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Impact of irrigation on interannual variability in United States agricultural productivity

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ABSTRACT

Irrigation contributes to enhance and sustain agricultural production in the U.S. across all aridity regimes, via mitigation against interannual environmental variability. Currently, a quantitative understanding of the role of irrigation in stabilizing agricultural yields is lacking, limiting the realization of irrigation-adoption impacts. Here we use > 220,000 historical (1950–2015) county-year irrigated and rainfed yield records for the top-nine U.S. crops [maize (*Zea mays* L.), soybean (*Glycine max* (L.) *Merr.*), spring wheat (*Triticum aestivum* L.), winter wheat (*Triticum aestivum* L.), alfalfa (*Medicago sativa* L.), sorghum (*Sorghum bicolor* (L.) Moench), cotton (*Gossypium hirsutum*), barley (*Hordeum vulgare* L.) and oats (*Avena sativa*)]. To comprehensively quantify the "Irrigation-Induced Reduction in Crop Yield Variability" (IIRYV, defined as the percent reduction in crop yield variability when irrigated with respect to rainfed yield variability). Averaged across all crops, national-level IIRYV was 41 %, which varied from 0 to 90 % across various regions and crops. IIRYV was highly crop-specific, and maize and cotton crops demonstrated the highest and least magnitudes. IIRYV substantially varied spatially within the constituent growing regions for each crop, and thus national scale assessments masked significant spatial differences. IIRYV was subject to interannual (temporal) variability; however, in general, IIRYV increased over time (1950–2015) for most crops. These findings will help in the evaluation of the contribution of historical irrigation development policy and adoption in the U.S in mitigating external shocks (variability) in U.S. agricultural productivity. The demonstration of spatial and temporal dynamics in IIRYV will aid in irrigation-water allocations and adoption by prioritizing irrigation development for vulnerable crops and regions.

1. Introduction

Agriculture in the United States (U.S.) has experienced a productivity revolution starting in 1930's (Gardner, 2009). Potential factors have caused this sharp productivity rise, including farm mechanization, advances in plant breeding and efficacy of chemical inputs, regulatory policy including research support, price and farm credit programs, advanced agronomic management, farm electrification etc. (Rasmussen, 1962; Clarke, 2002; Kitchens and Fishback, 2015; Mann, 1999; Tester and Langridge, 2010). In addition, the advent and adoption of irrigation has had a significant role in contributing towards higher agricultural yields. Irrigation allows for crop production in arid/semi-arid regions that do not receive sufficient precipitation to meet crop water demand. An ideal example of this is the farmland to the west of the 98th Meridian, where the annual precipitation received is less than 500 mm (PRISM Climate Group, 2018), and significant portion is not received during the crop growing season. Nevertheless, the western and Midwestern states account for more than 80 % of the total U.S. farmland and two-thirds of the nation's irrigated land (USDA, 2013), producing substantial proportions of nation's wheat (70 %), horticultural crops (> 33 %), vegetables (> 50 %), cotton (> 40 %), fruits, tree nuts and berries (> 80 %). If deprived of irrigation, millions of hectares in the western U.S would be rendered barren or low value grazing lands with considerably small economic value (Selby, 1949; Stubbs, 2016). The economic benefits of irrigation also extend to humid and sub-humid regions with sufficient precipitation, as it acts as a buffer against within-season precipitation variability and extremes. With increasing precipitation variability (Svoma and Balling, 2010; Pendergrass et al., 2017), drought conditions, increased commodity prices in certain periods, low-cost and relatively easy access to groundwater resources for irrigation (Vories and Evett, 2010; Schaible and Aillery, 2012) as well as irrigation's substantial impact on increasing grain yields, the irrigated land area in the humid eastern states in the United States has increased by over 3.5 million hectares since 1984 (USDA, 2013, 1984). In fact, the U.S. eastern states have increased their irrigated area by 50 % since 2003, as opposed to reduction in

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irrigated area in majority of western states (USDA, 2013). Thus, irrigation has immense significance for croplands irrespective of aridity regimes at any given location. Due to increasing trend in water availability as well as challenges in water quality degradation for freshwater resources used for irrigation and uncertainties in terms of impact(s) of change in climate variables and their variability on agricultural operations and productions and water resources, irrigation's role in reducing the inter-annual variability in grain yield production may become more important in the future.

Given the fact that irrigated yields, on average, are 2.7 times greater than rainfed yields (Rosenzweig and Parry, 1994) and this advantage of irrigated yields over the rainfed yields (irrigation-limited yield gap) varies across crops, space and time (Kukal and Irmak, 2019a), we anticipate and hypothesize that a similar behavior should be revealed by comparing interannual variability among irrigated and rainfed yields. Interannual variability in agricultural yields for various crops, locations and time periods have been discussed by some studies (Kucharik and Ramankutty, 2005; Ray et al., 2015; Ben-Ari and Makowski, 2014; Iizumi and Ramankutty, 2016; Kukal and Irmak, 2018a). However, very limited research has been conducted on quantifying and studying the interannual variability among irrigated and rainfed crop yields distinctly, especially at finer scales. Irrigated and rainfed yield variability for maize, soybean and sorghum in the U.S. Great Plains were compared and it was found that the interannual variability (defined by coefficient of variability) in rainfed yields was 77 % (maize), 69 % (sorghum) and 63 % (soybean) greater than that in irrigated yields (Kukal and Irmak, 2018a). In another study, irrigated and rainfed yield residuals for maize in Nebraska were compared and found that irrigation reduced maize yield variability by a factor of three, i.e. positive and negative deviations in irrigated yields were 5.6 % and −7.4 %, whereas they were 18.5 % and −19.7 % in rainfed yields, respectively (Kucharik and Ramankutty, 2005). While it is a well-accepted notion that irrigated crop yields should and do present lower interannual variability than their rainfed counterparts, quantitative estimates of this reduction in variability are currently unknown or insufficient for all major U.S. crops and the regions. Moreover, the spatial and temporal patterns associated with the reduction in variability under irrigated conditions, if any, are unexplored. Since irrigation technology and efficiency have evolved and improved over time, and has regional differences (Caswell, 1991; Green et al., 1996), there is a strong likelihood that it could result in spatial and temporal variations in the reduction in variability post irrigation-adoption. Moreover, almost all of the studies are limited to addressing the issue of yield variability only for major crops that have significance for national and global agricultural production, i.e., maize, soybean, wheat and rice (in global studies). However, other crops that although account for relatively lower production nationally/globally, are of considerable economic significance for specific regions where they are grown. Furthermore, these secondary crops account for a considerable portion of the total national irrigated land area (alfalfa, cotton, sorghum, barley and oats production contribute to 12 % of the total 2017 production) (USDA, 2018). Thus, a gap exists in our assessments and knowledge on comparative interannual variability among irrigated and rainfed crop yields at finer (sub-state or county) scales, especially for crops that are integral part of U.S. agriculture, but have not been discussed sufficiently.

Here, we address these issues by quantifying and comparing interannual variability among irrigated and rainfed yields for nine major crops. To select these major crops, we ranked the crops on the basis of their national production in 2018, which is mostly consistent with the long-term mean production as well. These crops include maize (*Zea mays* L.), soybean (*Glycine max* (L.) *Merr.*), spring wheat (*Triticum aestivum* L.), winter wheat (*Triticum aestivum* L.), alfalfa (*Medicago sativa* L.), sorghum (*Sorghum bicolor* (L.) Moench), cotton (*Gossypium hirsutum*), barley (*Hordeum vulgare* L.) and oats (*Avena sativa*). We aim to quantify comparative differences in interannual variability among irrigated and rainfed yields at county-level during the complete USDA survey records available. Moreover, we decipher and report spatial and temporal patterns/trends in the irrigated vs. rainfed yield variability. Our overall goal in regards to these objectives is to characterize the benefits of irrigation, i.e., stabilization of agricultural crop yields against interannual variability caused by all the external influences such as weather variability, extreme weather, water availability, pests, weeds, and soil and crop management practices.

2. Methods and data

2.1. Data source and pre-processing

Data for irrigated and non-irrigated yields and harvested area for maize, soybean, spring wheat, winter wheat, alfalfa, sorghum, cotton, barley and oats were obtained from the National Agricultural Statistics Service, United States Department of Agriculture (USDA, 2018) using the QuickStats online tool. These crops were selected to include major U.S. agricultural commodities, based on current production statistics (account for 80 % of the 2017 U.S. harvested area). All the county-level yield records for each crop were retrieved from around the year 1950 until the end of records around 2015, when available from the NASS records. The data were subjected to certain processing steps prior to use. Firstly, raw NASS data were assessed for missing records and temporal extents were decided for each crop. It has to be noted that NASS publishes irrigated and rainfed yield data separately only for states (or counties) that have substantial cropland under both irrigated and rainfed cultivation. Only those counties that reported a minimum of 15 data records for both irrigated and non-irrigated yields were selected for analyses. Supplementary Table S1 lists the start, end and period of analysis as well as the number of counties that met the preprocessing criteria and hence qualified for analyses. Additionally, yield data were converted to metric units (kg ha^{-1}) from commercial units for each crop to maintain consistency. The conversion factors were: 1 kg ha^{-1} = 0.0159 bu ac^{-1} for maize/sorghum; 1 kg ha^{-1} = 0.0149 bu ac^{-1} for wheat/soybean; 1 kg ha^{-1} = 0.0185 bu ac^{-1} for barley; 1 kg ha^{-1} = 0.0279 bu ac^{-1} for oats; 1 kg ha^{-1} = 0.8922 lb ac^{-1} for cotton; and 1 kg ha^{-1} = 0.0004047 t ac^{-1} for alfalfa.

2.2. Quantifying irrigated and rainfed crop yield variability

The crop yield variability (CYV) metric represents the magnitude of interannual deviations from the long-term linear trajectory of yield growth. Crop yields are controlled by a variety of factors, among which the overall long-term increasing trend is caused due to agronomic and technological advances such as improvements in plant breeding and genetics (eg. development of high-yielding, herbicide resistant or drought-tolerant hybrids), fertilizer, pesticides, farm mechanization), as well as weather and climate factors. On the other hand, the high-frequency fluctuations are mainly caused by weather and climate factors. In this research, we are particularly high-frequency (year-to-year) variability, and thus detrending the crop yield data to remove the trends in non-weather factors (genetics and technology) is critical. This technique has been extensively applied in empirical modeling of agricultural systems (Maltais-Landry and Lobell, 2012; Lobell and Field, 2007; Kukal and Irmak, 2018a, b). The interannual deviations contain signatures for environment-induced crop performance fluctuations (abiotic stresses), and hence should be different under irrigated and non-irrigated crop production systems.

To quantify interannual crop yield variability (CYV) for a given county, a linear function was fit to crop yield (individually for irrigated and non-irrigated) vs. time (years) pairs of observed data. Residuals from the fitted linear function were calculated; a modulus function was applied to the residual and a ratio was computed by dividing it by the predicted value derived from the linear fit. This quantity is what we interpret as crop yield variability for a specific county and year. Supplementary Fig. S1 graphically represents the computation of CYV for Chase County, Nebraska as an example. We conducted the abovementioned series of steps individually for irrigated and non-irrigated crop yields in a given county. For the purpose of analyzing long-term spatial patterns and inter-crop differences, we averaged the CYV magnitudes for each county over the total number of annual records available.

2.3. Quantifying overall (weighted) crop yield variability

To estimate a representative value of overall crop yield variability for a county, we first calculated long-term mean irrigated and rainfed area fractions (f_{irr} and f_{rf}, respectively) for each county, which are dimensionless (Eqs. 1 and 2). These were calculated by dividing the crop harvested area (ha.) under irrigated/rainfed production by total harvested land area (ha.) and averaging over the annual records available for each county. Then, f_{irr} and f_{rf} were used as a weighting factor to compute a weighted mean of irrigated and rainfed yield variability ($CYV_{overall}$) based on the relative prevalence of irrigated/rainfed production in each county (Eq. 3).

$$\boldsymbol{f_{irr}} = \frac{\textbf{\textit{Harvested area under irrigated production}}}{\textbf{\textit{Total harvested area}}} \tag{1}$$

$$\boldsymbol{f_{rf}} = 1 - \boldsymbol{f_{irr}} \tag{2}$$

$$\boldsymbol{CYV_{overall}} = (\boldsymbol{CYV_{irr}} \times \boldsymbol{f_{irr}}) + (\boldsymbol{CYV_{rf}} \times \boldsymbol{f_{rf}}) \tag{3}$$

where, $CYV_{overall}$ is the overall crop yield variability for a given county and year (in percent), CYV_{irr} is the irrigated crop yield variability (in percent), CYV_{rf} is the rainfed crop yield variability (in percent), f_{irr} is the irrigated area fraction (ranged from 0 to 1) and f_{rf} is the rainfed area fraction (ranged from 0 to 1).

2.4. Quantifying irrigation induced reduction in crop yield variability (IIRYV)

Following the computation of irrigated and rainfed crop yield variability individually for each county, the difference among CYV_{rf} and CYV_{irr} relative to CYV_{rf} was computed and a modulus function was applied to the term (for cases where CYV_{irr} and CYV_{rf} are comparable or the difference is slightly negative, if any). The denominator of the metric was CYV_{rf} to aid in comparison of IIRYV across geographic scales, as rainfed yields will be free from influence of irrigation. This resulting quantity was termed as "Irrigation-Induced Reduction in Crop Yield Variability" (or IIRYV), as presented in equation 4. Since IIRYV was calculated as a difference of CYV_{irr} from CYV_{rf} and ratioed with CYV_{rf}, the range for IIRYV will be 0-1. The methodology used here is partially similar to that adopted by Kucharik and Ramankutty (2005).

$$\boldsymbol{IIRYV} = \left| \frac{\boldsymbol{CYV_{rf}} - \boldsymbol{CYV_{irr}}}{\boldsymbol{CYV_{rf}}} \right| \tag{4}$$

2.5. Mapping

All the spatial data were mapped at county-level using ArcMap 10.4.1 (ESRI, 2017).

3. Results

3.1. Interannual crop yield variability in the U.S

We start by answering our most fundamental question, i.e. what has been the historical interannual variability in the U.S. agricultural yields. To the best of our knowledge, there is no previous knowledge on comparative crop yield variability (CYV) for the major national and regional crops in the U.S... In fact, not much is known about the CYV of crops such as alfalfa, cotton, sorghum, barley and oats at the regional, or even national scale. Moreover, for all of the crop panel, distinct estimates of irrigated and rainfed CYV (CYV_{irr} and CYV_{rf}, respectively) are unknown. We find that for irrigated crops, on a national basis, cotton showed the highest interannual variability, followed by winter and spring wheat, oats, barley, sorghum, alfalfa, maize and soybean (Supplementary Fig. S2). However, rainfed crops compared in a different fashion on the national basis, with cotton showing the highest interannual variability [due to its momentous sensitivity to both magnitude and timing of water stress (Smith and Cothren, 1999)], followed by maize, oats, spring wheat, sorghum, barley, winter wheat, soybean and alfalfa (Supplementary Fig. S2).

Each county has a distinct partitioning of irrigated and rainfed crop harvested area, where the fraction of irrigated area to total cultivated area follows an increasing pattern similar to the spatial precipitation gradient (irrigated fraction is lower in regions with higher precipitation and vice-versa). Although, this partitioning of total harvested area into irrigated and rainfed land area can change temporally, we can rely on long-term mean magnitudes to represent irrigated fraction of total area or f_{irr} (Supplementary Figs. S3 and S4). We found that on a long-term mean basis, f_{irr} ranged from 0.51 to 0.21 and was highest in alfalfa, followed by oats, corn, soybean, barley, cotton, spring wheat, winter wheat and sorghum (Supplementary Fig. S3). To quantify county-specific overall crop yield variability ($CYV_{overall}$), which is representative of actual proportions of both irrigated and rainfed area in a given county, we compute a weighted average of CYV_{irr} and CYV_{rf} by using f_{irr} as a weighing factor. We found that, on a national basis, maximum $CYV_{overall}$ was still observed in cotton, followed by sorghum, spring and winter wheat, oats, corn, barley, soybean and alfalfa (Supplementary Fig. S2).

The high standard deviation observed in mean national CYV (Supplementary Fig. S2) insinuates high variability found in CYV across geographical domains for each crop. The degree of spatial variability in CYV_{irr} was 19 % greater than that in CYV_{rf} across all the crops, and equal to that in $CYV_{overall}$ (Supplementary Fig. S5). Both irrigated and rainfed alfalfa demonstrated the highest degree of spatial variation in CYV as compared with the rest of the crops. However, maize exhibited the highest degree of spatial variability in $CYV_{overall}$. We find that there are distinct regions of low, moderate and high magnitudes of both irrigated and rainfed CYV (Supplementary Figs. S6 and S7, respectively). CYV_{rf} demonstrates a longitudinal pattern of decreasing CYV from west to east (especially discernible in the Great Plains region, because of relatively smoother gradient of increasing precipitation form west to east), which is non-existent in CYV_{irr}. This absence of a geographical pattern in CYV_{irr} is likely due to the varying effectiveness of irrigation practices at different regions, which is challenging to address. While rainfed yields are a direct consequence of growing season precipitation that follows a geographical pattern, in turn translating into geographical patterns in CYV_{rf}. On the other hand, the application of irrigation water distorts these natural precipitation-induced patterns, and convey a management-induced signal. Since farm-level management and decision-making is highly variable, even across farms in the same region, and on broader scales, recognizing these management-induced signals is a challenge. Development of datasets that record spatial and temporal variation in farm-level management at reasonable resolutions is a momentous task, although continuous high-resolution satellite data hold significant promise (Deines et al., 2019).

For a given county, $CYV_{overall}$ ranges between CYV_{irr} and CYV_{rf} depending on the f_{irr} (Supplementary Fig. S4). For instance, regions such as central Nebraska, where maize production is almost entirely irrigated (i.e. $f_{irr} \sim 1$), show overall maize yield variability magnitudes that are equal to that of irrigated maize yield variability and vice-versa (Fig. 1). It is evident that among all the crops at all the constituent locations, cotton in Texas was the most variability-prone crop-region combination [Fig. 1(F)], followed by others such as maize in eastern Kansas, winter wheat in Texas Panhandle, and barley in southern California. Top performing crop-regions in terms of yield stability (low

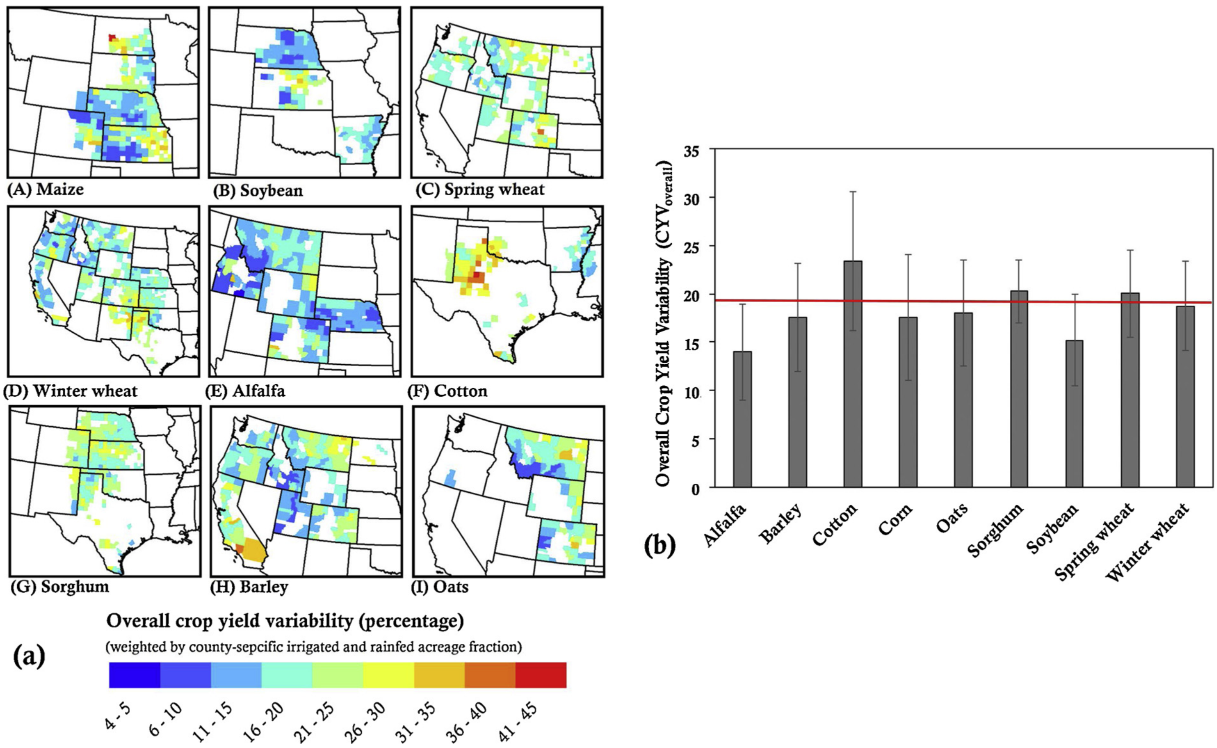

Fig. 1. (a) Overall crop yield variability (CYV$_{overall}$) for the top nine (production-wise) crops in the U.S. counties; (b) National-level comparison of CYV$_{overall}$ for each crop. The error bars represent standard deviation around the mean. CYV$_{overall}$ is represented as yield variability as percentage of mean yields. The red horizontal line represents the mean CYV$_{overall}$ across nine crops. The maps were developed using ESRI ArcMap 10.4.1 software. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

CYV$_{overall}$) were maize in Nebraska and southwest Kansas, soybean in Nebraska, and alfalfa in Nebraska and Idaho. The underlying reasoning for this behavior is moderately high to high f_{irr} in these regions, an ideal example being Nebraska (with the highest irrigated land area in the nation).

3.2. National-level irrigation-induced reduction in crop yield variability (IIRYV)

Until now, we have recognized and established that CYV$_{irr}$ and CYV$_{rf}$ for a given crop are different and when averaged nationally, CYV$_{irr}$ is lower than CYV$_{rf}$. This section quantifies and compares as to how does the yield stabilization effect seen in irrigated crops, evidenced by lower magnitudes of CYV$_{irr}$ than CYV$_{rf}$, varies across different crops studied. Overall, the U.S. rainfed crop yields historically showed two-fold (1.96) interannual variability than the U.S. irrigated crop yields, when averaged across all crops. This long-term mean fraction of rainfed to irrigated long-term crop yield variability ranged from 2.71 to 1.94 and was the highest in maize (2.71), followed by soybean (2.43), alfalfa (2.13), oats (1.94), sorghum (1.85), barley (1.84), spring wheat (1.78), winter wheat (1.52) and lastly, cotton (1.44). The extremes of the standard deviation associated with the mean ratio of rainfed to irrigated variability show that at a minimum, the irrigated crop yield variability was equal to rainfed crop yield variability; however, at a maximum, rainfed crop yield variability was as high as 3.6 times the irrigated crop yield variability (Fig. 2a).

For all the crops, averaged nationally, the ratio of CYV$_{rf}$ to CYV$_{irr}$ was greater than 1, which implies that irrigation mitigates interannual crop yield variability (stabilizes yields) when compared to rainfed production. We refer to this stabilization benefit that occurs under irrigated production as “Irrigation-induced Reduction in Yield Variability” (IIRYV). Simply, IIRYV can be considered as the reduction in CYV achieved if a producer in a particular county converts from rainfed production to irrigated production. We justifiably presume that the reported irrigated and rainfed yields representing a particular county to be comparable because of similarity of growing conditions such as weather, soils, management practices, etc., within a county. On a national scale, we found that irrigation has led to lowering of crop yield variability historically by 41 % (IIRYV = 41 %) than what was shown by rainfed yields, averaged across all nine crops studied (Fig. 2(b)). Long-term mean IIRYV ranged from 57 % to 28 % and was highest for maize (57 %), soybean (55 %), oats (45 %), alfalfa (43 %), sorghum (42 %), barley (39 %), spring wheat (36 %), cotton (28 %), and winter wheat (28 %), which is slightly different from the magnitudes demonstrated by the ratio of rainfed and irrigated yield variability. The extremes of the standard deviation associated with the mean crop-specific IIRYV imply that we encountered IIRYV of as high as 79 % and as low as 7%. This wide range of IIRYV stems from significant spatial variation, which was even greater than found in CYV$_{irr}$ and CYV$_{rf}$. We find that the highest spatial variability in IIRYV was demonstrated by winter and spring wheat (CV > 0.65), followed by alfalfa, barley, cotton, maize, sorghum, oats and soybean (Supplementary Fig. S8). The higher spatial variability in wheat is likely due to larger and relatively more geographically distributed growing regions, which encompasses greater environmental variability relative to other crops (most likely due to its growing season period being different than other crops), especially in contrast to soybean, which shows least spatial variation due to its smaller growing region.

3.3. Spatial heterogeneity in irrigation-induced reduction in crop yield variability (IIRYV)

The national-scale assessment of IIRYV informed us not only about the national mean magnitudes of IIRYV, but also the variation associated with the mean IIRYV [see standard deviation bars in Fig. 1(b)]. This variation stems from the spatial heterogeneity in IIRYV when individual counties are considered, rather than averaging them nationally. In this section, we discuss the patterns of this spatial heterogeneity

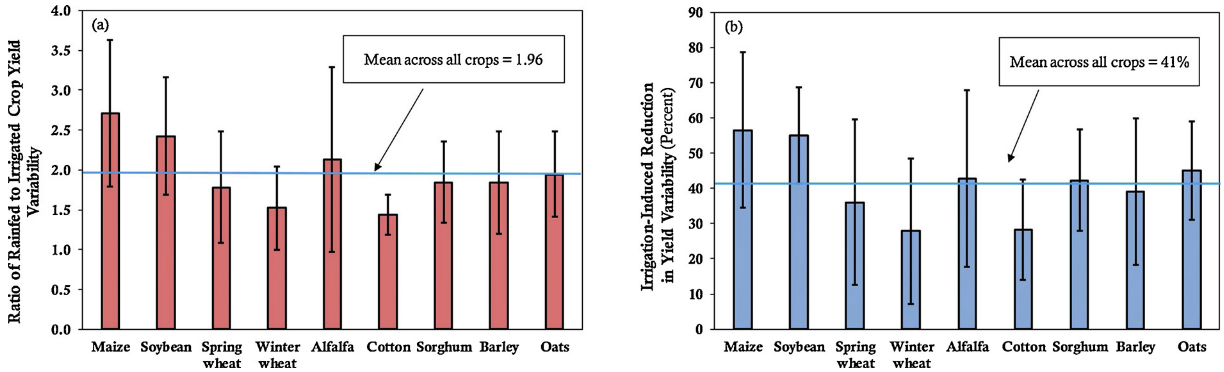

Fig. 2. National-level comparison of (a) Ratio of rainfed to irrigated crop yield variability and (b) Irrigation-Induced Reduction in Crop Yield Variability (IIRYV). The error bars represent standard deviation around the mean value. The blue horizontal lines in (a) and (b) represent mean indices across nine crops. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

in IIRYV for each crop within their growing regions.

We find that while national assessments are useful, they mask spatial (inter-county) differences in the IIRYV. Pooling all the crops and regions, rainfed yield variability varied from being 0.5–5 times the irrigated yield variability (Supplementary Fig. S9) and IIRYV varied from 0 (no reduction in variability) to up to 90 % (Fig. 3). Here we list some insights into the features of spatial heterogeneity of IIRYV in various crops:

- Maize IIRYV ranged from none to 80 % and the spatial distribution of IIRYV (Fig. 3) shows that the highest magnitudes existed in central Nebraska and was generally higher than 50 % in Nebraska and Kansas. However, it was relatively lower in the Dakotas (< 40 %), and the easternmost counties in the Dakotas demonstrated no reduction in maize yield variability, which could be due to limited adoption of irrigation and also due to relatively higher humidity and precipitation, and hence lack of water stress.
- Soybean IIRYV ranged from 4 % to 78 % and was the highest in central Kansas, with most of the soybean growing regions showing IIRYV > 50 %, with the exception of eastern Nebraska and some parts of Arkansas. Again, this low IIRYV could be due to lack of water stress in these regions.
- Spring wheat IIRYV, ranging from 0 to 81, demonstrated lesser regional coherence as compared with maize and soybean, with greater variability even at smaller scales. Overall, eastern Wyoming and Colorado show reasonably high spring wheat IIRYV, while the northwestern region of the nation showed lower and inconsistent IIRYV magnitudes overall (due to higher precipitation and low irrigation adoption in northwestern U.S.).
- Winter wheat, being grown on greater land area than spring wheat (irrigated classes) shows more spatial coherence than that observed in spring wheat. The IIRYV in winter wheat ranged from 0 to 75 % and was generally higher (> 60 %) in California, Utah and Idaho, while also demonstrating a greater proportion of counties with no reduction in variability in Montana and Oregon (IIRYV = 0). Another interesting feature of the winter wheat IIRYV was the west-east decreasing gradient found in the Great Plains, with the counties adjoining the eastern boundary of winter wheat growing regions showing very low to no reduction in variability.
- Alfalfa showed generally high IIRYV values (> 50 %), similar to maize and soybean, while also showing the maximum IIRYV in a county among all crops at 90 %. Similar to winter wheat, a west-east decreasing gradient was found in Nebraska, with counties showing very smooth transition from high IIRYV in the west to low or no IIRYV in the east. In addition to eastern Nebraska, some parts in Colorado and Idaho showed lower or zero IIRYV.
- Cotton IIRYV ranged from none to 51 %, which is the lowest among the maximum IIRYV for any county among all crops. Cotton IIRYV mostly was low (< 40 %) and was quite homogenous across the complete cotton growing areas.
- Sorghum demonstrated medium to low IIRYV (< 60 %), with the extreme values in IIRYV ranging from none to 83 %. Central Nebraska, western and central Kansas and Panhandle Texas showed generally higher IIRYV, while western Nebraska, Colorado and New Mexico showed lower IIRYV. Interestingly, for sorghum, the regions displaying no IIRYV were negligible.
- Barley IIRYV ranged from no reduction to 78 % reduction and was the highest in Idaho, with the eastern states of the region showing generally moderate to high IIRYV. The western states had lower IIRYV magnitudes with considerable counties in Oregon showing no reduction.
- Oats was observed to show a IIRYV ranging from 14 % to 75 %, with the distinction of showing the highest magnitude of the lower extent of variability reduction (14 %), and none of the counties showed no reduction, a trait similar to what we found in sorghum.

Thus, we establish that both geographic location and crop type have a considerable influence on the yield stabilization benefit under irrigated production.

3.4. Temporal variability and trends in irrigation-induced reduction in crop yield variability (IRYV)

The long-term mean behavior of crop yields to demonstrate lower variability when under irrigated conditions can mask the year-to-year variation of this stabilization effect of irrigated production. This section explores and discusses this temporal variability and trends in this phenomenon for each crop. We find that there is substantial variability of the IIRYV demonstrated by various crops with time (Supplementary Fig. S10). For example, maize CYV_{rf} (58 %) was 630 % greater than CYV_{irr} (8%) in 2012, which is one of the driest years in U.S. history (Supplementary Fig. S9), while the long-term mean is considerably lower. On the other hand, the former (19 %) was only 12 % greater than the latter (17 %) in 1995. In fact, in one of the wettest years, in 1993, the difference between CYV_{rf} and CYV_{irr} was even negative (−2%). Similar observations were true for all other crops. It was also found that the degree of year-to-year variability that exists within the CYV_{rf} was higher than CYV_{irr} (visually evident from the higher magnitudes of deviation for the broken line than the solid line in Supplementary Fig. S10). In other words, the "variability within the variability metric (CYV)" is higher for rainfed than irrigated yields. To quantify this difference, the coefficient of variation (CV) of the CYV_{irr} and CYV_{rf} series were computed, which revealed that across all crops, variability in CYV_{rf} was 38 % greater than that in CYV_{irr}, except soybean and cotton.

IIRYV also has a temporal characteristic, and the data indicated positive linear trends overall (Fig. 4). Specifically, the IIRYV increased

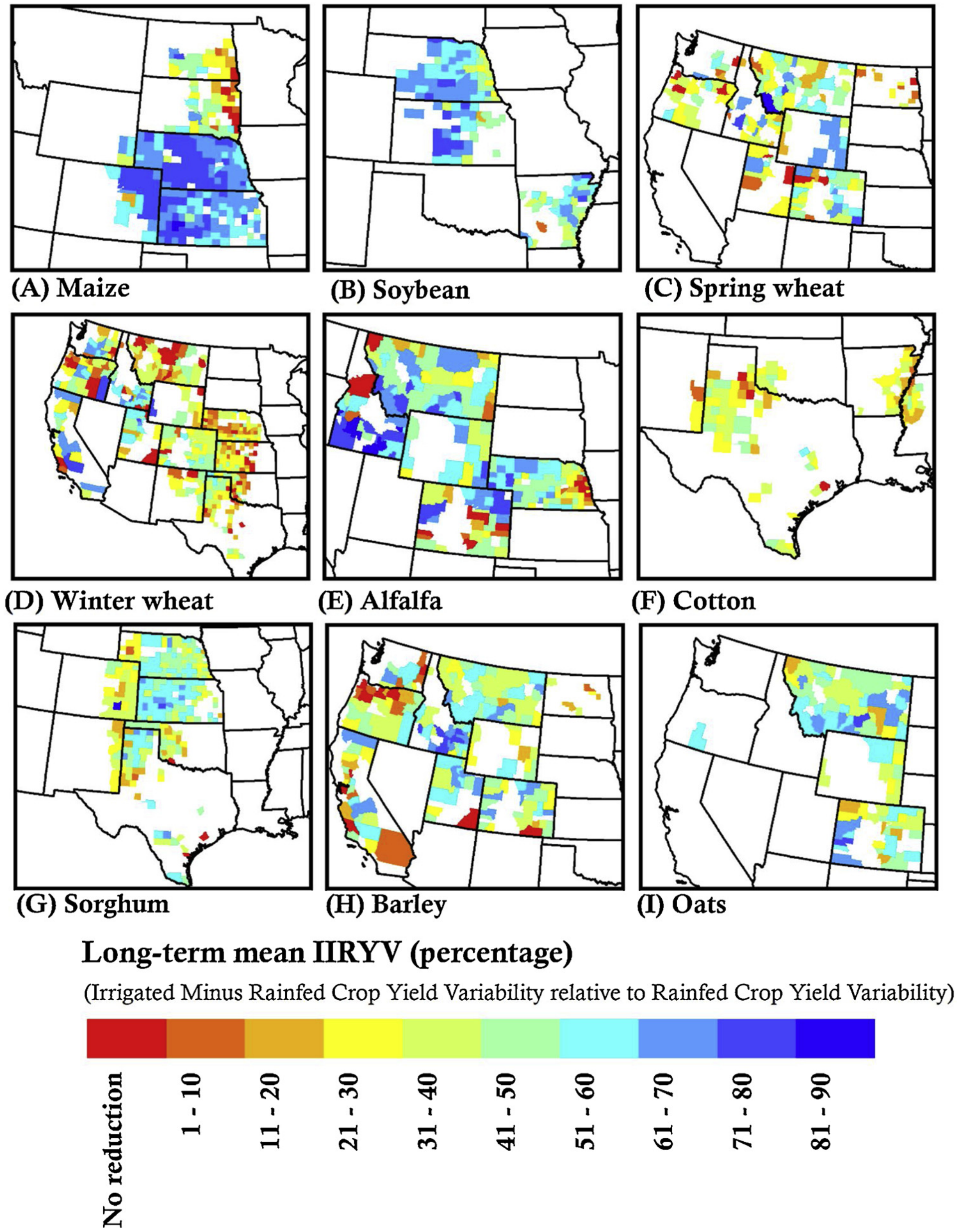

Fig. 3. Long-term mean Irrigation-Induced Reduction in Yield Variability (IIRYV) for top-nine (production-wise) crops in the U.S. counties. IIRYV was quantified as the irrigated minus rainfed crop yield variability relative to rainfed crop yield variability represented as percentage. The maps were developed using ESRI ArcMap 10.4.1 software.

at a statistically significant (α = 0.05) rate for the following crops in the decreasing order of rate of increase: cotton (9% decade^{-1}), followed by soybean (7.8 % decade^{-1}), alfalfa (5.2 % decade^{-1}), barley (2.2 % decade^{-1}), and spring wheat (1.7 % decade^{-1}). Other crops such as maize (1.6 % decade^{-1}) and winter wheat (1.3 % decade^{-1}) and lastly sorghum (0.02 % decade^{-1}) had increasing rates of IIRYV, but were statistically non-significant. Oats IIRYV had a non-significant decreasing trend (2.1 % decade^{-1}). Thus, in addition to crop type and location, time has been found to be an influencing factor in IIRYV assessments.

4. Discussion

We quantified the overall yield variability for the top nine U.S. agricultural crops (production-wise) at the finest scale possible (county), by individually computing both CYV_{irr} and CYV_{rf}, and consequently, the difference between the latter and former, which was termed “Irrigation-Induced Reduction in Yield Variability” or IIRYV. For each of these variables, we focused on differences encountered in them among crops, locations and time. The outcomes and the information generated through our analyses hold crucial significance for assessing, planning, forecasting and strategizing the U.S. water resources diverted from surface water and withdrawn from groundwater resources to irrigation. First and foremost, we can derive from our analysis (Fig. 2) that some crops such as maize, soybean and alfalfa present a higher degree of stabilization in yields at national level when irrigated vs. rainfed production are considered. This can also be interpreted as a proxy to the higher sensitivity of these crops to available water. Moreover, this advantage of certain crops over others is presented in different spatial and temporal domains (Figs. 3 and 4). Maps such as Fig. 3 present the long-term patterns of the stabilization benefit of irrigated agriculture over rainfed agriculture and profoundly aid in identification of regions which are crucial to sustain irrigation (eg. central Nebraska for maize production, see Fig. 3a) and the areas that

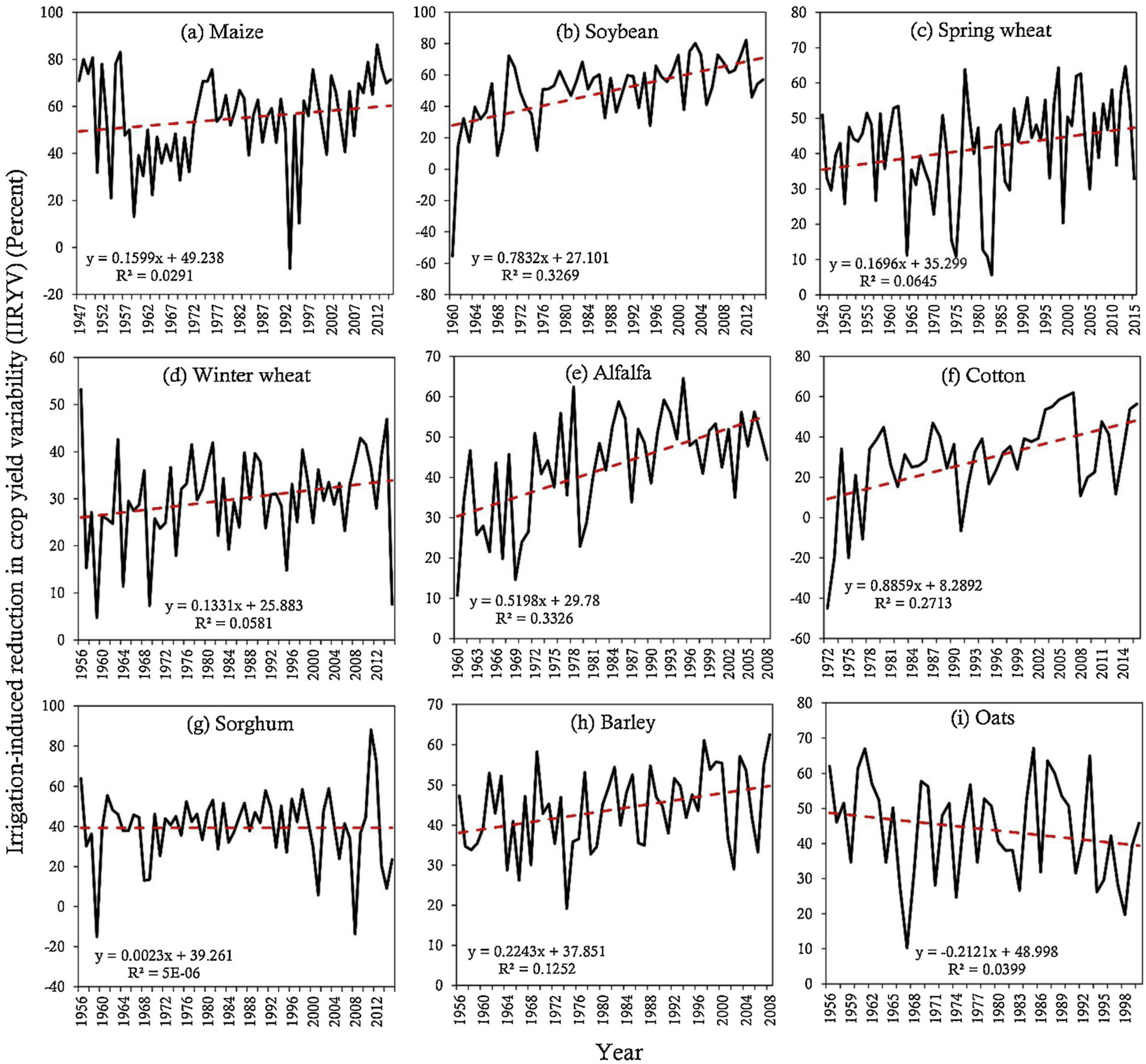

Fig. 4. Temporal trends in national-level Irrigation-Induced Reduction in Crop Yield Variability (IIRYV) for the nine crops. The red trendline shows the linear function fitted through the IIRYV time series. The linear function and coefficient of determination (R^2) of the fitted linear function are provided for each crop. The trend lines for soybean (b), spring wheat (c), alfalfa (e), cotton (f) and barley (h) were statistically significant at the 95 % confidence interval. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

present little or no advantage (eg. eastern Nebraska for alfalfa production, see Fig. 3e). It should be noted that a IIRYV magnitude of 0 (i.e. no reduction in variability) does not mean no benefit of irrigated agriculture over rainfed agriculture, because the advantage in terms of producing greater crop yields under irrigated production still prevails, which has been referred to as "Irrigation-Limited Yield Gaps by Kukal and Irmak (2019a). In the time domain, our findings suggest that IIRYV's for major crops have been increasing, which justifies the growing need of irrigation as we proceed in time. For example, crops like cotton, soybean and alfalfa which show greatest rates of increase in IIRYV need to be given greater focus in terms of irrigation infrastructure and management in the future, given the IIRYV projections are similar. Other studies (e.g., Iizumi et al., 2013; Hazell, 1985) addressed the dynamics of temporal crop yield variability, but none have proposed and quantified difference among irrigated and rainfed production, which we quantified, analyzed and presented here for a wide variety of agronomic crops.

There could be several potential causes of IIRYV variation in space, time and across crop species. It is likely that the spatial variation of IIRYV is driven by change in precipitation received within the crop growing season, primarily because of strong association of rainfed yield variability with precipitation (Kukal and Irmak, 2018a). The role of precipitation in dictating relative magnitudes of irrigated and rainfed crops has been quantified for maize in Nebraska across both spatial and temporal domains (Kukal and Irmak, 2019a). Other plausible factors that could influence spatial differences in IIRYV are differential spatial response of irrigated and rainfed yield variability to coupled temperature and precipitation (Kukal and Irmak, 2018a), crop growing degree days (Kukal and Irmak, 2018; Kukal and Irmak, 2019b), soil types, increased use of inputs, and other spatial changes in environmental conditions (Kucharik and Ramankutty, 2005; Porter and Semonov, 2005; Osborne and Wheeler, 2013; Smith et al., 2007; Chen et al., 2004; Isik and Devadoss, 2006; Calderini and Slafer, 1998; Iizumi et al., 2014), differential weather/climate sensitivity of the same crop under irrigated and rainfed management (Kukal and Irmak, 2018a; Li and Troy, 2018; Troy et al., 2015), irrigation method (sprinkler vs. gravity vs. subsurface or surface drip irrigation) and consequently irrigation efficiency or any other soil and crop management factors (Kucharik and Ramankutty, 2005; Smith et al., 2007; Irmak et al., 2019) to which irrigated and rainfed yields could respond differently. As an exploratory exercise, we used irrigation intensity from MIrAD-US dataset (Pervez and Brown, 2010), as it is the best available indicator of prevalence of irrigation across the U. We found that CYV_{irr} is an inverse function of irrigation intensity for maize, soybean, alfalfa, cotton and sorghum (Supplementary Fig. S11), which are the major crops that potentially govern investment on irrigation infrastructure. This implies that higher the intensity of irrigation (irrigated lands as a fraction of total land), the more stable the crop yields tend to be, although the high scatter implies that there are other confounding factors (listed above) that affect this relationship. One of these factors could be that the MIrAD-US dataset was developed for 2002, whereas the CYV_{irr} magnitudes represent long-term means. Temporal variation in IIRYV could be driven by changes in sensitivity of crop hybrids, cultivars and varieties (Kucharik and Ramankutty, 2005; Lobell et al., 2014; Shi et al., 2013) to changes in precipitation and other hybrid characteristics that differ among irrigated and rainfed production, conversion of gravity irrigation to sprinkler irrigation, and weather variability over time (Kukal and Irmak, 2018a, b).

The inter-crop differences in IIRYV may stem from several reasons. First, these differences, as perceived from a national perspective (Fig. 2b) are a consequence of distinct crop distribution patterns i.e. prevalence of different crops in different regions, which translates into different growing season lengths, environmental conditions (Kukal and Irmak, 2018b), precipitation regimes (Kukal and Irmak, 2016a, b), and differential nature and rates of weather variability encountered (Kukal and Irmak, 2018a). These factors ultimately alter the crop irrigation requirements, which differ both among different crops as well as the same crop grown at different locations, different years, and hence most certainly have an impact on IIRYV. Secondly, the inter-crop IIRYV difference is also driven by the balance among the precipitation received by the rainfed crop and its consumptive use (evapotranspiration) in a given area. A given amount of growing season precipitation might be sufficient to meet crop water requirements for some rainfed crops, so as to be as productive (or approach) as their irrigated counterparts, but that might not be the case for some crops. The relative patterns of IIRYV found in this research are roughly directly related to the crops' consumptive use (Howell et al., 2006; Kukal et al., 2017). For example, cotton and sorghum have lower consumptive use than maize, thus lower IIRYV for former than latter. Finally, differences in intrinsic crop characteristics can impact IIRYV, particularly contrasting drought tolerance characteristics. Plants differ in their response to water limitation by showing a wide range of adaptations at physiological, biochemical and molecular levels (Xoconostle-Cazares et al., 2010). For example, drought-tolerant plants can cope with stress by temporarily diminishing their metabolic functions, regulation of stomatal closure, hygrotropism, reduction of foliar area via leaf rolling etc. (Xoconostle-Cazares et al., 2010). However, some plants have more developed drought tolerance than others, or have received greater focus from the technological advances. The photosynthetic pathways (C_3 vs. C_4) are one aspect of these crop-specific differences (Sage and Kubien, 2007; Kukal and Irmak, 2020) that impact water use efficiency. Thus, the comparative productivity of crops under rainfed and irrigated management is dictated by the drought-tolerant capacities in these crops, and thus governs differences in inter-crop differences in IIRYV. Moreover, different sensitivities towards biotic stresses such as diseases, weed pressure, etc., also contribute to the inter-crop differences in IIRYV.

IIRYV can act as a useful tool in applications in the areas of water resources and agricultural commodities planning and decision-making. Firstly, IIRYV can be a crucial variable when strategizing ground-and surface water withdrawal regulations, which currently do not account for variable returns from irrigation for certain regions and crops. Identifying regions of high IIRYV where irrigation water is groundwater/aquifer-based is becoming crucial (Irmak, 2018). The recent policy updations on groundwater withdrawal regulation and water-rights transfer from agriculture to urban/municipality domains cause conversion of irrigated crop production to rainfed production, rangeland, or ecosystem conservation/wildlife habitat (Brewer et al., 2007; Olmstead et al., 2016) or irrigating in a deficit/limited fashion. In these situations, referring to IIRYV magnitudes in these regions could provide both the user, managers and the policy-makers to understand the detrimental effects of water rights transfer on crop yields and make necessary short- and long-term planning to develop research and science-based precautions/strategies to minimize the impacts. For example, the regulation can be designed such that the dominant crop in a given region shows low IIRYV. Secondly, IIRYV can also be used to plan future spatial crop distribution prioritizing water management challenges, based on long-term historical patterns of crop performance in presence or absence of irrigation. For instance, crops that consistently show higher IIRYV magnitudes than others in a region can imply relative superiority when prioritizing irrigation investments. Thirdly, these findings can inform future efforts in plant breeding and genetics. For example, technological advancements can be selectively carried out in crop cultivars which consistently show greater IIRYV, provided that all the regions can be characterized in terms of cultivars that are generally prevalent. Finally, regions and crops with higher IIRYV can be identified for moisture conservation programs eg. conservation agriculture and other key agronomic practices to increase rainfed productivity. Overall, the information and data presented here can be extremely valuable to enhance overall productivity of the nation's agricultural commodities and aid in sustainability of water resources as well as aiding in meeting the growing demand of rapidly-growing population's demand for food, fiber, feed and fuel.

In the recent past, limited/deficit irrigation has been proposed to optimize crop performance by irrigating at critical crop growth stages in limited-water conditions. Although the impacts of limited irrigation on crop yields has been studied extensively, yet its impacts on long-term crop yield variability due to environmental fluctuations (conceptually IIRYV) are unknown. Theoretically, under deficit irrigation, crop yield response will be less optimum than full irrigation, and thus IIRYV should decrease. Identifying limitedly irrigated regions and growing seasons on a large spatial and temporal extent as this study is a daunting task, and hence, these impacts cannot be appropriately quantified currently. Local research in the field of deficit or limited irrigation impacts on crop yield (Djaman and Irmak, 2012; Payero et al., 2009, 2008; Payero et al., 2006; Zhang et al., 2004; Traore et al., 2000; English and Raja, 1996; NeSmith and Ritchie, 1992; Comas et al., 2019; Howell et al., 2007) should be studied in conjunction with IIRYV findings. This is because, in areas with low to moderate regulation, producers are more likely to employ deficit irrigation, and only in severe cases of regulation, the discourse is to convert an irrigated field to rainfed, if irrigated crop production becomes economically unviable. From an idealistic standpoint, it might seem optimal to allocate irrigation resources to crops and regions with high IIRYV magnitudes. However, when socioeconomic variables and the dependence of different regions on certain crops and consequent industrial and economic implications of such an allocation is considered, this is an enormously challenging pathway. By no means, we intend to propose, in this study, increased adoption of irrigation practices on rainfed area, by highlighting the reduced variability in irrigated agriculture. In fact, increased adoption of irrigation must be weighed carefully against the depleting freshwater resources. It is not recommended to achieve a more stable and reliable food supply at the expense of water resource overuse that could be better used elsewhere (Troy et al., 2015). Moreover, it has to be considered that what the source of irrigation water abstraction is (groundwater or surface water), and depending on region, the current water availability for these sources. Thus, other critical information, especially in regards to freshwater availability and its alternate consumers has to be compounded with our findings. In fact, recent modeling efforts in the Ogallala aquifer ecosystems have shown that due to decreasingly sustainable pumping in significant irrigated areas, transitioning to pasture or dryland production will be a function of land suitability and economic impacts (Deines et al., 2020). Our results should be interpreted as science-based analyses and quantitative resources to understand and recognize the contribution of irrigation in a historical framework in stabilizing crop yields in addition to the benefits of increased yield (Irrigation-limited yield gaps) (Kukal and Irmak, 2019a). The manifestation of the historical levels of IIRYV in the US, especially in the recent past might also be governed by the inter-dynamics among (1) economic investment in irrigation; (2) returns from increased crop yield and profitability; (3) contrasting water availability and water management regimes; and (4) crop-specific characteristics. For example, grain sorghum is a water efficient crop with low input costs. Compared to maize, it has lower consumptive water use, comparable feed value (Chen et al., 1994), 90–95 % energy content, 120–130 % crude protein, 5 % lower 10-year average price (USDA). However, there is a large disparity between irrigated acres among maize and sorghum in the US. Economic profitability of irrigation investments is what has driven these trends. Research has shown that net revenue is greater in maize than grain sorghum when irrigation capacity (water availability) is not limited, however, in water-limited environments, crops with lower cost of production and greater water use efficiency like grain sorghum is an economically superior alternative (Warren et al., 2017). Further, this superiority is further complicated by differences in crop-specific genetic advances. Traits such as pest (insect and weed) protection in maize are not currently present in sorghum, making it challenging to manage.

Although we present the first quantitative evidence of the role of irrigation to alleviate crop yield variability, our study possesses certain cautions, which mainly stem from incompleteness of the USDA-NASS crop yield dataset. Firstly, our period of analysis was not uniform for across the crop panel. For instance, we used data from 1947 to 2015 for maize, whereas, for alfalfa, it was from 1960 to 2008, because of varying availability of yield data from NASS. Due to these dissimilar periods of analysis, the inter-crop comparisons we studied could possibly be examined, although this was an unavoidable challenge. Nevertheless, all the crops included in the analyses have at least 45 years (up to 71 years) of data, which is reasonably long to infer long-term assessments. Secondly, the county-level yield data had missing records within the selected start and end years. To avoid inclusion of counties with unacceptable amount of data, we decided that a county was to be included only if a minimum of 15 years of yield records exist.

Despite data-constraints, the study successfully quantifies the yield-stabilizing trait of irrigated over rainfed crop production (against interannual environmental variability) in the entirety of the conterminous US for nine major national crops. Apart from development of a variable (IIRYV) that is usually referred to, but not mathematically/quantifiably addressed, the strength of the study also lies in its inclusive nature. The study addresses IIRYV for a large range of crops, which accounted for 80 % of the total U.S. crop harvested area (98.5 million hectares) in 2017, and hence, characterizes almost the entire U.S. agricultural crop production. In fact, no study exists that includes the extent of crop variety (nine), and for some crops, is the first-and-only resource to look into in terms of irrigation availability vs. crop yield relationships at large scales. The study also comprehensively addresses the substantial changes in the IIRYV that have occurred historically in both spatial and temporal domains. Thus, we suggest that the study is a pioneer step to spatially and temporally quantify the impacts of irrigation on U.S. agriculture on large scales and offers significant contributions not only to the scientific literature, but is also an invaluable tool for policy and decision-makers for assessing, planning and forecasting the irrigation vs. productivity relationships to enhance future agricultural productivity. While the analyses and findings of this research are limited to US agroecosystems, the use of the IIRYV metric can be extended in its present form to global irrigated agroecosystems to include a wider range of atmospheric water deficit conditions (precipitation vs. evaporative demand), cropping systems, productivity levels achieved, and water availability regimes.

Declaration of Competing Interest

The authors declare no conflict of interest.

Acknowledgments and Disclaimer

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2020.106141.

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