, http://websoilsurvey.nrcs.usda.gov). Chi-square (χ^2) tests were used to detect differences between fields in CD *versus* AB for categorical variables such as frequency of irrigation scheduling method, tillage, prior rotation, etc. For this analysis, irrigation scheduling methods were grouped into three irrigation scheduling categories: (A) soil water sensors or computer software (22% of fields), (B) examination of soil samples ("feel the soil", 64% of fields), and (C) visual inspection of the crop, fixed schedule, or follow neighbor's schedule (14% of fields). These three irrigation scheduling methods range from high-level technological approaches (A) to very little technology (C). Irrigation surplus (defined as the difference between actual irrigation and irrigation requirement) was compared between the three scheduling methods. Tillage practice was likewise grouped into three categories: (A) no-till fields

(56% of fields), (B) reduced-till (*i.e.* ridge and strip till) fields (17% of fields), and (C) disk-till (27% of fields).

2.5 Upscaling potential water savings from field to region

Following the analysis of irrigation water use, this study sought to determine what potential irrigation water savings would be on a regional scale if every field in the study with a RWS > 1.05 had instead been irrigated to avoid irrigation surplus, that is, a RWS of 1.0. A spatial framework was needed to upscale field-level data findings to the regional level. For this purpose, Technology Extrapolation Domains (TEDs) were utilized (Rattalino-Edreira et al., in preparation). A TED is defined as a spatial unit within which soil and climate can be assumed to be relatively homogenous. A TED consists of a specific combination of annual growing degree days, aridity index, temperature, and seasonal and total available water holding capacity within the rootable soil depth. Four TEDs, numbered regions 1-4, covered most of the area where the fields were located (Fig. 2.3). These four TEDs accounted for 43% and 52% of irrigated maize and soybean area in Nebraska, respectively (USDA-NASS 2014).

Actual annual volume of irrigation applied within each region-crop-year combination (m^3 yr^{-1}) was calculated as follows:

$$V_{Aijk} = I_{Aijk} \times A_{ij}$$ (Eq. 5)

where V V_{Aijk} was actual volume of irrigated water applied for a given crop (*i*) region (*j*), and year (*k*), I_{Aijk} was the average producer irrigation for a given crop (*i*), region (*j*), and year (*k*), and A_{ij} was the harvested area covered by *i* crop in *j* region. Annual irrigation

water volume was re-calculated for each region-crop-year combination for a scenario in which all fields with relative RWS ≥ 1.05 would reduce their RWS to 1.0, reflecting adoption of best irrigation scheduling methods and technologies. The adjusted volume was calculated as follows:

$$V_{ADJijk} = I_{ADJijk} \times A_{ij}$$ (Eq. 6)

where I_{ADJijk} was the average irrigation for a scenario with RWS <1.0 across all producer fields for a given crop (i), region (j), and year (k). The difference between the two annual irrigation water volume estimates (actual *versus* scenario) represents the potential irrigation water savings for each crop-region-year case. Total water saving on annual basis were calculated by summing the estimated water savings in the four regions.

3. Results

3.1 Diagnosis of on-farm irrigation water use and surplus

The fitted boundary function for maize fields was RY= -0.51+2.4x-0.77x^2 when RWS < 0.85, and RY = 1.0 if x ≥0.85. Soybean boundary function was defined as RY= -0.91+4.3x-2.4x^2 when RWS<0.78, and RY = 1 if RWS ≥ 0.78 (Fig. 2.6). Reaching yield potential was possible for soybean fields at lower seasonal water supplies than maize (Fig. 2.6). The breakpoint below which potential yield was unattainable was 0.78 RWS for soybean fields and 0.85 RWS for maize fields. Breakpoints below a RWS of 1.0 indicated that there was potential to reduce irrigation while achieving high yield.

There was large variation in RY and RWS across fields, with RY ranging from 0.6 to 1 (maize) and 0.45 to 1 (soybean) (Fig. 2.6) and RWS ranging from 0.58 to 1.9

(maize) and 0.32 to 1.9 (soybean). Interestingly, while soybean fields generally had lower average RWS (*i.e.*, smaller irrigation surplus) relative to maize field (0.98 *versus* 1.14, $p<0.01$), average RY was lower for soybean than for maize (0.82 *versus* 0.84, $p<0.05$), indicating a larger yield gap in soybean than in maize. Indeed, the majority of maize fields (73%) fell into categories C and D (irrigation surplus), while 41% of the soybean fields exhibited irrigation surplus. In contrast, *ca.* 60% of maize fields achieved at least 80% of potential yield (categories A and C) while less than half of soybean fields fell into these categories. Remarkably, approximately a quarter of the total fields (26%) reached $RY > 0.8$ with RWS between 0.95 and 1.05 (category A), indicating that achieving yields near yield potential and irrigating without exceeding irrigation requirements are not conflicting goals in high-yield irrigated maize and soybean fields.
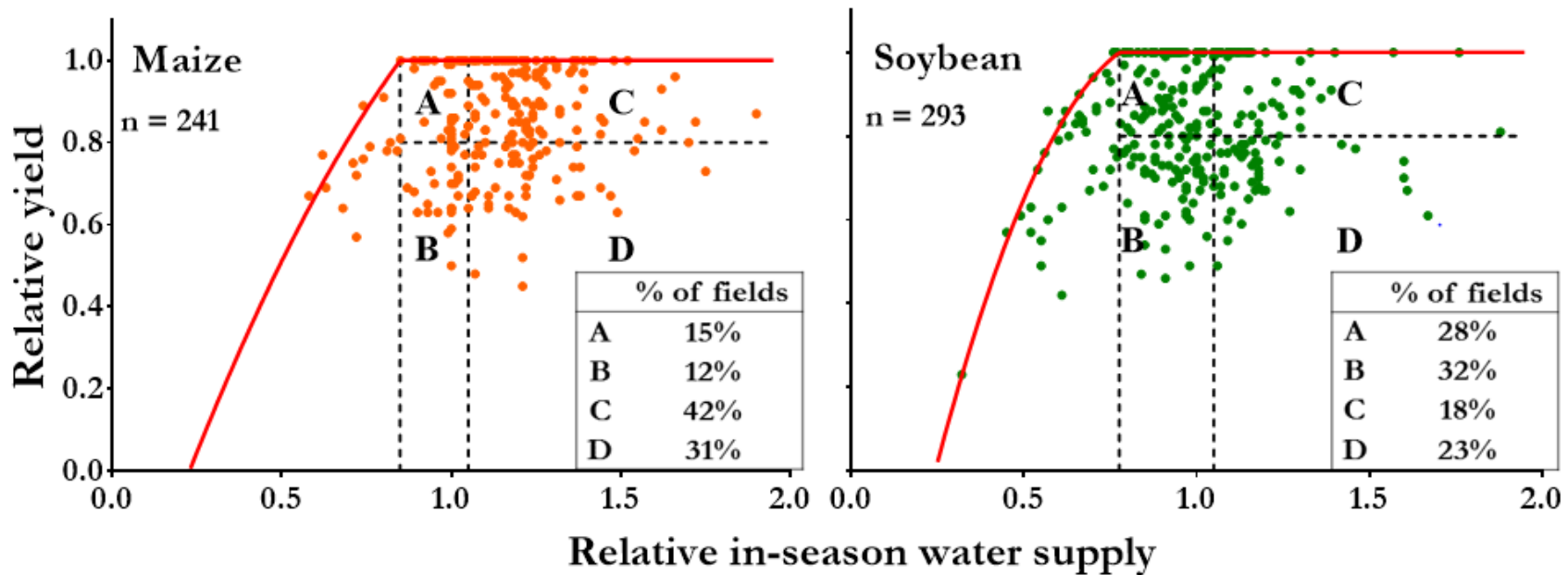
Figure 2.6 Relative yield (RY) *versus* seasonal water supply (RWS) for producer irrigated maize (left) and soybean (right) fields. Each data point represents a field-year case. Efficiency frontiers are shown in red separately for maize (RY= -0.51+2.4x-0.77x² when RWS < 0.85; RY = 1 if x ≥ 0.85) and soybean (RY= -0.91+4.3x-2.4x² if RWS<0.78; RY = 1 if RWS ≥ 0.78). A small number of fields (7%) with RY>1.0 were constrained to RY = 1.0. Causes for RY>1.0 include incorrect yield reporting by producers, model error, or incorrect inputs of specific model parameters.

3.2 Factors contributing to irrigation surplus

Variation in precipitation and ET_o across year-region influences magnitude of irrigation surplus (Fig. 2.7). About 79% and 64% of total maize and soybean fields, respectively, exhibited irrigation surplus in 2010 and 2011. In contrast, in the drought year (2012), only a small proportion of all fields (30%) exhibited irrigation surplus and, indeed, there was a large proportion of fields (68%) receiving irrigation amounts below irrigation requirements.

Magnitude of irrigation surplus was influenced by soil type, with increasing irrigation surplus as soil water holding capacity decreased ($p<0.01$, Table 2.1, Fig. 2.8). When analyzed using AWHC classes, Tukey comparison indicated significant difference in irrigation surplus between the AWHC groups ($p<0.01$) with the exception of the comparison between fields with AWHC of 50-100 mm and 100-150 mm, for which irrigation surplus was not significantly different ($p=0.21$). Remarkably, the 90th percentile increased from 569 mm, 471 mm, and 381 mm when moving from low to high AWHC field classes, while the 10th percentile exhibited smaller differences amongst AWHC classes and remained below zero (*i.e.*, irrigation below crop water requirement) (Fig. 2.8). The latter may reflect a sub-population of fields where pumping capacity could not meet field irrigation capacity irrespective of soil type and weather conditions.
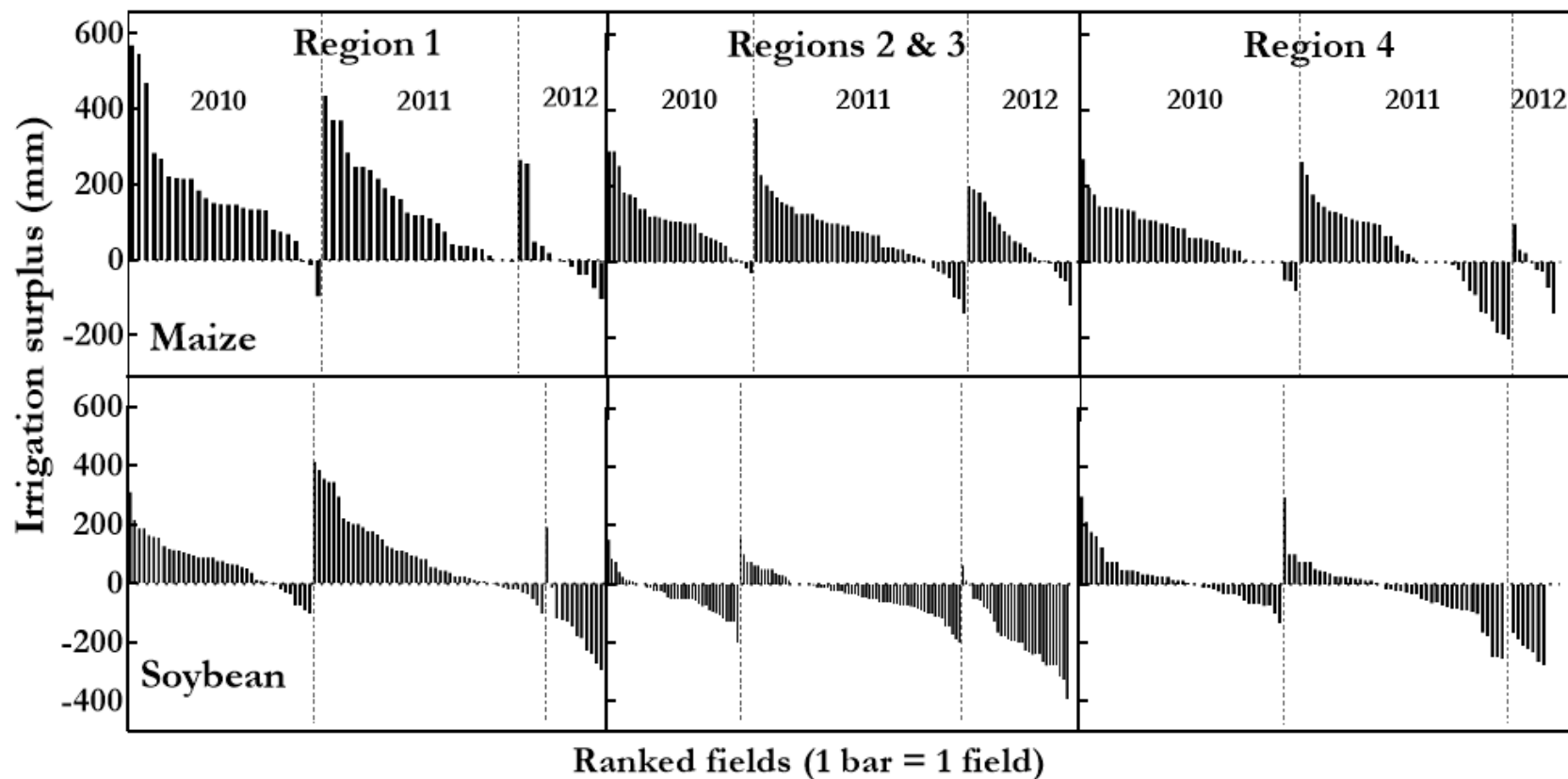
Figure 2.7 Estimated irrigation surplus across producer fields sown with maize (upper panel) and soybean (bottom panel) in each region-year. Fields were ranked from highest to lowest irrigation surplus. Regions 2 and 3 were pooled as irrigation surplus profiles were nearly identical between those regions.
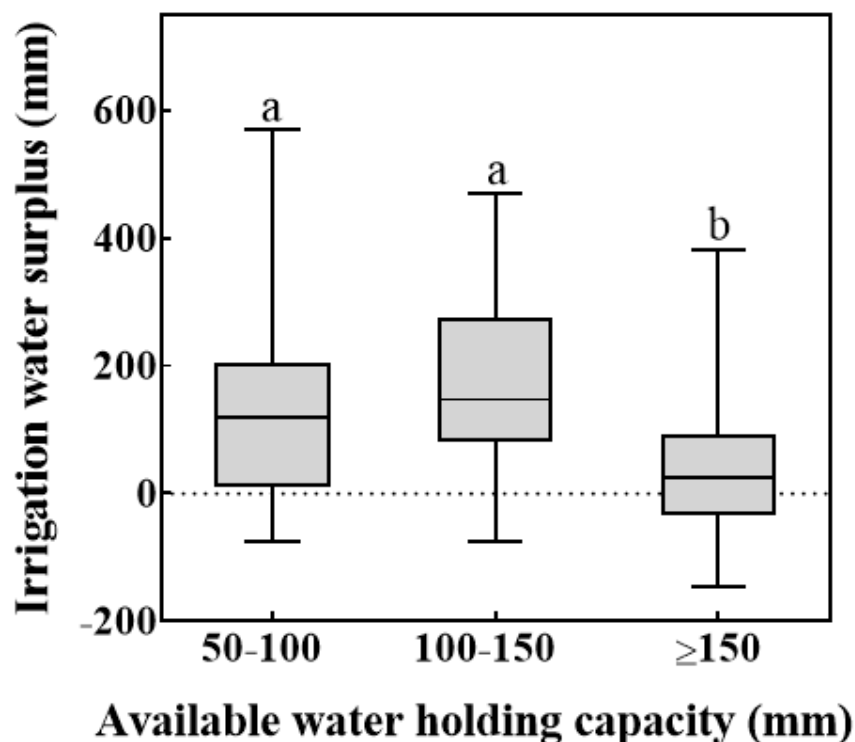
Figure 2.8 Irrigation surplus, defined as reported irrigation minus model minus determined irrigation requirement, and available water holding capacity (AWHC) in the upper 1 m of soil. Upper and lower boundaries of boxes indicate 75th and 25th percentile, respectively. There was no difference between maize and soybean distributions within AWHC classes ($p<0.01$); hence, maize and soybean data within each AWHC category were pooled. Horizontal line within boxes is the median value. Whiskers (error bars) are maximum and minimum values.

RWS was significantly different between categories C/D and A/B, with an average difference of 0.3 RWS between the two categories (Table 2.1). This shows that fields in C/D were irrigated well above irrigation requirements since a RWS of 1.05 represents one additional irrigation event above requirements and average RWS for C/D fields was 1.2 (Table 2.1). Statistical analysis indicated that AWHC and irrigation scheduling method had a significant impact on irrigation surplus. Fields in management categories C and D, *i.e.* those categories with irrigation surplus *versus* those without

surplus, had an average AWHC of 160 mm while categories without irrigation surplus (A

and B) had an average AWHC of 180 mm (Table 2.1). Irrigation scheduling method was

also found to significantly affect irrigation surplus.

Table 2.1 Analysis of factors influencing magnitude of irrigation surplus in producer
irrigated maize and soybean fields.

Factors & statistical analysis	Crop	Mean		P-Value
		Category C/D	Category A/B	
t-test				
Relative in-season water supply	Pooled	1.2	0.9	<0.01*
Sowing date (DOY)[a]	Maize	115	118	0.07
	Soybean	127	128	<0.01*
Planting date (DOY)[a]	Maize	115	118	0.07
	Soybean	127	128	<0.01*
Plant population (x1000, seeds/ha)	Maize	78	78	0.88
	Soybean	418	412	0.26
Slope (%)	Maize	2.9	2.5	0.35
	Soybean	2.8	2.8	0.99
AWHC, 0-1m (mm)[b]	Pooled	160	180	<0.01*
χ^2				
Irrigation scheduling method	Pooled			<0.01
Tillage	Pooled			<0.01
Prior crop	Maize			0.17

*Indicates p-value as a result of Wilcoxon test
[a] DOY: day of year
[b] AWHC: available water holding capacity for upper 1 m of soil

Irrigation scheduling method significantly impacted magnitude of irrigation

surplus in both maize and soybean fields ($p<0.01$) (Table 2.1, Fig. 2.9). Average

irrigation surplus in fields in irrigation scheduling category A (8 mm), where irrigation

was scheduled based on best available cost-effective technologies, was not statistically

different from zero ($p=0.21$), indicating that near-optimal synchronization of irrigation

inputs and crop water requirements is possible when irrigation decisions are guided by

tools that take into account real-time weather and soil water content. In contrast,

irrigation surplus was much higher in fields in irrigation scheduling category C (103

mm), where irrigation was scheduled based on more rudimentary methods such as crop visual inspection and fixed calendar dates ($p<0.001$). The difference in irrigation surplus between irrigation scheduling categories A and C is equivalent to four irrigation events of approximately 25 mm each. Irrigation surplus was 35% smaller in fields where irrigation was scheduled based 'soil feeling' (irrigation scheduling category B) compared to fields in irrigation scheduling category C ($p=0.04$) but still larger than irrigation surplus in irrigation scheduling category A fields. A striking finding was that yield did not differ between fields using different types of irrigation scheduling methods ($p=0.54$), with RY averaging 0.86 across irrigation scheduling method classes (Fig. 2.9). The fact that only 22% of the total fields fall within irrigation scheduling category A highlights the large room that is available for saving irrigation water, without hurting current crop yields.
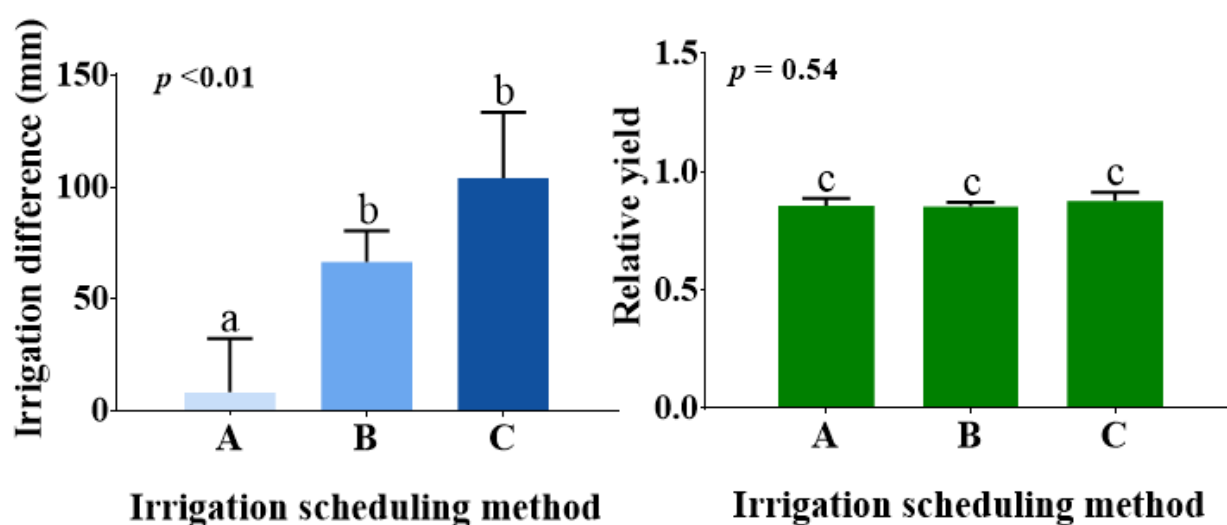
Figure 2.9 Average irrigation surplus (left) and relative yield (right) for irrigated maize and soybean fields (n=339) where irrigation is scheduled based on different irrigation scheduling methods: (A) computer software or soil water sensors, (B) soil sample probe, and (C) crop visual inspection, fixed schedule, neighbor, etc. Values inside bars indicate percentage of total fields falling in each scheduling method category. There was no difference between maize and soybean distributions within irrigation scheduling method ($p<0.01$); thus, maize and soybean data within each scheduling method category were pooled.

3.3 Potential regional irrigation water savings

If irrigation in maize and soybean fields exhibiting irrigation surplus supply (*i.e.*, categories C and D in Fig. 2.6) would have been optimally managed such that actual irrigation matched simulated irrigation water requirements, 50% of the irrigation volume applied in 2010 and 2011 could have been saved. These water savings are equivalent to 515 and 516 million m^3 in 2010 and 2011, respectively, for the area contained within the four regions (Fig. 2.10). In contrast, in the drought year (2012), only 10% of irrigation water would have been saved (equivalent to 290 million m^3 across the four regions). Hence, irrigation water savings are likely to be greater in years with above- or near-average precipitation. While reduction of yield gap would result in increased irrigation to reach potential yield in fields currently with deficit irrigation, the additional volume of water from those few fields would be negligible in comparison with the volume of irrigation water saved by reduction irrigation in fields with irrigation surplus. Fields in southeast Nebraska (region 3) accounted for the largest percentage of irrigation water savings in all years (*ca.* 50%) because, although field-scale irrigation surplus is not the largest in this region (Fig. 2.10), it accounts for the largest portion of irrigated cropland area amongst the four regions. In contrast, while irrigation surplus is the largest in region 1, this region accounts for a relatively smaller fraction of cropland area, accounting for *ca.* 25% of estimated regional water irrigation savings. To summarize, there is substantial room for saving irrigation water in years with precipitation near or above average without negative impact on crop yields.
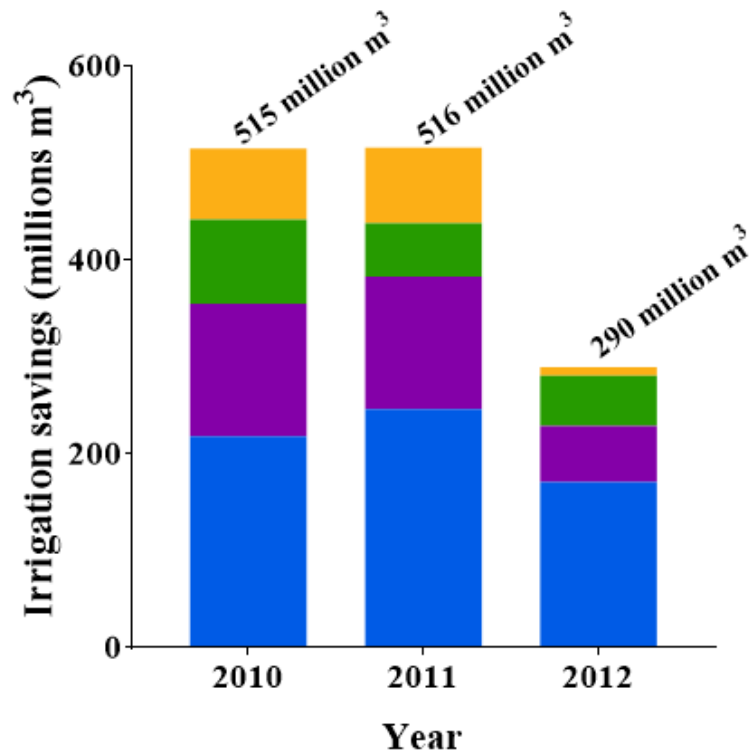
Figure 2.10 Potential irrigation water saving in each year (2010, 2011, and 2012) in regions 1 (purple), 2 (green), 3 (blue), and 4 (yellow). Total volume of potential water saving, calculated as the sum across the four regions in the same year, is indicated above each bar.

4. Discussion

This study presented a novel framework to diagnose on-farm irrigation water use, identify opportunities for improvement, and assess potential water saving and crop production increases for different scenarios. Although Nebraska was used as a proof of concept, the framework is conceptually robust, generic, and can be applied in other irrigated cropping systems of the world. And while this framework requires field-specific data on yield, irrigation, and management, we expect that availability of this information will increase due to increased pressure to develop agricultural datasets worldwide to address growing environmental concerns over water quality and quantity.

The combination of a solid conceptual framework to assess irrigation water use in producer fields, together with a robust spatial framework to upscale findings from field to region, provides a novel approach to assess potential water savings at different spatial scales, prioritize research and extension, and better inform policy and incentive programs. While the potential water savings estimated here may not be entirely possible because not all of the sources of irrigation surplus can be fully eliminated (*e.g.*, a precipitation event right after irrigation), the framework presented in this study allows estimation of the overall room for saving irrigation without penalties in crop yields. Potential end users of such a framework include water resource managers, policy makers, and governmental agencies, which could utilize the framework to forecast future water demand, identify areas prone to future water scarcity based on current water use and available freshwater resources, and implement water-use allocations to conserve water resources while minimizing impact to crop yield in times of drought.

The concept of managing farm inputs to reduce surplus in order to minimize the environmental footprint while maintaining or increasing crop yield is not new in agriculture (Broadbent and Carlton, 1978) and only recently this concept has been rediscovered and used to assess N losses in crop systems (Grassini et al., 2012, van Groenigen et al., 2010). The present study is the first to apply the 'surplus' concept to irrigation inputs in producer fields. N fertilizer recommendations, for example, are based on crop N requirements roughly calculated on expected end-of-season yield and most fertilizer is applied early in the season in one or few doses. In contrast, irrigation can, in principle, be synchronized to perfectly match water inputs with crop water requirements throughout the growing season depending upon the real-time weather conditions. We

argue here that, given appropriate knowledge and technologies to track soil water status and flexible irrigation equipment that allow delivering water right on time and in the right amount, reducing current irrigation surplus represents "low-hanging fruit" to increase farm net profit relative to the fine tuning of other aspects of crop and management which is sometimes difficult due to increasing risk or costs.

In the framework example using Nebraska, results can help answer questions such as: how and where should $1 million USD allocated to save irrigation water in Nebraska be spent to get the greatest return on investment? In this example, region 1 (northeast Nebraska) has greatest potential to improve irrigation water use per field due to the influence of sandy soils and risk on irrigation but region 3 (southeast Nebraska) represents a higher percentage of irrigated cropland. If the goal is to reduce the volume of water used state-wide for irrigation, extension educators would focus on region 3 and may use financial incentives (*e.g.* cost sharing for investment in new irrigation scheduling technology) to encourage water-saving practices. However, if the goal is to reduce water use on the most intensely irrigated fields or in areas with highest potential for contaminant leaching due to irrigation, the sandy soils in region 1 would be the focus of extension education. The incentives and outreach approach for water saving in region 1 would likely be different than region 3, instead focusing on managing risk by improving irrigation technology and providing evidence of fields in the region which achieved high yields with better technology.

The finding of greater irrigation surplus in soils with low AWHC confirms the findings in Chapter 1 that risk aversion toward irrigating on coarser texture soils leads producers to apply large water inputs relative to crop water requirements. Previous

studies have indicated that producers in high-risk systems (identified as regions with sandy soil) tend to adopt new irrigation water saving technologies more readily (Koundouri et al., 2006). However, increasing use of technology by itself is not always effective without skill gap assessment, and incentives are needed to accelerate the adoption of new irrigation practices and technologies (Levidow et al., 2014). The framework presented here can be used to incentivize producers to adopt new technologies by illustrating, using examples from actual producer fields rather than field experiments, that it is possible to change irrigation technology without decreasing yield. Better still, the framework has potential for producers to benchmark their own fields, not only relative to their fields' potential yields and irrigation requirements but also to compare their yield and irrigation to that of producers in the same region with similar soils and weather. Effectiveness of extension outreach can then be monitored over time by using the framework to track changes in technology usage and irrigation practices from year to year.

Summary and concluding remarks

Analysis of on-farm irrigation data complemented with field-specific weather, soil, and management data revealed that variation in irrigation over time and space strongly depends on field-specific properties. Producers respond to their field conditions and attempt to make irrigation decisions accordingly. However, use of a robust and transferrable framework to benchmark irrigation water use revealed that many fields received surplus irrigation in Nebraska. Potential exists to reduce surplus irrigation usage without decreasing maize and soybean yield. Key f of the study include:

- Field specific soil and weather accounted for field-to-field variation in irrigation.

- Across two independent databases, irrigation was disproportionally higher in coarse-textured soils.

- In homogeneous, fine-textured soils, producers in the highest and lowest irrigation categories consistently irrigated higher and lower than average across 9 years of study.

- ~70% of maize fields and 40% of soybean fields in a three year benchmarking analysis in Nebraska were irrigated in surplus of model simulated irrigation requirements.

- Potential exists to reduce surplus irrigation without yield loss through better, more advanced irrigation scheduling techniques and through educational efforts targeting producers with coarse-textured soils.

- 50% of current irrigation volume in near or above-average rainfall years represents surplus irrigation relative to irrigation requirements, and could potentially be reduced without decreasing yield. In drought years, relatively little room exists for improvement in terms of reducing irrigation surplus.

Future research is needed to fully understand the impact of neighbor behavior on the irrigation habits of individual producers. While certain factors related to surplus irrigation are manageable, further research is required to determine what degree of risk is manageable when irrigating on coarse-textured soils. The framework presented in this study provides a utility to support future research on irrigation water use, specifically with regard to tracking implementation and effectiveness of new irrigation technologies, management practices, and efforts by cooperative educational extension services.

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Appendix

Groundwater level dynamics in northeastern and south-central Nebraska

In an attempt to contextualize irrigation data with groundwater (GW) levels and analyze impacts of irrigation on groundwater level dynamics, publically available groundwater data were analyzed for the 9 years (2005-2013) of study (Chapter 1). Data were obtained from USGS (U.S. Geological Society) online groundwater well data, with data collected on a daily or bi-annual basis by the USGS or Nebraska NRDs. Well data for 12 groundwater wells in south-central (SC) Nebraska and 30 wells in northeastern/north-central (NC) Nebraska were analyzed for changes in groundwater level over the growing season using linear regression. Well locations were within the boundaries of the maize and soybean fields used in the study of spatial and temporal variation in irrigation. Partial motivation for choosing field locations in SC and NC was an attempt to limit complication of groundwater analysis due to surface-water and groundwater interactions. Field areas in these regions are relatively isolated from these interactions.

Due to the paucity of wells with daily groundwater level measurements, a single spring and autumn data point was used to capture groundwater level both before and after the irrigation season, with the exception of figures A1 and A2, for which all available data were included for each well. The data of spring measurements varied between wells, being taken in late April or early May, while autumn measurements were typically in late October or early November. Although data were available for a higher number of fields

in NC, significant data gaps existed for these wells. With the exception of two groundwater wells in NC, all wells in that region had a gap in groundwater level data for two or more years, with most wells lacking data from 2010 to 2012. No measurements were taken in those years by the NRD responsible for the majority of wells in NC as the NRD had no well measurement technician employed during those years. Because 2010 and 2012 were exceptional years in terms of precipitation, 2010 being an above-average year for rainfall and 2012 being a year of extreme drought, the lack of data for these years hindered the scope of the groundwater analysis in the northeast.

The objective of groundwater analysis was to determine to what extent groundwater levels change during the growing season due to irrigation and whether that change persists through the non-growing season. Results were incomplete and therefore included as supplemental findings in this appendix.

Main findings were as follows:

- Groundwater level trends were similar over the nine years of the study between the SC and NC regions of Nebraska (Fig. A1 and Fig. A2). For each well, groundwater level peaked at the spring measurement and fell to their lowest at the autumn measurement, following the irrigation season. This seems to imply that irrigation withdrawals are at least partly to blame for the drop in groundwater level over the growing season. Entering spring 2012 for both regions, groundwater levels in wells with sufficient data indicated that levels were at an eight year high from 2005. However, the decline during the 2012 growing season was extreme, resulting in drops of 1.5 meters in some wells from spring of 2012 to autumn of that year. While groundwater levels recovered between autumn of

2012 to spring of 2013, they were not able to recover to spring 2012 levels,

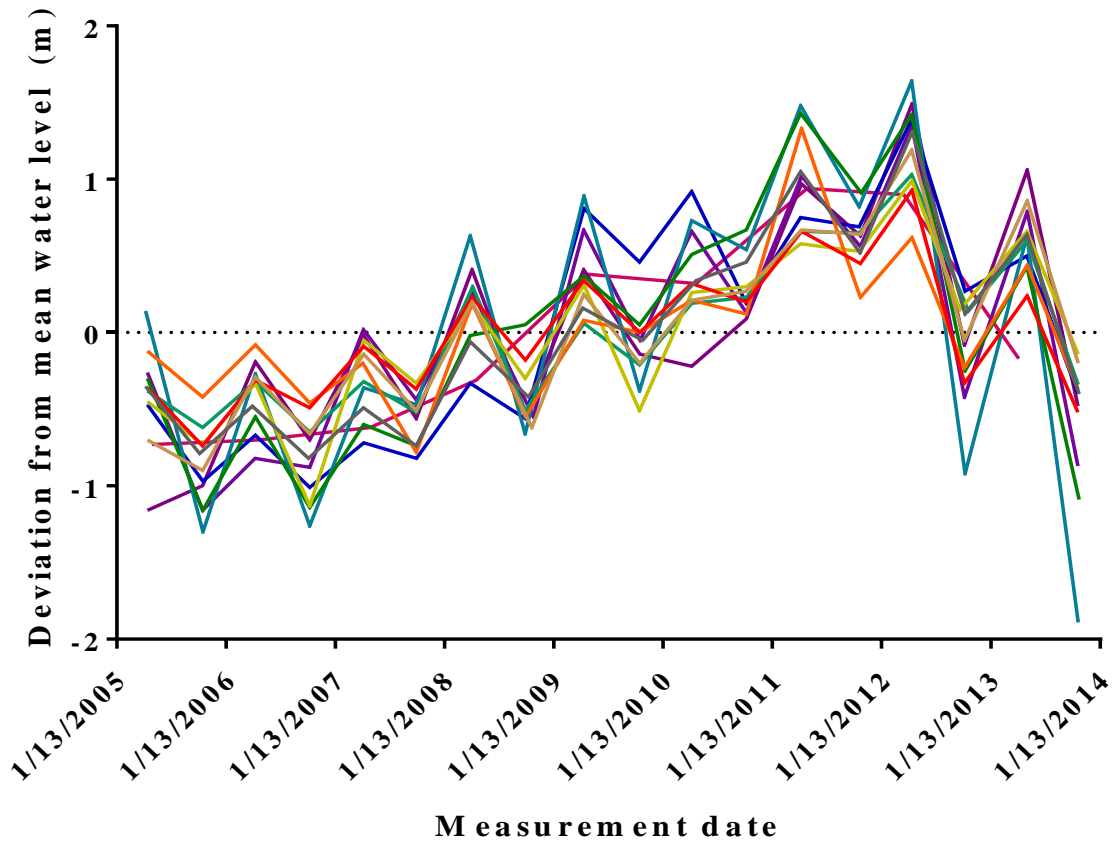indicating a carry-over effect of severe weather events on groundwater dynamics.

Fig. A1 Time series showing the deviation of groundwater level in each well from the well-specific 9-year mean groundwater level in the SC region of Nebraska. Each line represents an individual groundwater well. Negative deviation indicates below-average groundwater level while positive deviation values indicate above-average levels. Peaks in the series corresponded to spring measurements (April/May) while troughs generally corresponded to autumn measurements (October/November).
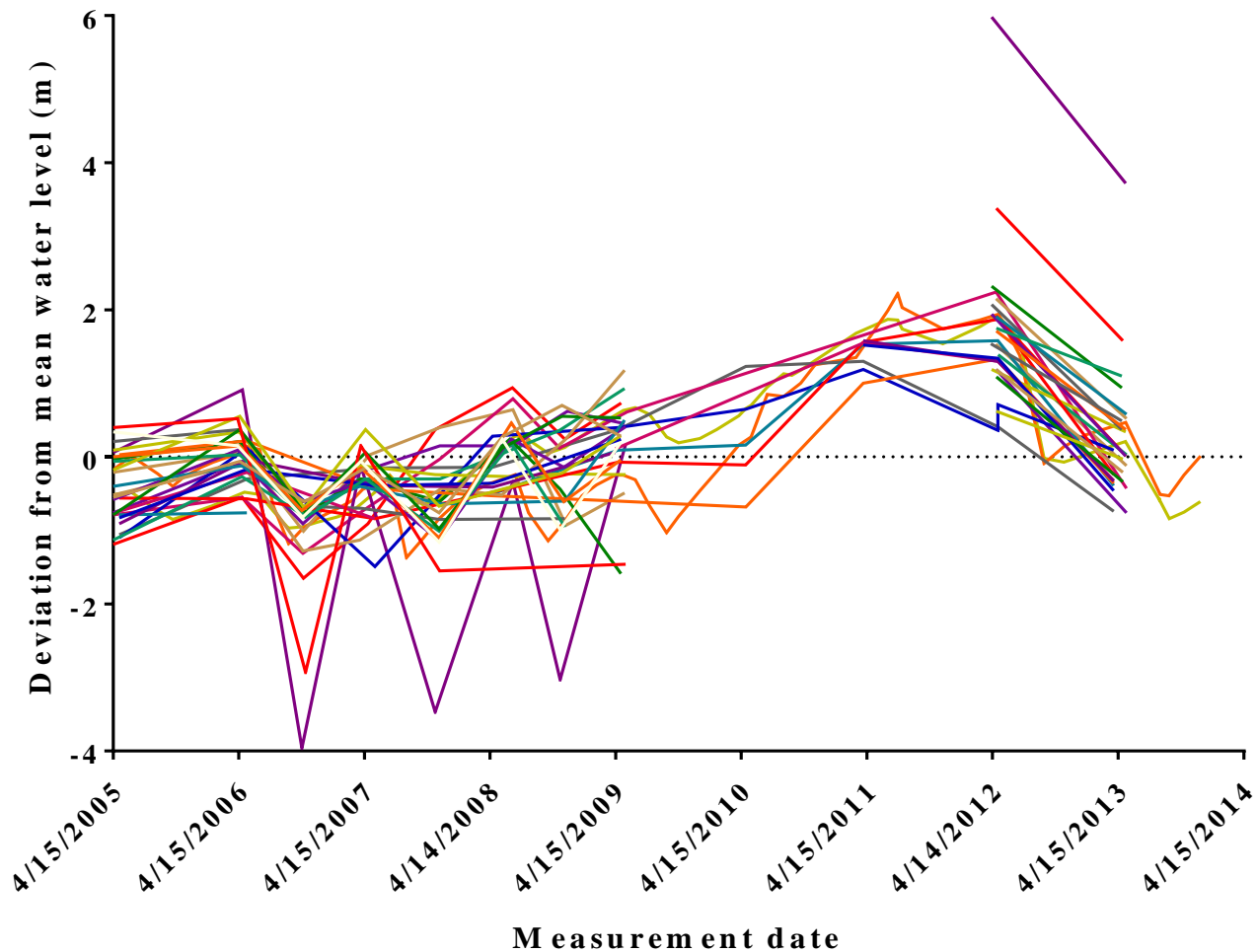
Fig. A2 Time series showing the deviation of groundwater level in each well from the well-specific 9-year mean groundwater level in NC. Each line represents an individual groundwater well. Negative deviation indicates below-average groundwater level while positive deviation values indicate above-average levels. Peaks in the series corresponded to spring measurements (April/May) while troughs generally corresponded to autumn measurements (October/November). Gap between April 2009 and April 2012 was due to a lack of water level monitoring personnel at the NRD managing many of the wells in the northeast. Wells with data between those dates were largely monitored/measured by USGS.

- Average groundwater well level declined during the crop season as average

  irrigation increased for both regions and across all years, with the exception of the

  wet year 2010 in which average groundwater level in NC increased (Fig. A1). The

  slope of decline across years was two times greater in NC than in SC, possibly

due to differences in aquifer media. The greatest amount of groundwater level decline occurred in the drought year (2012), which relates to large irrigation withdrawals in that year (Chapter 1).
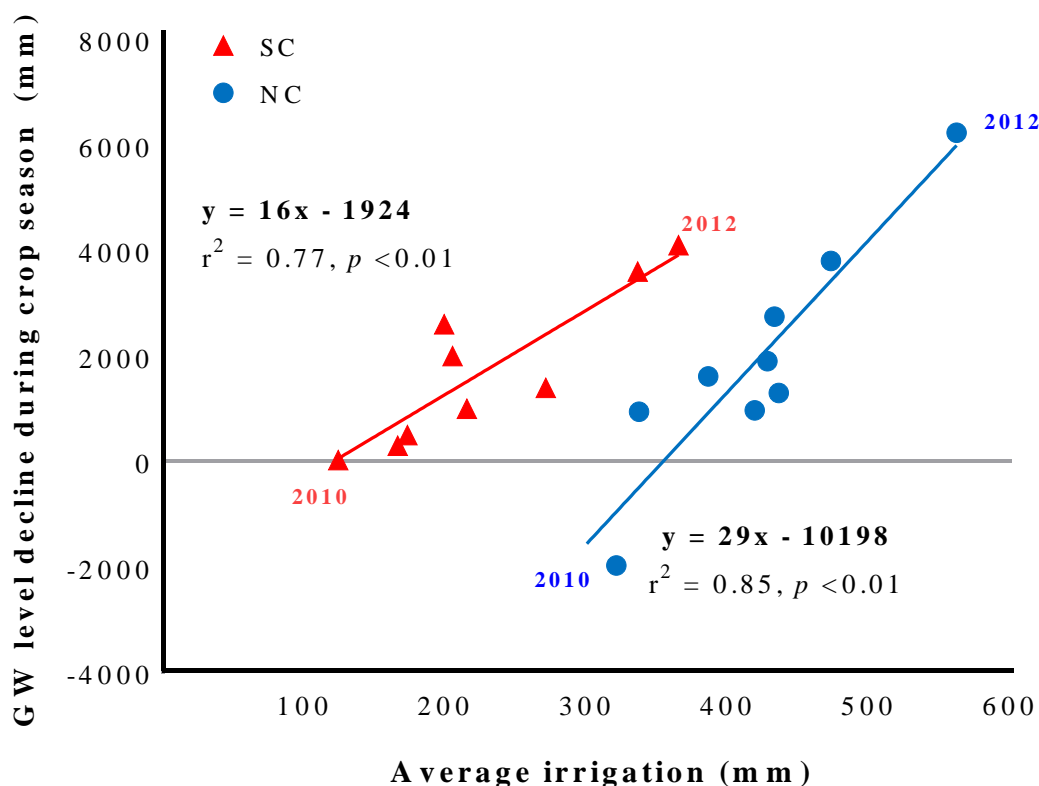

Fig. A3 Average groundwater (GW) level decline over the growing season as a function of average irrigation in NC (red triangles) and SC (blue circles) Nebraska. Negative groundwater decline indicates an increase in groundwater level. Data points represent region-year averages.

- Groundwater level increases during the fallow period/non-growing season (*i.e.* autumn following growing season until next planting) exceeded or were nearly equal to seasonal groundwater level decline in all years for both regions with the exception of the drought year (Fig. A2).
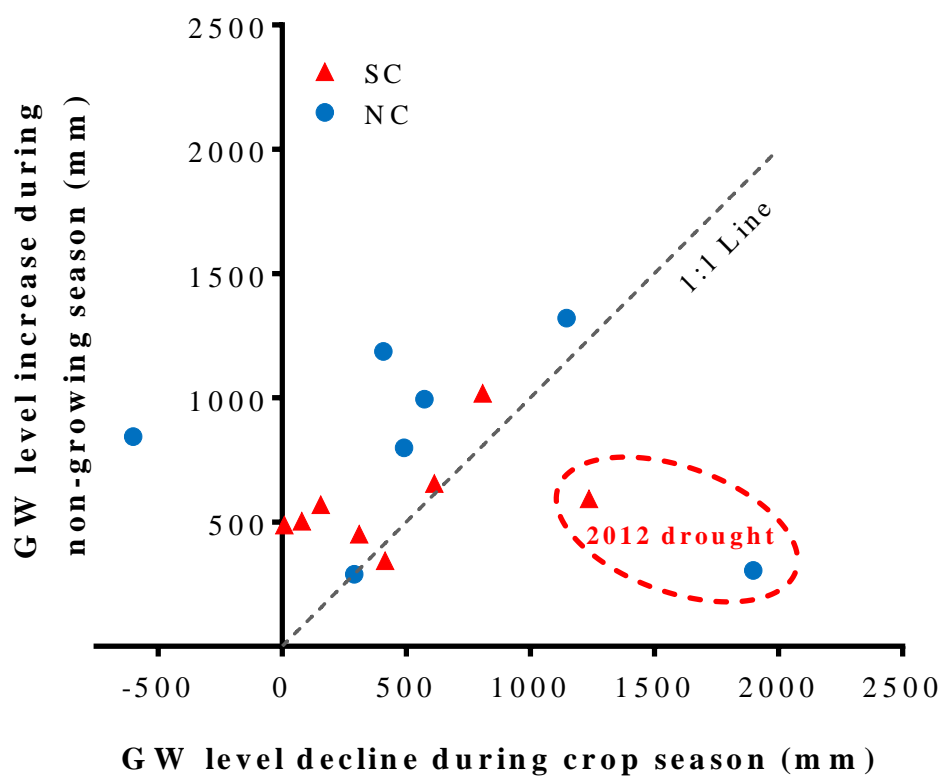
Fig. A4 Average seasonal groundwater level decline relative to groundwater level increase following the growing season for wells in SC (red triangles) and NC (blue circles).