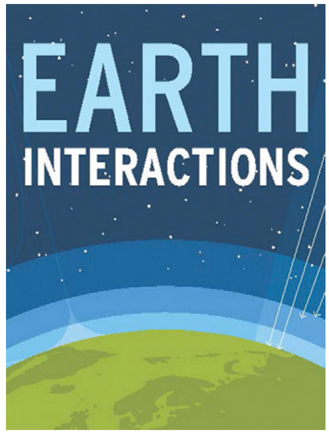

Adaptation of Irrigation Infrastructure on Irrigation Demands under Future Drought in the United States*

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Received 27 September 2014; in final form 19 March 2015

ABSTRACT: More severe droughts in the United States will bring great challenges to irrigation water supply. Here, the authors assessed the potential adaptive effects of irrigation infrastructure under present and more extensive droughts. Based on data over 1985–2005, this study established a statistical

* Kansas Agricultural Experiment Station Contribution Number 15-066-J.

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DOI: 10.1175/EI-D-14-0035.1

model that suggests around 4.4% more irrigation was applied in response to a one-unit reduction in the Palmer drought severity index (PDSI), and approximately 5.0% of irrigation water application could be saved for each 10% decrease in the areas supplied by surface irrigation infrastructure. Based on the results, the model-projected irrigation infrastructure has played a greater role in changes in irrigation than drought in most areas under the current climate except some southwestern counties. However, under the predicted future more severe drought in 2080–99 under the representative concentration pathways 4.5 scenario, the model projected that the drought will require 0%–20% greater irrigation amounts assuming the current irrigation efficiency. Under the predicted drought scenario, irrigation depth can be maintained at or below the baseline level in the western United States only when better irrigation infrastructure replaced 40% of the current surface irrigation infrastructure areas. In the northeast United States, limited changes in irrigation depth were predicted under different irrigation infrastructure scenarios because the percentage of surface irrigation area is already low under the baseline climate, and thus there is limited opportunity to adapt to future drought with advanced irrigation infrastructure. These results indicate that other effective solutions are required to complement these measures and aid U.S. agriculture in the future, more extensive drought.

KEYWORDS: Agriculture; Policy; Risk assessment

1. Introduction

Based on the recent National Climate Assessment (Georgakakos et al. 2014), seasonal drought is expected to intensify in most U.S. regions, and long-term drought will occur in large areas of the southwest, southern Great Plains, and southeast. This drying trend may pose a substantial threat to the U.S. food security because nearly two-thirds of the country's freshwater diversions are used for agricultural irrigation (Kenny et al. 2009). Irrigation has been effectively mitigating drought damage throughout the history of U.S. agriculture (Rogers and Lamm 2012); thus, a critical issue is whether the adaptive capacity of irrigation can keep pace with rapid drying trends and meet the demands for irrigation.

Many studies have found that climate change will substantially increase demands on U.S. irrigation water supply (Doll 2002; Fischer et al. 2007; Cook et al. 2014). For example, based on a hydrologic model, Doll (2002) estimated an increase in irrigation demand of around 10% by the 2070s. Fischer et al. (2007) gave an even more pessimistic prediction of around 25% more irrigation water required as the consequence of climate change, even considering the potential ameliorating effect of elevated CO_2. Potentially more severe droughts and limited potential to increase irrigation water supplies clearly necessitate finding solutions to these conflicting issues to maintain the resilience of irrigated agricultural production.

Despite the availability of many options to adapt to drought, the conventional approach is the adoption of more technically efficient irrigation infrastructures (Osteen et al. 2012; Zhang et al. 2015). According to a national U.S. irrigation survey (Kenny et al. 2009), by 2005 a large portion of irrigation areas were equipped with sprinkler irrigation systems (12.3 million ha), which are slightly larger than the area irrigated by surface irrigation systems (10.8 million ha). Sprinkler irrigation exhibited 13% greater water productivity than the surface irrigation system in experimental fields in Nebraska (Sadras et al. 2011).

However, meeting the current irrigation demand may not be sufficient in a future with more extensive drought. Earlier studies have projected that the extent of future drought resulting from climate change may outpace the existing irrigation adaptive capacity in some countries (Wada et al. 2013; Zhang et al. 2013). Given that the top reason for yield reduction in the United States is water stress (Lobell et al. 2013), understanding the current role of irrigation infrastructures on water supplies will have profound implications on future irrigation under climate change.

The objectives of this study were to (i) identify the effects of climate and irrigation infrastructure on irrigation uses and (ii) evaluate the potential adaptive effects of more efficient irrigation infrastructure on irrigation uses in present and future drought conditions. We define irrigation use as an irrigation depth, that is, the depth of irrigation applied on one unit area. An increase in irrigation depth indicates more demand for irrigation water.

2. Material and methods

2.1. Data sources

Data on irrigation withdrawals and irrigation areas in the United States were collected from the online database of the United State Geological Survey (USGS; USGS 2013). The survey was carried out on the county level every 5 years for the period 1985–2005. We calculated irrigation depth in each combination of county and year in Equation (1):

$$\mathrm{IR}_{i,t} = \frac{W_{i,t}}{A_{i,t}} \times 1000, \tag{1}$$

where IR is irrigation depth (mm); W is the freshwater total irrigation withdrawals specifically for agriculture (m^3); A is total irrigation area (m^2); and i and t denote county and time, respectively.

We also obtained the area served by surface irrigation infrastructures and calculated the percentage of surface irrigation area relative to the total irrigation area in each combination of county and time. The USGS database (USGS 2013) includes three types of common irrigation infrastructures in the United States (i.e., surface irrigation, sprinkler irrigation, and microirrigation). The latter two have greater efficiency than surface irrigation in typical field practice, so a smaller percentage of surface irrigation area implies more advanced irrigation infrastructures and should be associated with a reduced irrigation depth. Here, we use an index to quantify changes in the irrigation infrastructure that occurred during the study period [Equation (2)]:

$$\mathrm{PSIA}_{i,t} = \frac{\mathrm{SA}_{i,t}}{A_{i,t}} \times 100\%, \tag{2}$$

where PSIA is the percentage of surface irrigation area (%), and SA is the surface irrigation area (m^2).

Conversely, a drier climate should be associated with greater irrigation depths required for the crop water demands. We calculated the Palmer drought severity index (PDSI), which has been reported to reflect actual soil moisture conditions (Dai 2013). Our calculation was made by an algorithm from the National Climatic Data Center (NCDC; NCDC 2013). Available water content for the upper and lower soil layers in each county used to calculate PDSI was extracted from the Gridded Soil Survey Geographic Database (Soil Survey Staff 2013). Climate inputs for PDSI calculation were obtained from the Parameter–Elevation Regressions on Independent Slopes Model (PRISM Climate Group 2013) dataset for each county. The calibration period was set to 1931–90, which is the default period in the algorithm.

2.2. Statistical model

Based on county-level data, a fixed-effect model was established to quantify the effects of changes in drought and irrigation infrastructures on irrigation depth. Here, we explored both potential linear and nonlinear effects of climate and irrigation infrastructure. Based on the analysis, the final form of the statistical model would be determined. We assessed the significance of predictive factors' effects to simulate the irrigation depth by comparing five statistical models as follows:

1) Model 1, only the difference among counties was included: $\log(\mathrm{IR}_{i,t}) = c_i + \varepsilon$.
2) Model 2, climate effects were included: $\log(\mathrm{IR}_{i,t}) = \beta_1\mathrm{PDSI}_{i,t} + c_i + \varepsilon$.
3) Model 3, changes in both PDSI and PSIA were included: $\log(\mathrm{IR}_{i,t}) = \beta_1\mathrm{PDSI}_{i,t} + \beta_2\mathrm{PSIA}_{i,t} + c_i + \varepsilon$.
4) Model 4, the quadratic term of PDSI was included to detect the potential nonlinearity effects of climate: $\log(\mathrm{IR}_{i,t}) = \beta_1\mathrm{PDSI}_{i,t} + \beta_2\mathrm{PDSI}^2_{i,t} + \beta_3\mathrm{PSIA}_{i,t} + c_i + \varepsilon$.
5) Model 5, the quadratic term of PSIA was included to detect the potential nonlinearity effects of surface irrigation area: $\log(\mathrm{IR}_{i,t}) = \beta_1\mathrm{PDSI}_{i,t} + \beta_2\mathrm{PSIA}_{i,t} + \beta_3\mathrm{PSIA}^2_{i,t} + c_i + \varepsilon$.

In the above equations, $\log(\mathrm{IR}_{i,t})$ is the natural log-transformed irrigation depth in county i in year t, c_i is the dummy variables of county, and ε is the model's error term.

The contribution of including each term in the regression model was assessed by Akaike's information criterion (AIC) (Burnham and Anderson 2002) for each model. The model with the lowest AIC has the greatest support, and the new included predictive factors are significant contributors when $P < 0.05$.

2.3. Impacts on irrigation depth due to historical PDSI and PSIA

To understand the effects on irrigation depth due to historical changes of climate and irrigation infrastructure, we used the final selected model from the above steps to explore four combinations of fixed and actual PDSI and PSIA. The fixed PDSI or PSIA refers to the level in 1985. The detailed procedure is described as follows using a regression model [f(PDSI, PSIA)]:

1) Simulated irrigation depth with actual PDSI and PSIA: $f(\mathrm{PDSI}_{i,t}, \mathrm{PSIA}_{i,t})$.
2) Simulated irrigation depth with actual PDSI and fixed PSIA: $f(\mathrm{PDSI}_{i,t}, \mathrm{PSIA}_{i,1985})$.

3) Simulated irrigation depth with actual PSIA and fixed PDSI: $f(\mathrm{PDSI}_{i,1985}, \mathrm{PSIA}_{i,t})$.
4) Simulated irrigation depth with fixed PDSI and fixed PSIA: $f(\mathrm{PDSI}_{i,1985}, \mathrm{PSIA}_{i,1985})$.

Thus, the impacts on irrigation depth due to the historical changes of PDSI, PSIA, and combined PDSI and PSIA can be quantified by calculating the differences between 1 and 3, between 1 and 2, and between 1 and 4, respectively.

2.4. Scenario analysis

We obtain the PDSI prediction based on the IPCC Fifth Assessment Report (AR5) ensemble-mean climate under the representative concentration pathway 4.5 (RCP4.5) scenario reported by Dai (2013). The RCP4.5 scenario is representative of an intermediate greenhouse gas emission scenario. The difference in anticipated annual PDSI for the future climate period (2080–99) relative to the baseline climate (1985–2005) was calculated as the PDSI changes due to climate change, which was then input into our statistical model.

To understand the potential adaptation of the current and greater-efficiency irrigation infrastructures under the drier climate, we estimate the change in irrigation depth in above future PDSI scenarios under different PSIA scenarios, that is, keeping the current PSIA and artificially decreasing PSIA at 10%, 20%, 30%, 40%, 50%, and 60% until to zero relative to the baseline level.

3. Results

3.1. Irrigation depth and major irrigation infrastructure in the United States

There is a clear spatial distribution for both the irrigation depth and major irrigation infrastructure applied (Figure 1). The irrigation depth in the eastern United States is much less than in the west. In the eastern region, 250–500 mm of irrigation water was applied annually; in contrast, no less than 750 mm was needed in 1985–2005 in the western region (Figure 1a). This difference is primarily because of the more humid climate in the east. However, the western areas with greater amounts of irrigation are not coincident with greater-efficiency irrigation infrastructure. More than 60% of the irrigation areas in the west were surface irrigation systems with relatively less efficiency compared with eastern systems, which primarily used more efficient sprinkler irrigation (Figure 1b). It should be noted that certain cropping systems are more suitable for or are more associated with certain types of irrigation infrastructures (e.g., rice and surface irrigation) and also geographical constraints can affect the selected irrigation infrastructure (e.g., surface irrigation unsuitable for undulating slopes). These aspects are inherently embedded in the results and probably do affect the adaptive change that has occurred and potentially can occur. However, further separation of these aforementioned cropping and geographical aspects on a national scale for the United States are not possible with the existing datasets available at the present time.

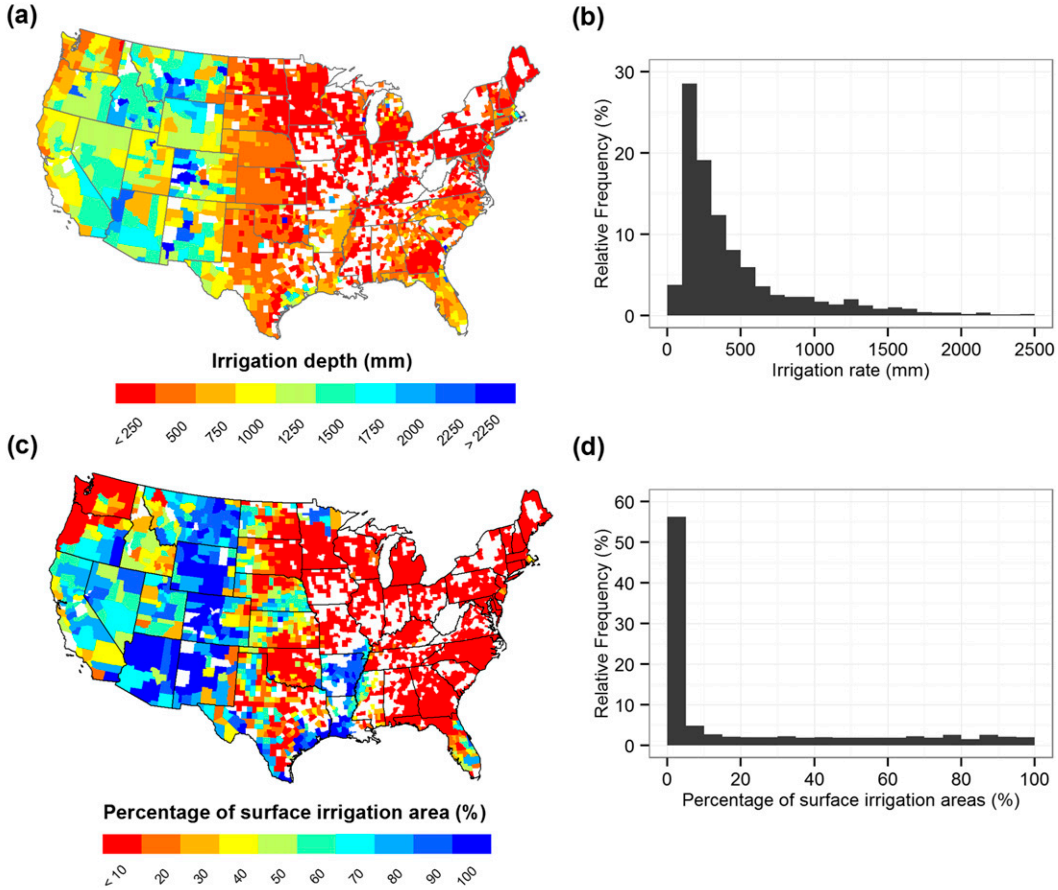

Figure 1. (a) Spatial distribution of average irrigation depth and (c) percentage of surface irrigation area during 1985–2005 and (b),(d) their histograms.

3.2. Statistical model construction

Based on those data, we compared the contribution of adding each predictive factor into the statistical models and detected the significance of each, as described in section 2. In a set of candidate models (Table 1), our analysis suggested that both PDSI and PSIA make a significant contribution to variance in irrigation depths because model 3 has smaller AIC than models 1 and 2. Both PDSI and PSIA exhibit a statistically significant meaning ($P < 0.05$) compared with the models including only one individual factor (Tables 1a,b). Model 4 is not more significant than model 3 ($P = 0.2676$), which indicates a weak quadratic effect for PDSI (Table 1c); however, the quadratic term of PSIA has a significant effect because model 5 showed a smaller AIC than model 3, and including the effect significantly improves the explanatory power of the model ($P < 0.05$) (Table 1d). Therefore, model 5 was selected for subsequent analysis in our study.

According to model 5, PDSI negatively affects irrigation depth (Table 2), indicating that drought would result in additional irrigation. PSIA had a positive

Table 1. Statistics summary of candidate models. The model forms can be found in section 2. RSS refers to the residual sum of squares and SS refers to the sum of squares.

Candidate models					
(a) Model 1 vs model 2					
Model	AIC	RSS	SS	*F* value	*P* value
Model 1	23 683.7	8832			
Model 2	23 550.48	8831	45.061	108.83	$<2.2 \times 10^{-16}$
(b) Model 2 vs model 3					
Model	AIC	RSS	SS	*F* value	*P* value
Model 2	23 550.48	8831			
Model 3	23 425.65	8830	41.766	102.03	$<2.2 \times 10^{-16}$
(c) Model 3 vs model 4					
Model	AIC	RSS	SS	*F* value	*P* value
Model 3	23 425.65	8830			
Model 4	23 426.11	8829	0.503 12	1.2291	0.2676
(d) Model 3 vs model 5					
Model	AIC	RSS	SS	*F* value	*P* value
Model 3	23 425.65	8830			
Model 5	23 389.86	8829	12.35	30.27	3.862×10^{-8}

effect on irrigation depth, showing that more advanced irrigation infrastructure would decrease irrigation depth and thus less water would be needed to counteract the same degree of drought. Interestingly, the quadratic term of PSIA was significantly negative, indicating that an inverse *U* pattern (the ascending part) exists on PSIA effects (Table 2).

3.3. Simulated irrigation depth impacts, 1985–2005

Figure 2 illustrates the average of PDSI and the trends of PDSI and PSIA in the period 1985–2005. Relative to the calibration period, the average PDSI for our study period indicates a wetter climate in the middle and northeast United States and a slightly dryer climate in the west (Figure 2a). In our study period, a clear drying trend occurs for climate in the counties located in the southwestern and central regions; PDSI decreased by 0.5–2.0 decade^{-1}. But climate tended to become wet in the west, as well as several other states, such as North Dakota, Florida, and Maine (Figure 2a). Conversely, the percentage of surface irrigation areas shows a decreasing trend in most states except Idaho and South Dakota, where surface irrigation increased by 10%–30% decade^{-1}.

By assuming the 1985 level of PSIA in our model, we found the PDSI change resulted in both increased and decreased irrigation depth, with variability of −15% to 15% from county to county. On average, the irrigation depth increased around 4.4% when PDSI decreased by one unit (Figure 3a). The counties with increasing

Table 2. Regression coefficients of modeling-estimated irrigation depths in model 5. Adjusted *R* squared is 0.9876 and the *P* value is $<2.2 \times 10^{-16}$.

Variables	Estimated	SE	*t* value	*P* value
PDSI	-4.21×10^{-2}	4.11×10^{-3}	−10.2473	<0.001
PSIA	1.22×10^{-2}	1.41×10^{-3}	8.650 429	<0.001
PSIA	-8.18×10^{-5}	1.49×10^{-5}	−5.501 83	<0.001

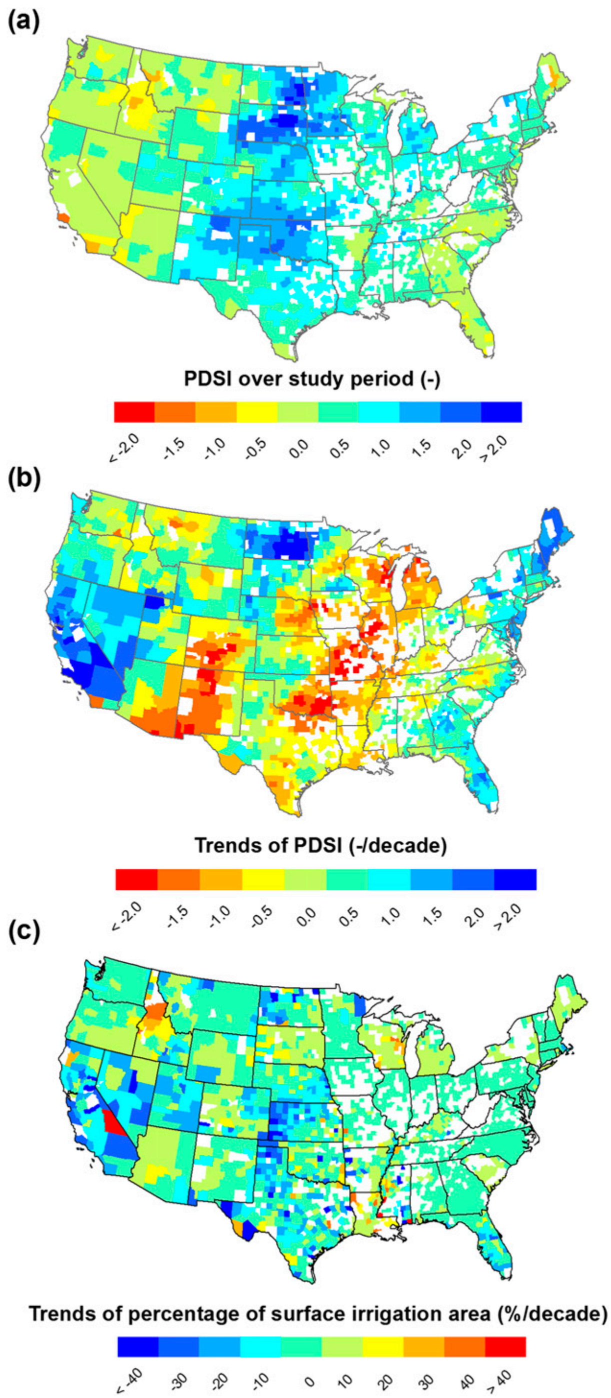

Figure 2. (a) Average, (b) trends of PDSI, and (c) trend of percentage of surface irrigation area in the United States in 1985–2005.

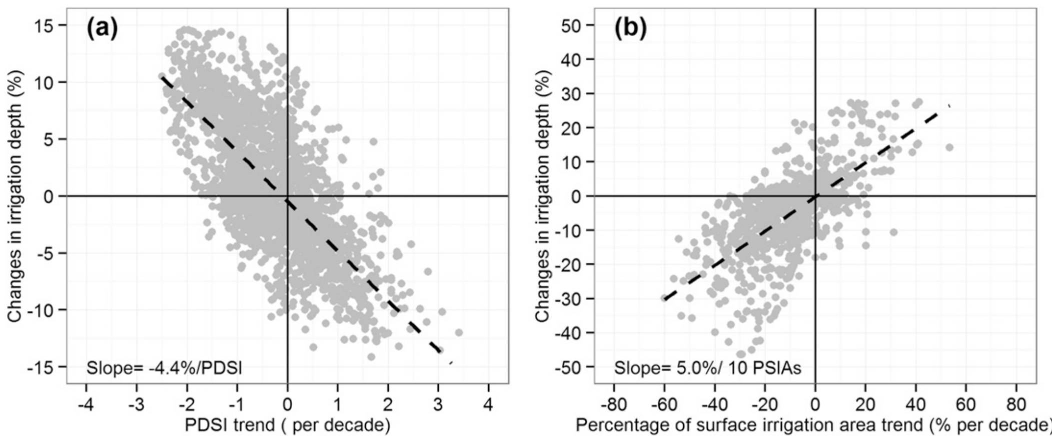

Figure 3. Changes in irrigation depth because of changes in (a) PDSI and (b) PSIA during 1985–2005.

trends were located in the southwest United States, such as Arizona, New Mexico, and Colorado, where an increase of 10%–20% resulted from changes in PDSI in the area, whereas the irrigation depth tended to decline in counties located in the north and northwest regions (Figure 4a). Conversely, changes in irrigation infrastructure also resulted in changes in irrigation depth with variability of −40% to 30%. Each additional 10% increase in PSIA raised the irrigation depth by 5.0% (Figure 3b). The irrigation depth tends to decrease as more advanced irrigation infrastructure is adopted, particularly in California, Nevada, Utah, Kansas, and Nebraska (Figure 4b), but for some counties in Idaho and South Dakota, an increase in irrigation depth was found because of the expanding surface irrigation area (Figure 4b). Figure 4c illustrates the combined effects of PDSI and PSIA. Counties in the states of Arizona, New Mexico, and Colorado exhibited a major increase in irrigation depth primarily because of the effect of PDSI (Figure 4a), unlike other areas in which changes in the irrigation infrastructure mainly drove irrigation depth and exhibited a pattern similar to that observed in Figure 4b.

3.4. Potential impacts of more extensive drought and adaptation

Figure 5a demonstrates the future PDSI changes as estimated by Dai (2013), which show a decreasing trend in the majority of the United States. The western part will see 0–6 lower PDSI than the baseline climate, and the northeastern region will show a 0–2 decrease. Only Florida and Maine were projected to have a slightly wetter climate, showing a 0–1 increase in PDSI. Consequently, keeping the constant PSIA under the baseline climate, the irrigation depth was projected higher than the baseline climate (Figure 5b). In the western part, irrigation depth was projected to be 10%–20% higher than the baseline climate level, and the projected change varies between 0% and 15% in northeast.

Figure 6 depicts spatial distribution of projected changes in irrigation depth when using six different PSIA scenarios under the predicted future drought conditions. We found that the western United States will require a greater irrigation depth induced by

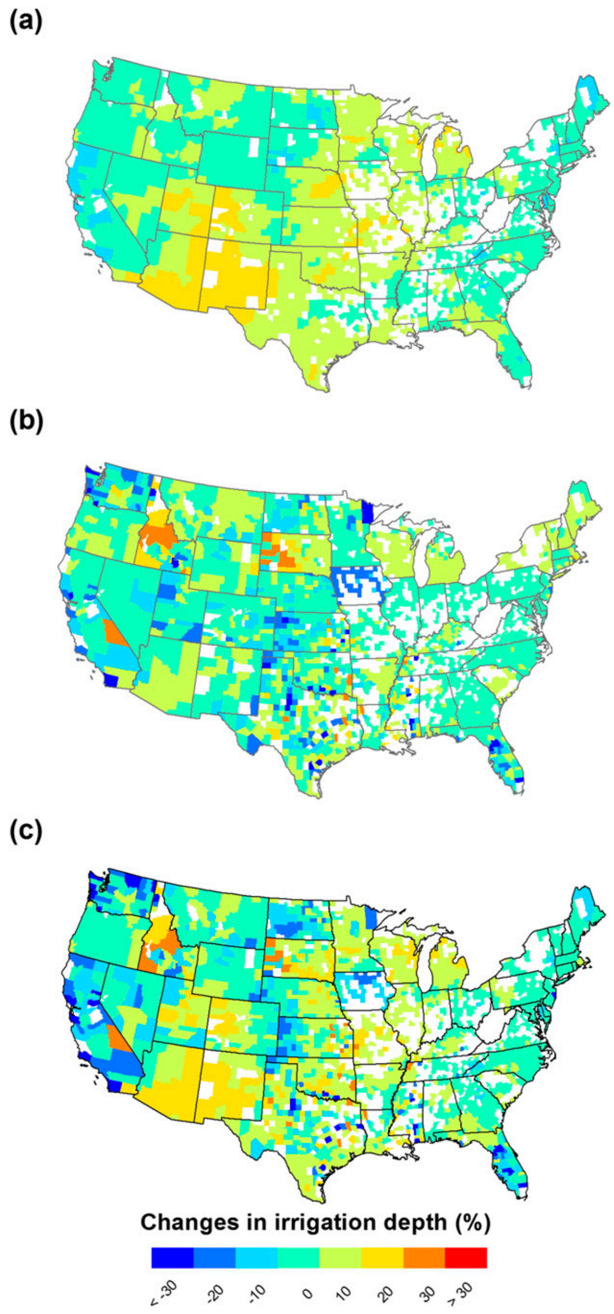

Figure 4. Spatial distribution of simulated changes in irrigation depth due to the trends in (a) PDSI, (b) PSIA, and (c) the combined effects of PDSI and PSIA in 1985–2005.

the future PDSI (Figures 6a–c) until PSIA was reduced by 40% (Figures 6d–f) at which time irrigation depth will become less than the baseline level. For the northeastern part, the projected changes in irrigation depth are quite similar under all six PSIA scenarios.

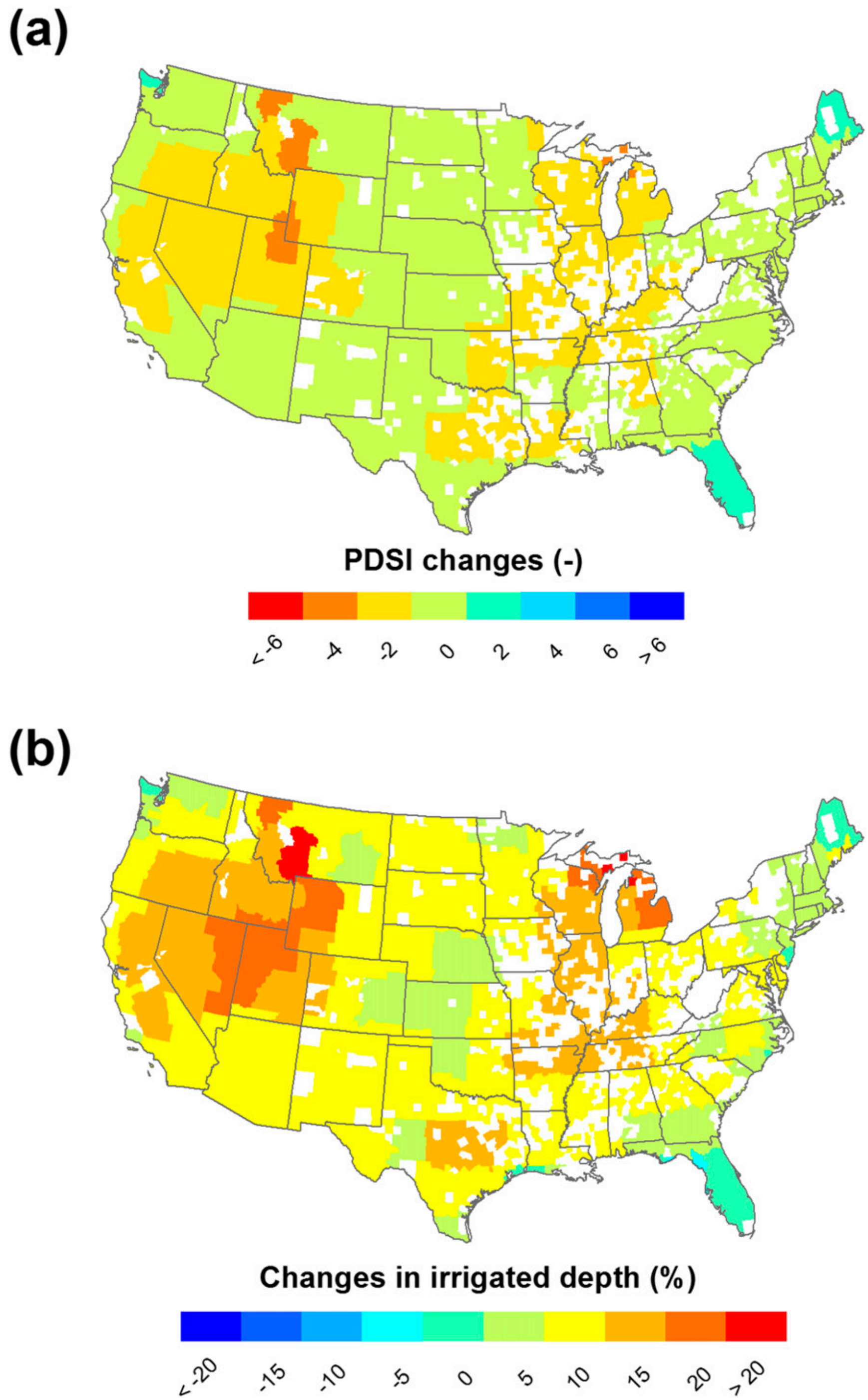

Figure 5. (a) Changes in annual PDSI over 2080–99 relative to the baseline climate based on the results of Dai (2013) and (b) simulated changes in irrigation depth under the anticipated PDSI in the future climate, keeping the PSIA of baseline climate.

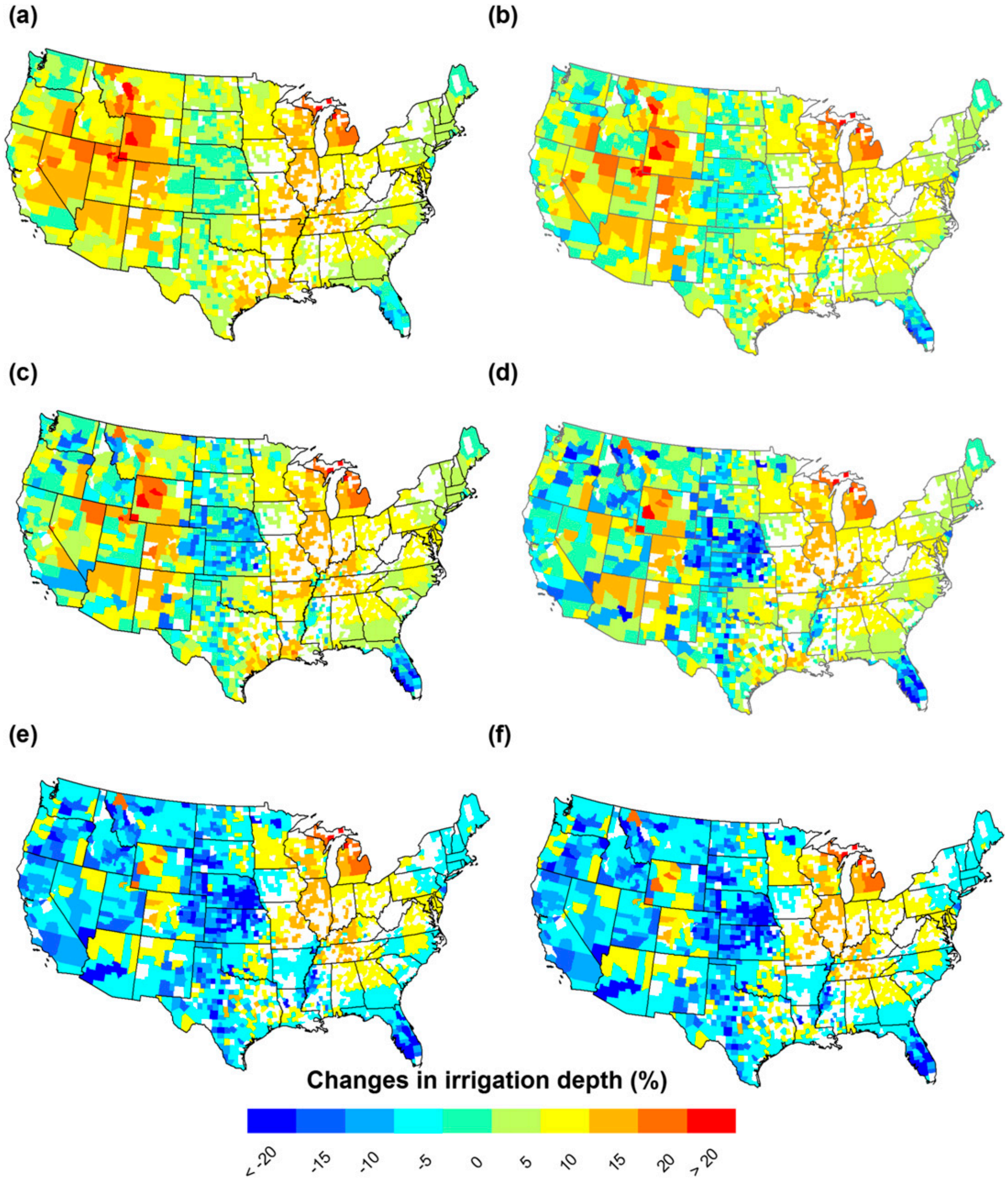

Figure 6. Simulated changes in irrigation depth relative to the baseline climate when reducing by (a) 10%, (b) 20%, (c) 30%, (d) 40%, (e) 50%, and (f) 60% PSIA in model.

4. Discussion

Future food security will to a large extent be determined by the capacity for adaptation of agriculture to cope with climate risks. Whether the irrigation infrastructure can supply enough water under drought conditions is one of the measures of the resilience of agriculture. In this study, we estimated the changes in U.S.

irrigation depth as affected by changes in irrigation infrastructure under current and potential future climate conditions.

Based on county-level data, we established a statistical model to quantify the potential effects of drought and irrigation infrastructure on irrigation depth. As shown by our model, changes in both drought conditions and irrigation infrastructure have proved to be significant contributors to changes in irrigation depths (Table 1). More severe drought would increase the need for irrigation; nationwide, an additional 4.4% of irrigation water would need to be applied for each one-unit reduction in PDSI (Figure 3a). Adoption of more technically efficient irrigation infrastructure would help offset the crop water needs; each 10% reduction in PSIA would decrease irrigation depth by approximately 5.0%, when holding other factors constant (Figure 3b). These results are similar to earlier studies conducted on experimental fields (Grassini et al. 2011; Masoero et al. 2013) and state-level data (McDonald and Girvetz 2013), which also suggested drier climate leads to additional irrigation use but that it can be partially counteracted by greater-efficiency irrigation technology. The county-level datasets used here not only confirm the past studies but also provide a broader-scale quantification.

Under the present climate, our model estimated that changes in irrigation infrastructure have played a more dominant role than climate factors in most areas (Figure 4) except in the southwestern region (Arizona, New Mexico, and Colorado), where progressively more arid climate has caused 10%–20% more irrigation application (Figure 4a), and this effect was stronger than the irrigation infrastructure (Figure 4b). Usually, more severe drought increases irrigation application, but if drought also begins to affect available irrigation water supplies, it can also limit irrigation, that is, a nonlinear relationship between irrigation and drought severity (Jones 2000). However, based on the historical data in the United States, we did not find the quadratic effect of PDSI to be statistically significant on irrigation depth (Table 1), which may indicate the threshold has not been reached for U.S. agriculture. Another possible reason is that drought may only affect available water supplies in specific regions of the United States. For example, some regions heavily depend on deeper groundwater that may remain as readily available during drought. Conversely, we detected a statistically significant quadratic effect for PSIA (Table 1), which suggests more irrigation water could be increasingly saved as more and more advanced irrigation infrastructure is adopted (Table 2).

Despite the dominant effect of irrigation infrastructure under the present climate, it may be inadequate to manage more extensive droughts. Based on the prediction by Dai (2013), most areas of the United States will be subjected to a dryer climate with a PDSI decrease of 0–6 (Figure 5a). This drying rate clearly surpasses historical rates (Figure 2a) and would lead to more irrigation water demand, which is consistent with previous studies using other modeling approaches (Fischer et al. 2007; Schlenker et al. 2005). In this study, our model projected whether the current irrigation efficiency is adequate to adapt more severe drought. Based on the model and assuming the current irrigation efficiency under the future climate conditions, a 0%–20% higher irrigation depth was projected in the most area of the United States with the western region showing the largest increase (Figure 5b). This indicates future drought conditions will result in considerably greater water demands given the current irrigation efficiency. By artificially reducing PSIA, our model suggested that only when surface irrigation infrastructure areas were decreased by 40% (Figure 6d) and replaced by more advanced irrigation infrastructure could the irrigation depth be maintained at the baseline level in the western United States. It has to be stressed that removing the 40% surface irrigation system and complete adoption of greater-efficiency irrigation systems is probably unrealistic because surface irrigation predominates in some regions for certain crops and for salinity control. Additionally, more advanced irrigation infrastructure often requires a larger investment that cannot be offset by the crop revenue (Seo et al. 2008; Schuck et al. 2005). Therefore, we prefer to view this result for the western United States not as predictions of actual adaptation but rather as the largest potential adaptive capacity obtainable by further adopting a greater-efficiency irrigation infrastructure. Conversely, we also noticed that irrigation depth was projected consistently higher in the northeastern region under all PSIA scenarios. This is because the percentage of surface irrigation area is already low under the baseline climate (Figure 1c), and limited adoption of advanced irrigation infrastructure can occur. In this case, the adoption of drought-tolerant cultivars (Chang et al. 2013), improved tillage management (Derpsch 2014), and the use of appropriate irrigation and fertilizer management (Sadras et al. 2011) could also contribute to greater crop water productivity and soften the harmful effects of more intensive and extensive droughts.

Our model did not explicitly account for CO_2 effects in which elevated CO_2 would improve crop water productivity and reduce water requirements, thus potentially reducing irrigation requirements (Ainsworth and Rogers 2007; Bernacchi et al. 2007). Whether this effect would be a major factor in actual field conditions has not been determined. Based on previous studies, the effect varies depending on region (McGrath and Lobell 2013), crops (Leakey 2009), and water status (McGrath and Lobell 2011), indicating that a large amount of uncertainty about the effect remains.

5. Conclusions

Our study provides a useful quantification to assess changes in irrigation use under current and future droughts in the United States. We found that adopting greater-efficiency irrigation infrastructure has dominated changes in irrigation depth in the climate of the United States from 1985 to 2005; however, this single approach is inadequate to cope with more extensive drought predicted in future climate. Based on our model in the western United States, only a significant reduction in surface irrigation area (at least 40%) can maintain the irrigation depth at the baseline climate. And, in the northeast, such adaptation is even more limited. This indicates that additional solute ions would be required to supplement changes in irrigation infrastructure and thus sustain U.S. agriculture at its present levels, not reflecting even greater food needs projected from world population increases. Our scenario analysis results may be useful in guiding agricultural water policy to meet the water demands resulting from climate change.

Acknowledgments. We appreciate the insightful comments of the reviewers and editor. The study was supported by the Ogallala Aquifer Initiative program, the U.S. Department of Agriculture (USDA)/Agricultural Research Service (OAP58-6209-2-73), and partially supported by the Kansas KWRI program.

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