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Water storage and agricultural resilience to drought: historical evidence of the capacity and institutional limits in the United States

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Abstract

Food systems are particularly sensitive to changing precipitation patterns. Resilience via irrigation will depend on baseline conditions, water source, and institutional constraints which have not been studied jointly. We draw on over 100 years of agricultural production and weather data across the United States to identify the extent to which access to stored water—distinguished by its source and location—affects drought resiliency. Arid regions with access to stored water avoided the 13% losses in crop value experienced in irrigated areas with more limited storage during droughts. Humid regions are also beginning to adopt irrigation, but with less aggregate impact during drought. The incomplete governance of groundwater withdrawals in many areas allow resiliency in the near-term, but potentially at the expense of future water availability. Conversely, surface water rights allow for the widespread application of irrigation water, but with less resiliency during significant periods of drought.

1. Introduction

As extreme weather events become more common under climate change, understanding the resiliency of food systems, which are particularly sensitive to changing precipitation patterns, is critical (Wheeler and Von Braun 2013, Challinor *et al* 2014, Rosenzweig *et al* 2014). Irrigation has been a long-term adaptation strategy to increase production in arid regions and has been shown to increase crop yields during extreme heat and drought (Troy *et al* 2015, Zhang *et al* 2015, Tack *et al* 2017, Edwards and Smith 2018, Zaveri and Lobell 2019). Irrigation's contribution to agricultural resilience, defined here as the capacity to absorb yearly deviations from mean weather without production losses, has become a key area of interest (Di Falco and Chavas 2008, Michler *et al* 2019). However, few studies integrate the multiple margins of adaptation, shaped largely by institutions, upon which farmers adjust irrigation to increase resilience. This paper considers how farmers have utilized stored water for resiliency in the Unites States across time, regions, and water sources, showing that 'irrigation' is not a panacea, and we should carefully consider how institutions and the natural and built environment affect farmer adaptation.

The physiological relationship between crops and water informs the challenges drought presents (Alexandrov and Hoogenboom 2000, Carter 2013) or conversely, the value of providing supplemental water through irrigation (D'Odorico *et al* 2020). In practice, however, effective deployment of irrigation for climactic resiliency requires access to water reserves—costly in dollars and to the environment whether through surface reservoirs or groundwater depletion—and is constrained by institutions, which differ across regions and by water source (Porter *et al* 2017, Martinich and Crimmins 2019). Consequently, empirical evidence of the *resiliency* maintained by stored water, and the associated institutional constraints that shape farmers' adaptation decisions, is critical to understanding agricultural performance under future climate scenarios (Famiglietti 2014, Grafton *et al* 2013).

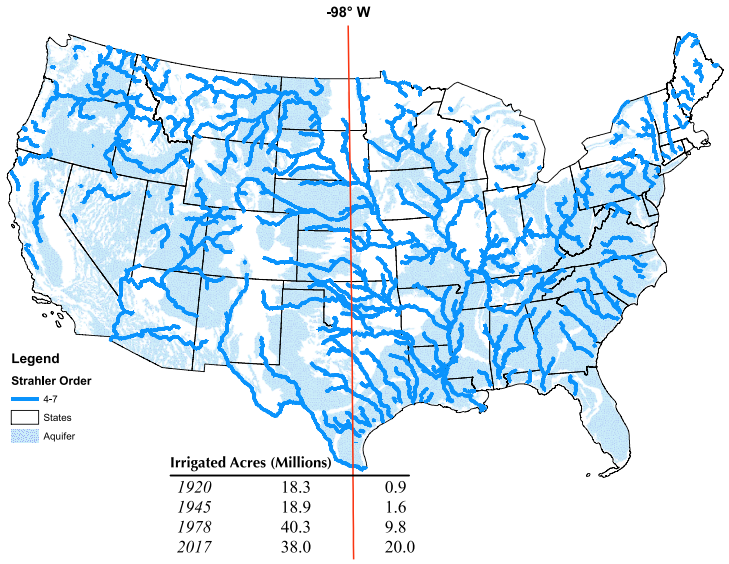


Figure 1. Water storage access in the United States.
Notes: Irrigated acres are bifurcated by the 98th meridian based on county centroids.
Sources: Authors' rendering of data; see text. Irrigated acreage tabulated from the U.S. Agriculture Censuses.

In pursuit of clean causal identification, many assessments of the economic impact of climate change and weather shocks on agriculture have excluded irrigated areas on the grounds that irrigation is institutionally complex (water allocation rules are locally specific) and their inclusion obfuscates the direct effect of weather, i.e. irrigated areas are poor proxies for non-irrigated areas (Schlenker *et al* 2005, Schlenker and Roberts 2009, Burke and Emerick 2016). Despite these challenges, a more complete accounting of irrigation's role in climate resiliency is necessary. Irrigated cropland, institutionally complex or not, comprises a large share of the world food production system, and in the U.S. produced 53% of total crop value in 2017 (USDA 2019).

Studies that explicitly examine the role of irrigation typically define areas as irrigated by their prior observed levels of irrigation at a particular time (Kuwayama *et al* 2019, Cui 2020). This approach assumes away some dynamic and endogenous year-to-year decision making that could help explain adaptation behavior. In addition, empirical trends undercut the narrative that irrigation is not a potential margin for adjustment in historically non-irrigated regions. Although it is unlikely that the U.S. will witness another dam bonanza like the arid West's in the mid-20th century, farms in the humid eastern U.S. have nonetheless doubled irrigated area since 1978, and now account for over one-third of the country's total irrigated acreage (Edwards and Smith 2018).

In this paper, we draw on over 100 years of county-level crop production and weather data across the U.S. to identify resiliency garnered through stored irrigation water to locally defined precipitation shocks. Our main analysis focuses on the arid West given its long history with irrigation adaptations. This historical perspective of agricultural adaptation to climate variation can provide a wealth of insights for future adaptation (e.g. Hansen *et al* 2011, Olmstead and Rhode 2011). Rather than taking the irrigation decision as given, we utilize the presence of larger streams (associated with large federal reservoir projects) and aquifers, both shown in figure 1, to predict the availability of stored irrigation water at the county level. Comparison before and after these stores of water were developed in the mid-twentieth century shows these counties saw significant overall gains in production, particularly in the arid West (Edwards and Smith 2018).

We account for the long-term average gains from irrigation, but our focus is on the extent to which stored water provides short-term resilience to drought. By differentiating the responses by the source—ground or surface water—our results identify distinct patterns, yielding an empirically-based foundation to assess emerging institutional challenges associated with water management for agricultural resiliency in the U.S. These challenges are shaped by the distinct water rights broadly differentiated by source and geography. While surface water rights in the western U.S. are shaped by quantified limits and other rules of the prior appropriation doctrine, groundwater was generally an open-access resource with local limitations emerging more recently in some areas (Ayres *et al* 2018, Hrozencik *et al* 2017, Smith *et al* 2017, Drysdale and Hendricks 2018). Eastern water rights remain unquantified and are generally less regulated across both water types.

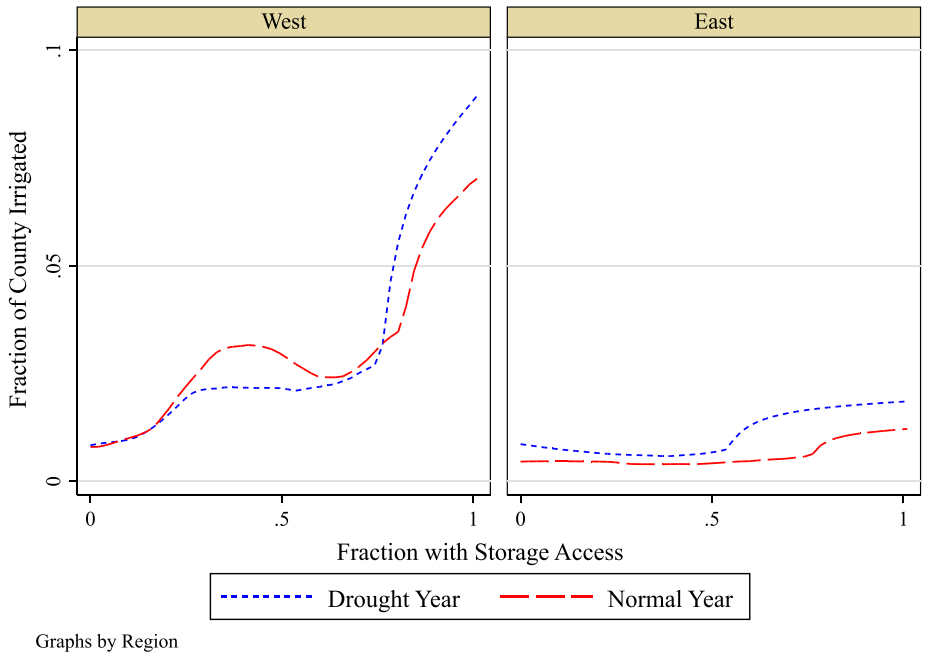


Figure 2. Fraction irrigated by east/west, storage access, and precipitation conditions, 1950–2017.
Notes: Local polynomial of the fraction of the county irrigated and the fraction of the county with access to an aquifer or within 15 miles of a large stream (or both). Drought is being below 1.5 standard deviations of the county's historical precipitation distribution. The left panel shows the response for irrigated counties west of the 98th meridian. The right panel shows the response for counties east of the 98th meridian.
Sources: Authors' rendering of data; see text.

2. Irrigation response to drought

In the U.S., irrigation is typically associated with the West. However, the eastern portions of the country are increasingly investing in additional irrigation infrastructure, often in response to recent drought conditions (see table A1, SI material available online at stacks.iop.org/ERL/16/124020/mmedia). The investment is not for annual use, but an adaptation used during drought. Over 90% of the acreage taken out of irrigation in 2018 was discontinued 'temporarily,' and the most common explanation for the action was 'sufficient soil moisture' (USDA 2019). Figure 2 shows local polynomials plotting the fraction of U.S. counties irrigated against the share of the county with access to stored water (surface or ground) separately for the west and east as well as by drought condition. Access to water storage leads farmers to irrigate more acres in normal precipitation years (defined at the county level). During drought years, access to water storage also allows farmers to add irrigated acres relative to areas with lower levels of storage access. This pattern is consistent in both the west and the east, but with some important distinctions. Indicative of more widespread water availability, overall irrigated share remains smaller and eastern counties increase irrigation across all storage access types. Conversely, in the west, areas with less storage are not able to increase irrigation in drought years. Only western counties with the most access to stored water are able to respond to drought by increasing irrigated acreage.

3. Empirical approach

A key barrier to statistically estimating the contribution of irrigation to resilience is that it is not randomly turned on and off. To overcome this issue, we go back in time to the adoption of significant additional stored water across the western U.S. to apply the intuition of a difference-in-difference framework. Prior to 1950, irrigation development across the West was limited to small diversion works for surface sources, and the storage potential of large rivers and subsurface aquifers remained mostly untapped and mattered little. But these water resources strongly predict the location of expanded water stores in the second half the century (Edwards and Smith 2018). The completion of Hoover Dam in 1936 was the first of numerous large federal reclamation projects augmenting water availability on large streams, far outstripping the storage previously made by private and early government efforts (see SI figure A1). Shortly thereafter, technological innovation made stored groundwater economically viable for irrigation on the Great Plains (Hornbeck and Keskin 2014) and across the West (Edwards and Smith 2018). We characterize two time-periods and two groups to assess the impact of stored water on resilience: pre/post-1950 and access/no-access to storable irrigation water.

The location where stored water is developed is likely endogenous to other productive characteristics of the immediate area, so we instead rely on 'access' to predict development choices. Specifically, for each county we calculate the share over an aquifer and the share within 15 miles of a 'large' stream (and share of both). Edwards and Smith (2018) demonstrate that these define areas more likely to develop groundwater wells, if over an aquifer, and receive stored water from Bureau of Reclamation projects, if near a large stream. To create the categorical assignments for counties used in the analysis, we took counties in the bottom 25th percentile of total access and assigned them as 'small streams'—those which may irrigate but have limited access to surface storage or groundwater supplies—assigning the remaining counties the access type that covers the largest share of county. See figure A2 in the SI for a mapping of the measures. Details on data construction and descriptive statistics (tables A2 and A3) are provided in the SI.

To test how storage access affects resiliency, we construct a panel data set measuring crop production (the combined value of all crops produced), irrigated acreage, and yields of corn and soybeans consisting of 2920 U.S. counties from the 20 Agricultural Censuses from 1910 to 2017 (Haines *et al* 2018, USDA 2019). To capture precipitation shocks, we calculate the mean cumulative growing season precipitation, $\bar{\mu}_i$, and standard deviation, $\bar{\sigma}_i$ over the sample period for each county based on historical records from PRISM (2004). Our measure of precipitation shock in year t is then calculated as a normalized precipitation anomaly:

$$\hat{y}_{i,t} = \frac{\bar{\mu}_i - \widehat{\text{precip}}_{i,t}}{\bar{\sigma}_i}. \quad (1)$$

This variable is used to group precipitation into five bins to facilitate interpretation of interacted variables in our empirical approach. Normal years are assigned as within one standard deviation centered at zero, somewhat dry years as falling between 0.5 and 1.5 standard deviations below the mean, and severe drought years precipitation below 1.5 standard deviations. We similarly define wetter years on the other side of the distribution. On average, severe drought corresponds to a reduction of 6 inches of growing season precipitation in the West and 9 inches in the East. Distributions, temporal and spatial, of the normalized measure in the arid west are provided in figures A3 and A4.

Our main analysis draws on the irrigated counties of the arid-West, delineated by the 98th meridian, allowing causal inference of the stored irrigation water developed after 1950 as predicted by the presence of potential stores of water. To ensure we are looking at the effect of stored water compared to other irrigated areas, we keep only the counties in the top 70% of average irrigated share in the post-1950 period. Counties excluded average 12% of farmland irrigated, whereas the sample of counties we analyze average 44% of farmland irrigated. Prior work has utilized percentage as cutoffs for 'irrigated counties' ranging from 5%–20% (Schlenker *et al* 2005, Fisher *et al* 2012, Kuwayama *et al* 2019) or simply the 100th meridian (Burke and Emerick 2016).

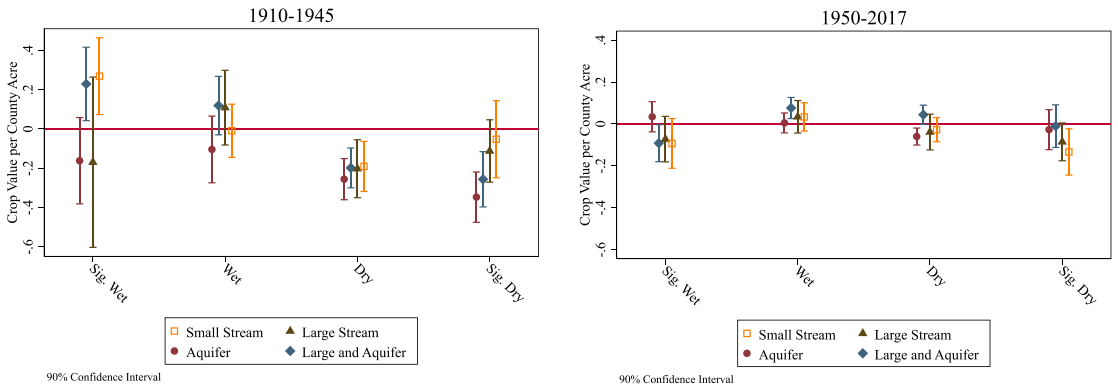
To examine the effect of increased storage across the k different types of storage technologies (surface dams, groundwater, and both) on resilience to precipitation anomalies, we regress the outcome variables of interest on the interactions between the realized precipitation shock bin, $\text{Bin}^j_{it}, j \in (-2,2)$, and indicator variables for whether county i receives a particular storage treatment after 1950, $\text{Stor}^k_i, k \in (1,3)$:

$$Y_{it} = \sum_{j=-2}^{2} \alpha^j \cdot \text{Bin}^j_{it} + \sum_k \sum_{j=-2}^{2} \beta^{jk} \cdot \text{Stor}^k_i \times \text{Bin}^j_{it} + \boldsymbol{f}(\text{temp}_{it}) + \tau_t + \gamma_i + u_{it}. \quad (2)$$

In these regressions we exclude the 'normal' precipitation bin ($\text{Bin}^0_{it} = 1[-.5 \leqslant \hat{y}_{i,t} \leqslant .5]$, where $\hat{y}_{i,t}$ is defined by equation (1)) and counties without storage are the baseline. Here the coefficient β^{jk} shows the effect of storage type k on climate bin j relative to the same county with precipitation in the middle bin and no storage. Our use of categorical storage availability eases the interpretation and visual representation of coefficient estimates, but we also provide results in the SI material that utilize the continuous measure of irrigation access—the fraction of a county (a) overlaying an aquifer, (b) within 15 miles of a large stream, (c) or both—for robustness. To get the average effect across storage types, we also provide in the SI material a specification and results that combine counties of different storage types into a single category of 'storage'.

We do control for annual growing season temperature using a flexible polynomial function, $\boldsymbol{f}(\text{temp}_{it})$. For the main analysis we utilize a third-order polynomial, but results are not sensitive to different ordered polynomials. τ_t and γ_i absorb time and county fixed effects. The key identifying assumption is that conditional on covariates county precipitation shocks affect outcome variables only through their effect on agricultural production.

The above regression is run separately on pre- and post-1950 observations. This comparative approach establishes different county means before and after 1950, netting out the average gains generated by the development of these water sources. The usefulness of the approach is demonstrated in figure A5 of the SI material. Before 1950, counties with and without future storage irrigated similar amounts while responding with less irrigation when water was plentiful (reduced demand) or lacking (reduced supply). After 1950, counties with more access to stored water irrigated more under 'normal' precipitation,



Panel A Panel B

Figure 3. Effect of irrigation water storage on crop value by precipitation conditions, in the West.
Notes: Coefficient estimates of equation (2) for crop value per acre (logged) by time period. The estimates represent deviations from a county's average relative to normal levels of precipitation.
Sources: Authors' estimation; see text.

but also had the ability to increase irrigated acreage in drier years whereas the low-access counties irrigate less.

Finally, we also run the regressions for the counties east of the 98th meridian. The natural experiment is not as strong in this context with little pre-1950 irrigation development to provide a baseline and we do not screen the sample by observed irrigation levels. These estimates are informative of emerging trends in the East, although the causal claim is weaker.

4. Results

Figure 3 shows that areas with access to stored water—particularly groundwater—provide resilience for crop production during severe droughts after those sources have been developed. Panels A and B of figure 3 plot the coefficients from estimating equation (2) with (logged) crop value per county acre as the outcome variable in the two different time-periods. Prior to 1950 (panel A), dry and significantly dry years reduced crop value per acre relative to normal years: counties predicted to gain access after 1950 to storage experienced large losses of up to 0.27 log points on average, or roughly 24%, in years of significant drought[4]. Notably, counties dominated by groundwater supplies suffered the most under drought before 1950, when technology did not exist to access the water at all. In contrast, small streams and large streams provided some resilience at average production levels pre-1950.

Panel B provides the estimates for after 1950. Consistent with other advances—in seed technology, better forecasting, advances in fertilizers, etc.—crop production is less variable across precipitation anomalies for all access categories after 1950. Still, absent access to expanded stored irrigation water, counties experiencing significant drought saw crop value fall 13%. In contrast, counties with access are able to maintain production value in dry years. This change, from losing 24% of crop value to experiencing no losses, indicates that water storage, not simply 'irrigation', provides resilience during severe droughts. Access to groundwater provides the most resilience post-1950, as indicated by severe drought coefficient estimates near zero. While small stream counties see the largest drought losses post-1950, counties with surface water storage access, unless combined with groundwater, also experience losses of around 8% relative to normal years. In other words, groundwater has emerged as the more resilient storage type for maintaining crop value during droughts.

The estimated cost of drought absent stored water appears larger than the relatively minor decreases in farm income found by Fisher *et al* (2012) and Kuwayama *et al* (2019). The contrast appears because these studies aggregate income results across all irrigated counties, pooling the estimates across high access and low access counties, and did not measure the drought effect in a nonlinear manner. Although looking at mean water availability rather than precipitation shocks, Hagerty (2021) reports that in irrigated areas of California, a 10% decrease in water leads to a 3%–4% decrease in revenue, suggesting a much larger direct response to reduced water availability. For comparison, our cutoff for a severe

[4] The 'average' comes from the specification that combines counties in all storage types into a single category of 'storage'. These results are in the supplemental material, figure A6 and table A4. Point estimates shown in figure 3 are provided in table A5. Results are similar if we utilize a continuous measure of stored water access (tables A6 and A7).

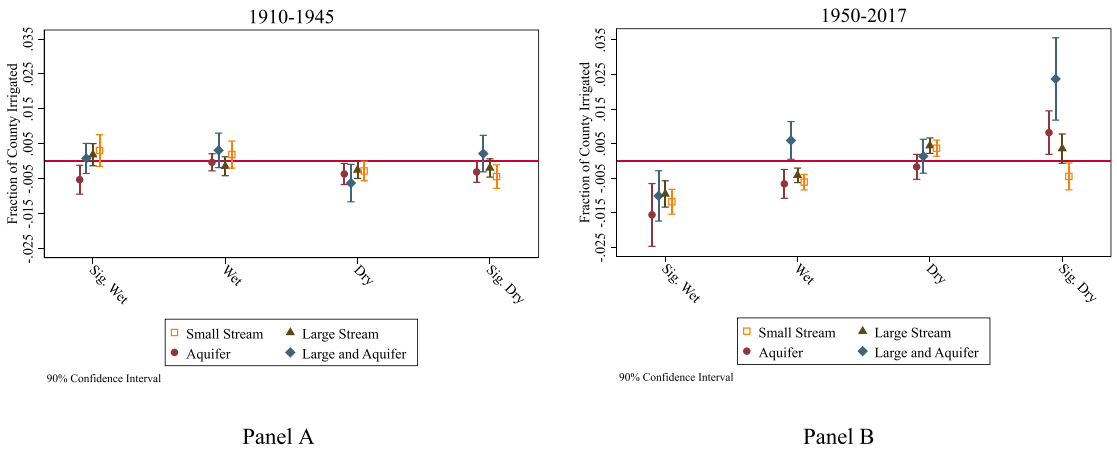


Figure 4. Effect of irrigation water storage on irrigated acreage by precipitation conditions, in the West.
Notes: Coefficient estimates of equation (2) for share of county irrigated by time period. The estimates represent deviations from a county's average relative to normal levels of precipitation.
Sources: Authors' estimation; see text.

drought year corresponds to a 32% reduction in precipitation.

5. Farmer margins of adjustment

Access to stored water can increase resiliency through two margins of irrigation: intensive, more water on a normally irrigated acre; and extensive, more acres brought into irrigation. Regression results of equation (2) with fraction irrigated as the outcome, presented in figure 4, confirm an extensive margin effect. Shown in panel A, share irrigated was not systematically responsive to precipitation deviations, regardless of storage type prior to 1950. After 1950 (panel B), irrigated land is more variable across precipitation conditions and counties respond generally in an inverse fashion: more precipitation leads to less irrigated land. The exception is that in significantly dry years, counties without access to storage are constrained and reduce irrigated share while those with storage are able to further expand irrigated share.

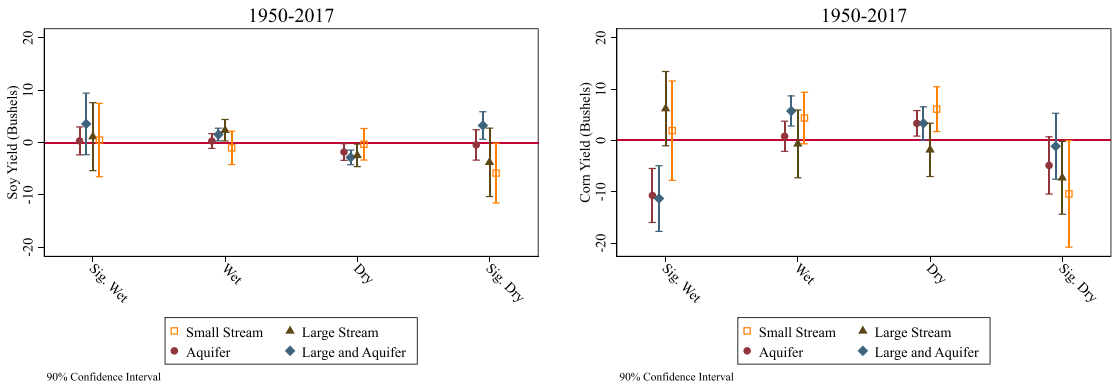
The ability to expand irrigated share is largest for counties with groundwater, particularly with access to both ground and surface water[5]. Aquifer counties exhibit considerable variation in the amount they irrigate across drought types, swinging up and down by 20% (see figure A7 of the SI). These results indicate that extensive margin adjustments are conditional on the source of storage: adaptation patterns are shaped by the distinct water governance institutions associated with each source—a subject we return to following some additional results.

[5] The observed increase is influenced by 2012 observations, the most severe drought in the post-1950 measure by our metrics: 23% of our sample is in a drought in 2012 and this accounts for 20% of all the 'drought' observations after 1950. Still, omitting 2012 from the analysis does not alter the results substantially, see SI material, figure A8.

Groundwater also provides the most resilience on the intensive margin. Intensive margin adjustments are harder to distinguish and can vary in form based on crops and region. In figure 5, we provide estimated coefficients for equation (2) again, this time using the yield per (harvested) acre for soybeans (panel A) and corn (panel B), the two most widely irrigated crops in the U.S. during the post-1950 period. Yields decline during significant drought across both crops in areas with low storage access, and fare only slightly better in areas with stored surface water access exclusively. Groundwater access provides a better buffer in significantly dry years, and counties with access to both ground and stored surface water see the most yield resilience.

The small stream results post-1950 can be compared to the findings in Li *et al* (2019), who develop a statistical model of corn yields on non-irrigated land and compare the results to 12 process-based crop models for the time period 1981–2006. At a precipitation anomaly equal to our significantly dry cutoff, Li *et al*'s crop models estimate corn yield declines in the range of 10%–30%. Our estimates of corn yield declines of 10% at this same significantly dry cutoff is near the lower bound of those crop model results. Our small stream results do include some irrigation, which would explain why they tend to be on the smaller end of the crop model estimates.

The irrigated acres and yield results show the benefit of our approach relative to past studies in isolating how the intensity of water use changes yields. Zhang and Lin (2016) suggest a 10%–13% increase in applied water per one unit decrease in Palmer Drought Severity Index (negative is drier) and we show this water application maintains yields when water is available, but that yields decrease when availability is constrained. In total, across the arid western U.S., groundwater resources provide more temporal flexibility, via both intensive and extensive margin



Panel A Panel B

Figure 5. Effect of irrigation water storage on crop yields by precipitation conditions, in the West.
Notes: Coefficient estimates of equation (2). Panel A: Soy yields; Panel B: Corn yields. The estimates represent deviations from a county's average relative to normal levels of precipitation.
Sources: Authors' estimation; see text.

adjustments. Whether the cost of this flexibility in terms of future water availability is fully balanced under the predominantly open-access governance of groundwater remains an outstanding question.

6. Humid region irrigation

Although irrigation adoption began decades later in the eastern U.S., we can examine its effectiveness in the more humid climate for the post-1950 period exclusively. Our statistical identification strategy is somewhat weaker in this setting as it is less predictive of where and when storage of irrigation water was developed. While groundwater access is still limited to areas overlying an aquifer, uptake remains relatively small and not as closely tied to the innovations in the 1950s. More notable is that in the East, surface reservoirs did not proliferate along large streams as they did in the West. Still, the results, shown in figure 6, are informative as a descriptive exercise[6]. Counties with only small streams, as in the West, appear constrained in their ability to expand irrigated acreage in a significantly dry year (Panel A). Although more modest in extent than in the West, areas with access to aquifers and large streams do exhibit a penchant to expand irrigation during significantly dry years. Notably, this is true for all access types, including large streams. This differs from the West where water property right institutions, not used in the East, limit increases in irrigated share for counties with large stream access.

Despite the fact that the East expands irrigation in the drier years, the scale of the change remains low and the resilience garnered is not yet robust. Panel B of figure 6 shows crop values decline across all counties in the East independent of storage access. This result is underscored by the impact on soy and corn yields (Panels C and D, respectively). Yields see a statistically significant decrease from normal across all counties during the significantly dry years. Stored water access is a measure of the *potential* for irrigation, indicating that although resiliency still lags in the East, additional adaptive irrigation investment is possible.

7. Policy implications under climate change

Our results, in light of the various allocation rules across water sources and geography, uncover important lessons for institutional and policy design to address a changing climate. A summary of our findings is shown in table 1. Areas with groundwater access were more resilient to severe drought in the western U.S. because users had flexibility in pumping when needed and could apply water to the cropland of their choice. While increasing resiliency in the short-run, unfettered groundwater access can exacerbate over-extraction, lead to costly externalities, and potentially reduce future resilience (Tsur and Graham-Tomasi 1991, Edwards and Guilfoos 2021). Accordingly, as local groundwater governance institutions emerge, our results suggest the need for a balance between limiting depletion overall and maintaining flexibility in the use of additional water during drought. Price-based instruments (e.g. pumping taxes) would build in this flexibility, whereas a quantity-based system (e.g. cap-and-trade) would need to adjust caps inversely to precipitation conditions or allow for inter-annual water banking (Guilfoos *et al* 2016, Smith *et al* 2017).

Surface water storage in the western U.S. saw limited resiliency response as a result of the nature of the underlying appropriative water rights. The 'first-in-time, first-in-right' allocation of water each

[6] See figure A9 of the SI for pre-1950 results and table A8 for point estimates for all of the eastern U.S. regressions.

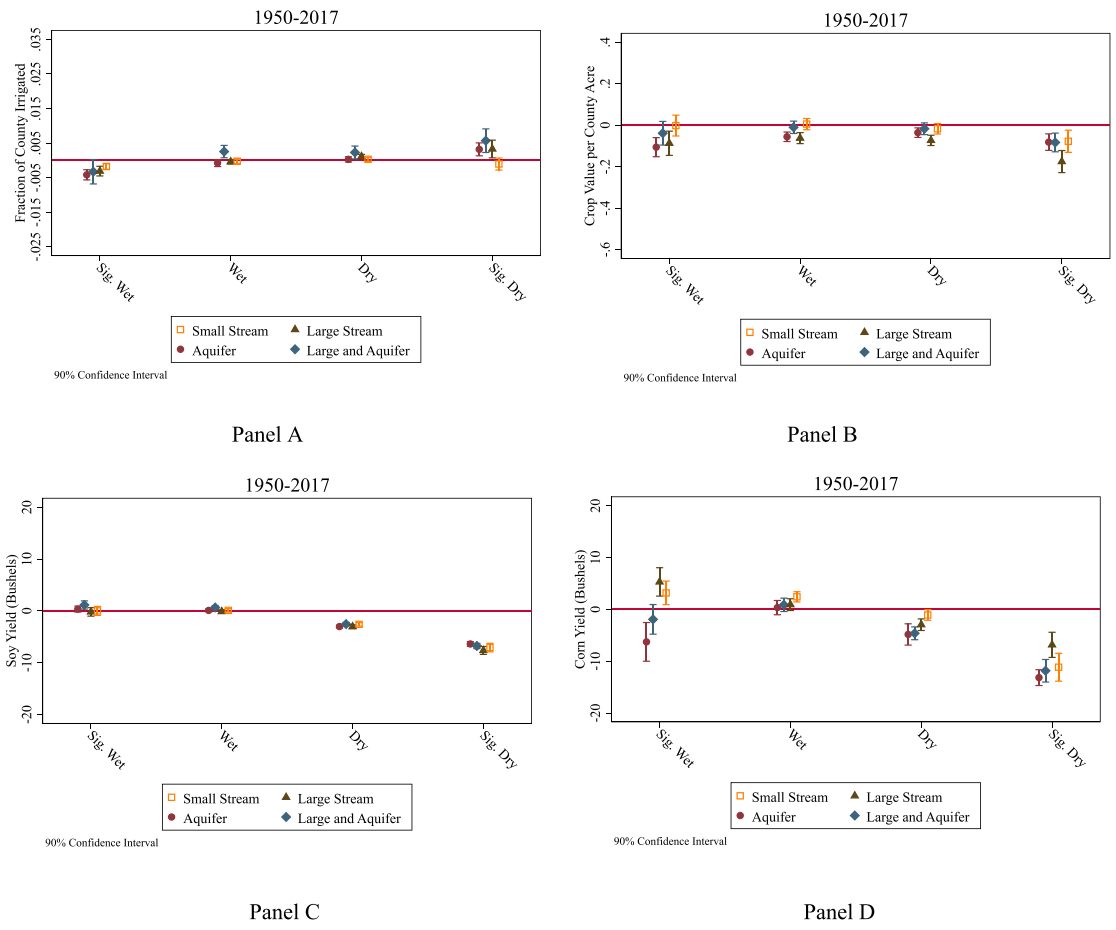


Figure 6. Effect of irrigation water storage on agriculture economics by precipitation conditions, in the East.
Notes: Coefficient estimates of equation (2). Panel A: Share of county irrigated; Panel B: natural log of crop value sold per county acre; Panel C: Soy yields; Panel D: Corn yields. The estimates represent deviations from a county's average relative to normal levels of precipitation.
Sources: Authors' estimation; see text.

Table 1. Irrigation resiliency and potential policy response matrix.

	Western U.S.	Eastern U.S.
Groundwater	*Correlative rights/ local management* • Strong resiliency response • Institutional adaptation needed to flexibly limit over-extraction	*American doctrine* • Largely untapped potential • Lack of experience and governance institutions
Surface Water	*Prior appropriation doctrine* • Appropriation limits resiliency • Need for flexibility in water right storage and use	*Riparian rights* • Extensive margin response to drought • Need for security in water rights

year limits the ability of users to smooth consumption between wet and dry years (Malek *et al* 2020). Whereas groundwater counties see wide swings in irrigated acreage (±20%), surface water adaptation is limited to the intensive margin (see figure A7). This arises because appropriative water rights are 'use-it or lose-it' and appurtenant to specific land. Farmers are limited in 'saving' water for dry years and bringing land in and out of irrigation. Finding ways to ease this institutional inflexibility could increase resiliency under projected climate scenarios.

In the East, adaptation via irrigation occurs on the extensive margin but investment remains limited. In contrast to the West, adjustments on the extensive margin are similar across all storage types, including large streams, underscoring that the limitations of the appropriative rights doctrine are not binding in the East. Although appropriative rights do limit resiliency

in the West, their absence may be limiting investment in irrigation in the East. The eastern U.S. applies the vague common law riparian doctrine as a result of high historic water availability. While allowing landowners abutting a stream or river to expand irrigated acreage, this doctrine disallows diversion of irrigation water to non-abutting landowners. Further, without the secure property rights to water as exist in the West, investment in expensive irrigation becomes riskier, as there is no guarantee of water access during drought (Leonard and Libecap 2019). Priority based rights are not the only option to quantify flows and alternatives, such as proportional shares, have been found to provide greater productivity efficiency, but may fail to fully address the development incentives on their own (Smith 2021). To address these tradeoffs, eastern states have an opportunity to adopt water rights that provide investment security and timing flexibility, which would enhance resiliency relative to the priority system.

Finally, the East's abundant groundwater resources have not been heavily utilized to date but have the potential to increase future agricultural resilience to drought. Widespread use of groundwater irrigation will be dependent on the experience of early-adopters because of the importance of peer-effects and social learning (Genius *et al* 2014, Sampson and Perry 2019). The collective organizations that have emerged to limit groundwater extraction in the West are also not yet present in the East, where governance currently relies on common law precedent, the so-called *American Doctrine*, that establishes few limits on agricultural pumping (Weston 2008). Establishing clear and secure caps on aggregate extraction early can maximize the resilience benefits of groundwater sources while minimizing over-extraction issues, particularly if use is limited to supplemental water, rather than being used as the dominant source as it is in many parts of the West.

8. Discussion

Our analysis offers key insight into the ability of additional irrigation water to increase resiliency to drought. Focusing on the development of large irrigation projects and groundwater wells in the U.S., this work offers insight into the resiliency gains achieved in adopting irrigation. The evidence suggests that stored irrigation water avoided the 13% losses of crop value experienced in counties with little access to storage during significantly dry years. In addition, the benefits of irrigation as a resiliency tool are also promising for humid areas, as they may be exposed to more intense and rapidly occurring drought under climate change (Trenberth *et al* 2014). Although some regions have additional scope to develop water stores, like in the eastern U.S., other regions are limited by historic development and further increases in water scarcity, suggesting increased stress on water systems (Joyce *et al* 2011). Accordingly, our analysis points not just to the value of the stored water, but the importance of the institutions shaping its use. Achieving the policy goals of increasing resiliency and limiting the costs of climate change will require accounting for hydrologic, climatic, and institutional differences.

There are some limitations to our findings. First, our measure of storage access is based on physical characteristics not actual access. While this approach allows us to interpret our statistical results as causal, it limits the precision with which we can estimate the effects. Second, we use a coarse measure of precipitation, yearly total, as a proxy for drought because it is available for the entire timeframe of our study. Irrigation may also provide resiliency to shorter, within-season droughts and additional work in this area would be beneficial. Conversely, prolonged and repeated drought may stress the food system beyond a single year anomaly. Third, although we account for the distinct overarching legal doctrines governing ground and surface water rights by region, micro-analysis of institutional effects on water use ought to continue. Fourth, beyond the water storage type, resiliency has been shown to depend on the technology used to apply irrigation water in certain regions (e.g. center pivots across the Ogallala aquifer (Cooley *et al* 2021)), which we cannot accurately account for at our national and historic temporal scale. Finally, further work is also needed to understand the role of irrigation in addressing increasing temperatures. Even given these limitations, our results show that irrigation offers significant capacity to provide resilience to drought, but that the institutions governing the underlying water resource are important determinants of its effectiveness.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Author contributions

E C E and S M S designed research, performed research, analyzed data, and wrote the paper.

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