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AMERICAN AGRICULTURE, WATER RESOURCES, AND CLIMATE CHANGE

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ABSTRACT

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Introduction

This paper highlights the role of agriculture in the American economy and society over time and points to farmer historical and contemporary responses to varying climatic conditions. It indicates the importance of water as an input to agricultural production and identifies possible impacts of climate change on access to water. It then summarizes a set of eleven papers from an NBER research project on water, climate change, and the agricultural sector.

A. Role of Agriculture in the American Economy and Society and Historical Responses to Changes in Access to Water

Agriculture has been critical in development of the American society and economy. It was a pathway for immigrant settlement; was a basis for employment and community formation; and has provided critical foodstuffs, fibers, and other sources of industrial production. Critical inputs have been land, labor, capital equipment, nutrients, and water. Until the late 19th century, agriculture was centered in the eastern part of the country where precipitation was frequent as was general access to water. The western part of the country always has been drier, and water supplies more limited and costly, leading to differences in water institutions and infrastructure. Even so, except in parts of the US West, water access has not been a critical constraint in agriculture. But this is changing.

With climate change water supplies are apt to be much more problematic in most parts of the country, affecting agricultural production and rural populations. Fortunately, the wide range of spatial climatic conditions encountered affecting water access as settlement and production moved across the continent, provides valuable insights to contemporary climate change. In the research briefly summarized below, focus is on farmer interpretation of available climatic data; their reactions and related investments; potential externalities; and institutional/coordination challenges posed by efforts to secure water.

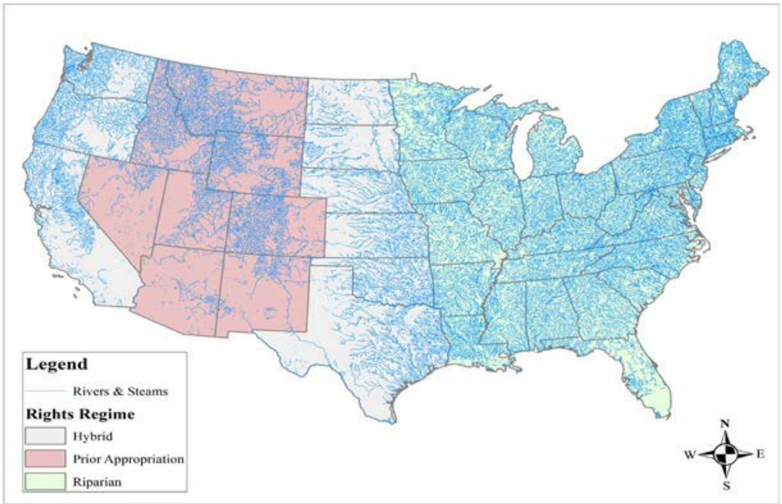
In terms of the overall impact of agriculture on American economic development, access to agricultural land was a primary driver of migration to temperate North America. Large-scale migration, mainly from Europe, of entire families in the colonial and subsequent federal periods resulted in dense population settlements and internal market development from the east coast through the 98th meridian (Wilcox 1929). Thousands of small, landowning farmers became the decision makers regarding farm size, input use, production, and responses to various climatic signals.

Small farms, organized under federal land laws, such as the Homestead Act of 1862 and the rectangular survey of the 1785 Northwest Ordinance (Libecap and Lueck 2011) relied upon family labor with minimal agency problems (Allen and Lueck 1998). Midwestern farm populations, in particular, invested in education, leading to high levels of human capital, perhaps the highest in the world by the early 20th century (Goldin 1998, 2001). The turnover of farmlands via very active land markets, encouraged the development of capital markets (Hartnett 1991). The capital gains from land sales, in turn, were a major source of wealth creation (Kearl et al 1980; Steckel 1989; Ferrie 1993; Stewart 2009). Overall, easy access to farmland resulted in a relatively egalitarian society in rural US areas compared to urban centers in the 19th and early 20th centuries (Pope 2000, 118).

The role of water for agricultural settlement and production was stressed early. Thomas Jefferson commented in 1811 that farmers wished for “a rich spot of earth, well watered, and near a good market…” (Atack et al 2000, 245). In the eastern US, farmers relied upon rain-fed agriculture possible from relatively reliable precipitation and absence of serious drought (Libecap and Hansen 2002, 91-92). Irrigation was uncommon and drainage primarily was aimed at shifting swamplands into farm production. Because water was available locally, there was little large-scale water movement, which would have posed significant coordination problems under the riparian doctrine. Riparian water rights granted use of water to all adjacent landowners, and collective agreement was required to transfer any water from its source.

Figure 1 shows stream densities in the US, along with the three major water rights practices by state (riparian, prior appropriation, and joint or hybrid practices). The figure clearly shows that local surface water sources for agriculture were far more prevalent east of the 98th meridian, running from North Dakota through Texas.

Figure 1: Stream Density



Source: Modified from Leonard and Libecap (2019, Figure 2).

To improve yields and profits farmers adopted innovative management practices, technologies, and varieties, such as novel seed types in corn, wheat, other grains, and cotton as increased aridity, lower mean and more variable temperatures, and insect pests were encountered (Griliches 1957; Olmstead and Rhode 2011; Sutch 2011). Research on new seeds and agricultural practices was provided by private companies, such as DeKalb and Pioneer; by land-grant colleges under the Morrill Act of 1862; and by the USDA experiment stations, Agricultural Research Service (established 1953) and the Economic Research Service (established 1961). Additionally, farmers invested in innovative capital equipment introduced by Ford, McCormick-Deering, and Farmall, including mechanized reapers and threshers, tractors riding plows, seed drills, and balers (Olmstead and Rhode 1995). Farmers also incorporated new chemical fertilizers and changes in tillage practices to raise yields.

Between 1870 and 1990 farm productivity grew by nearly six times (Olmstead and Rhode 2000, 701). At the same time, however, farm populations and their share of US total population fell dramatically as shown in Table 1, as farm sizes grew, farming became more capital intensive, and rural-to-urban migration increased.

Table 1: Farm Population

Year	Farm Population	Percent of Total US Population
1910	32,077,000	34.9
1912	32,210,000	33.9
1950	23,048,000	15.3
1960	15,652,000	8.7
1970	9,712,000	4.8
1980	6,051,000	2.7
1990	4,591.000	1.9

Source: Farms and Farm Structure Alan L. Olmstead and Paul W. Rhode 2006. Historical Statistics of the United States, Volume Four Part D, Series Da 1-13, 4-39.

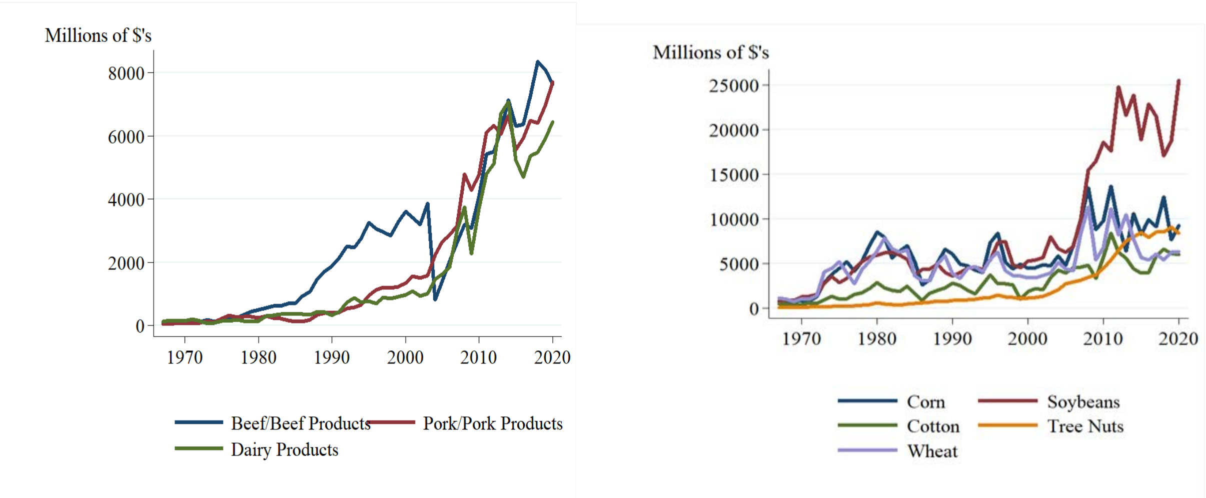
The data in Table 1, however, understate the continuing economic, social, and political role of agriculture in the US. In addition to farm populations, urban centers based on agricultural research and development, marketing, processing, manufacturing, and shipment emerged in Minneapolis, Chicago, Kansas City, Cincinnati, Fort Worth, Omaha, Stockton, and elsewhere. The value of agricultural output and processing remain key element of overall state GDPs as indicated in Table 2. Moreover, Figure 2 shows agricultural exports as major elements of US trade between 1970 and 2020 as well as critical sources of food worldwide. Beef and beef products exports approached $8 billion in 2020 and among commodities, soybean exports grew to over $25 billion by 2020.

Table 2: Agricultural Output and Processing Share of State GDP for Selected States 2020

State	Share of State GDP (%)
California	2.8
Colorado	2.3
Idaho	12.5
Illinois	2.9
Indiana	2.5
Iowa	9.3
Kansas	6.8
Montana	4.9
Nebraska	21.6
Ohio	3.2
Oregon	13.0
Washington	12.0
US	5.0

Source: USDA ERS

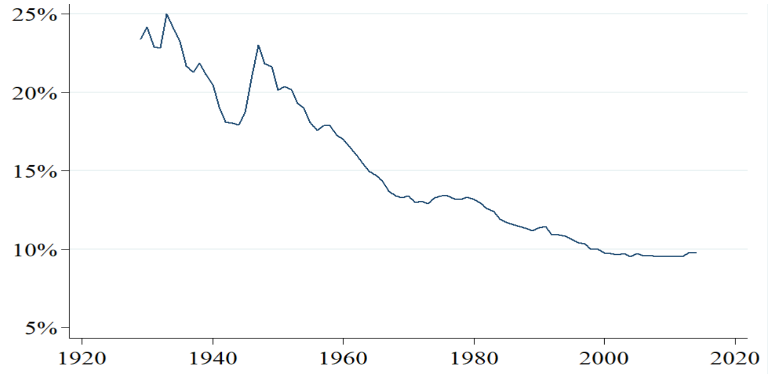
Figure 2: US Exports 1970-2020 in Chain-Weighted $



Source: https://apps.fas.usda.gov/gats/default.aspx

Figure 3 reveals the role of agricultural production in providing relatively low-cost domestic food supplies. The figure reveals a continuous decline in the share of household disposable personal income spent on food from 1920 through 2020.

Figure 3: Share of Household Disposable Personal Income Spent on Food



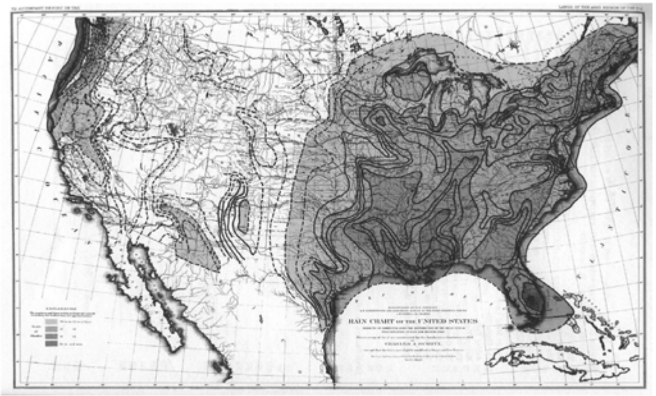
Source: USDA ERS, Food Expenditure Series
Disposable Personal Income = Post-Tax Income

As noted above, through the 19th century, agriculture largely was centered east of the 98th meridian with rich soil, flat terrain, dense streams (Figure 1) and abundant precipitation. After that time, however, the area west of the 98th meridian, especially the Pacific region, became a major source of domestic food production and exports, as well as employment in processing. Agriculture in the Pacific region, however, relied upon far different sources of water supply.

The region is more drought prone; generally is drier; depends upon water storage in surface reservoirs and aquifers (Libecap and Hansen 2002); utilizes canal and ditch networks for water delivery; and applies irrigation more than elsewhere in the US. As such, these experiences are indicative of future conditions with climate change that suggest greater prevalence of drought along with alternating very wet and dry periods with more reliance upon irrigation, longer distance of water transport from storage sites and need to dispose of drainage.

The western region has always been recognized as more arid. John Wesley Powell in his 1878 Report on the Arid Region of the United States quite accurately illustrated the dramatic change in precipitation beyond the 98th meridian.

Figure 4: John Wesley Powell, 1878's Indication of Increased Aridity



Source: J.W Powell, frontispiece. Report on the Arid Region of the United States (1878).

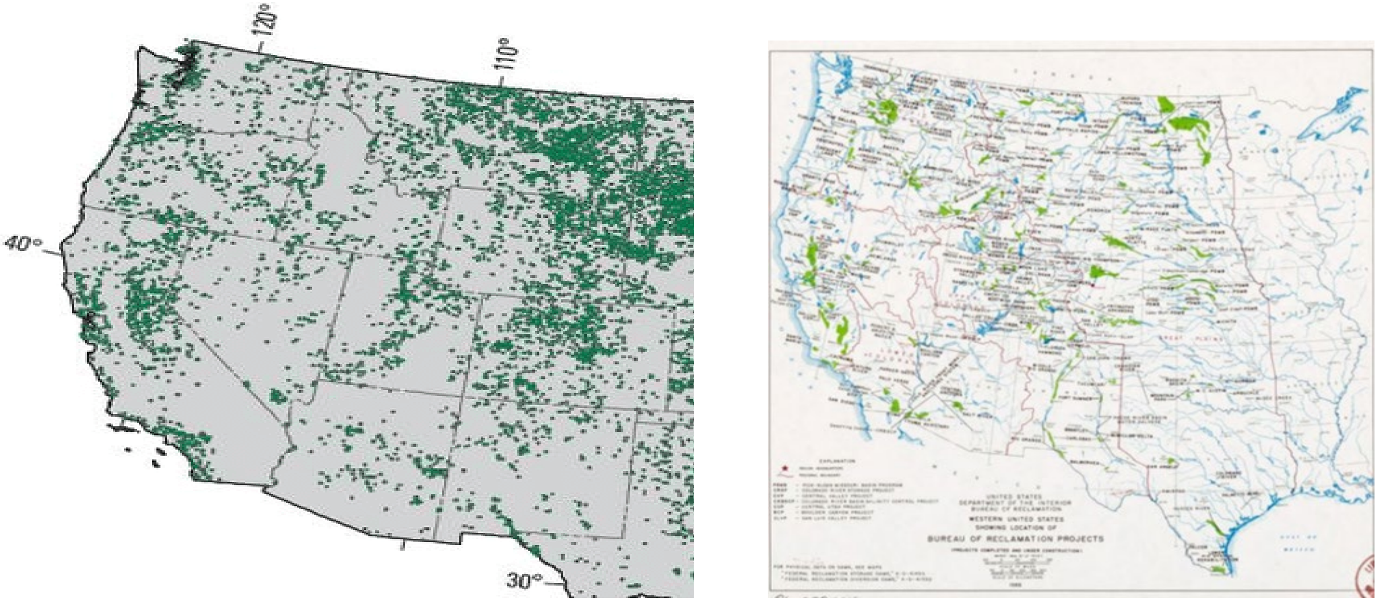
Drought led to Homestead farm failure (Hansen and Libecap 2004a, 2004b). Most of the region's more limited and variable precipitation comes as snow in higher elevations. Snow-pack melt has fueled stream flows, often with water stored behind reservoirs. Arable land generally is remote from streams, requiring water movement for irrigation. Water transport, however, has required a change in water rights from riparian to prior appropriation (Leonard and Libecap 2019).

Prior appropriation water rights are an institutional innovation that allowed water to be separated from the source and moved to the site of agricultural production. It was first introduced in California and Colorado and then spread to all western states and Canadian provinces either in full or as a hybrid with riparian systems. Irrigation districts were formed to coordinate diversion dam construction on streams, canal investments, ditch maintenance, and to protect the priority of diversion. Dams and irrigation systems initially were private, but followed the 1902 Reclamation Act with large-scale federal government investment, particularly after 1940 (Wahl 1989; Pisani 2002). By storing and moving water in an otherwise arid region, dams, related reservoirs, and water infrastructure, smoothed supplies during annual summer dry periods and droughts (Hansen et al 2011).

As shown in Figure 5A there are many dam sites in the western region of the US, and most are small for local stream water diversion and storage for irrigation. Larger dams, such as Shasta and Oroville in California, American Falls and Palisades in Idaho, Grand Coulee and Tieton in Washington, Canyon Ferry and Tiber in Montana, for example, may have multiple uses with reservoirs to support irrigation, hydroelectric power generation, and flood control.

Figure 5B details irrigation projects and networks in the western US that include dams, reservoirs, and extensive canal systems to deliver water to irrigated farmland, and acreage covered. The largest projects are associated with construction and operation by the Bureau of Reclamation (the agency name is indicative of the primary objective), while smaller, earlier developments are private (see details in the 1890, 1900, 1910, 1920 Agricultural Irrigation Censuses). In the most arid regions where arable lands were remote from streams and lacked sufficient precipitation, agriculture would not have been feasible without such supplemental projects.

Figure 5: Western Dams, Reservoirs and Irrigation Projects



A. Dam Site Locations

B. Irrigation Infrastructure Projects

Sources: Library of Congress https://hdl.loc.gov/loc.gmd/g4051c.ct011656
https://www.researchgate.net/profile/J-Flotemersch/publication/311846500/figure/fig3/AS:442454437568513@1482500766123/Map-showing-dams-in-the-conterminous-United-States-listed-in-the-National-Inventory-of Dams.png

Irrigation from snowmelt and reservoir storage and shipment was augmented after 1940 with groundwater pumping. Aquifer access became feasible with greater access to electricity, more powerful combustion engines and turbine pumps, deeper wells, and new pumping technologies. Advances in irrigation with new dam construction and groundwater delivery provided new water and led to major increases in agricultural production and higher productivity in the US West, especially in the Pacific region (Edwards and Smith 2018).

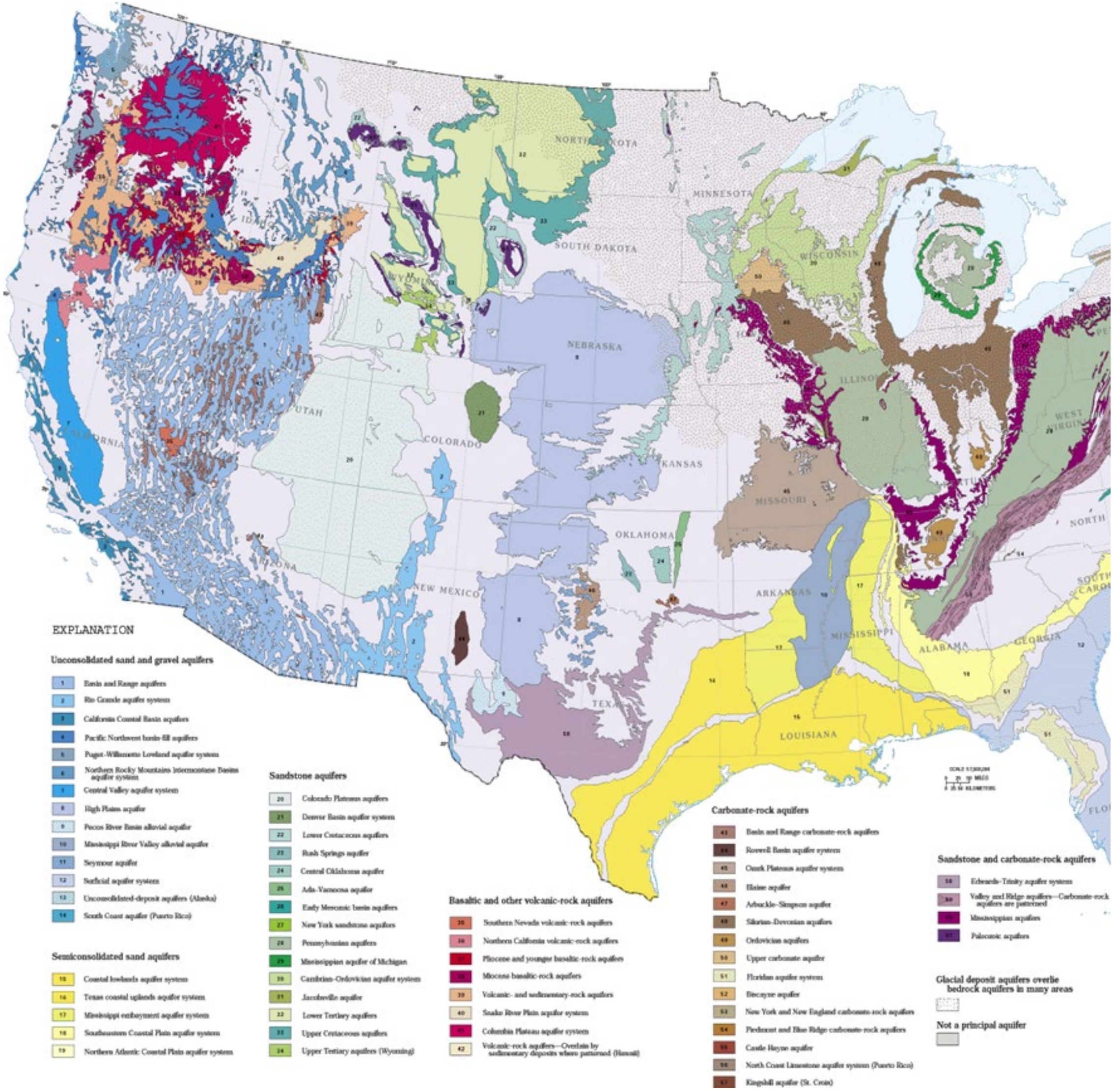
Figure 6 maps aquifers, primarily for the US West and Midwest, by surrounding geologic formation. These formations bound the subterranean basin; determine its size, depth, and uniformity; influence conductivity or movement of water within the aquifer; and affect recharge and leakage. As such geology helps to determine how much groundwater is available for pumping in various parts of the aquifer and for how long, and extraction costs. Although aquifers appear to cover much of the region, they are extremely heterogeneous in structure leading to important differences within and across groundwater basins in the stock of water, qualities, and linkages between recharge and extraction.

These variations make modeling and aquifer management difficult. The basins are not like uniform bathtubs as early discussions had assumed to simplify approaches (Gisser and

Sanchez 1980). They also have varying surface growing conditions and farming practices. Moreover, groundwater pumping occurs for a variety of uses—urban (especially in the southern San Joaquin valley and near Los Angeles in California), as well as for annual crops—hay, grains, and vegetables, and for permanent crops—fruit and nut orchards and vineyards).

These geologic and user differences as well as the open access nature of groundwater compound problems of coordinating pumping among users to address depletion and implement any sustainability objectives. Unlike surface water and prior appropriation, groundwater lacks clear water rights, making it subject to competitive withdrawal and associated externalities (Ayres et al 2018). For larger and more varied aquifers with more heterogeneous pumpers the challenges in controlling rent dissipation are formidable. As climate change leads to greater reliance upon groundwater for irrigation, these issues are likely to increase in severity.

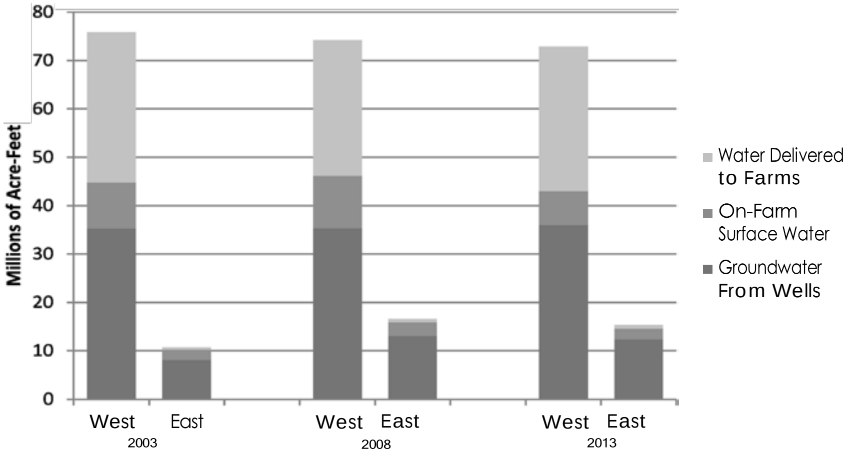
Figure 6: Aquifers (Primarily Western) by Surrounding Geologic Formation



Source: https://www.livescience.com/39625-aquifers.html

Figure 7 details differences in irrigation water delivery for farms in the eastern and western US between 2003 and 2013. Western farms rely far more on irrigation water, including water conveyed from reservoirs via canals and ditches and groundwater pumping, than do those in the eastern US. With climate change, these distinctions may become less apparent.

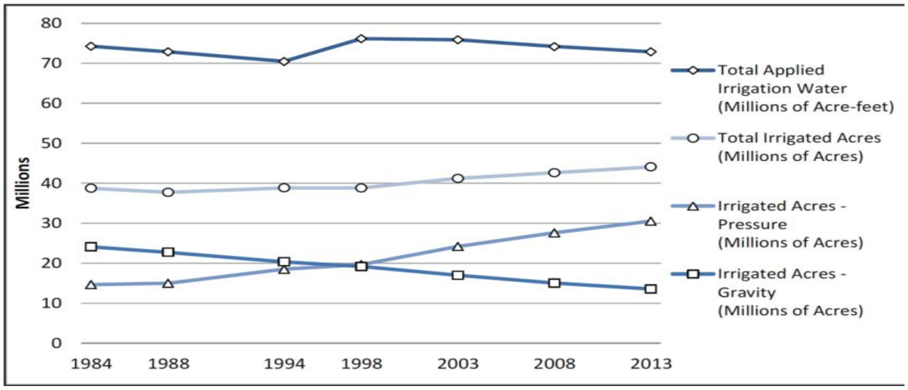
Figure 7: Sources of Irrigation Water, 2003-2013.



Source: Stubbs (2016, Figure 4).

Figure 8 illustrates the path of irrigation water use from 1984 through 2013. The data underlying the figure reveal that in addition to changes in crop varieties and management practices, US agriculture has witnessed a swift overhaul in irrigation technologies that not only saved water, but also increased yields and allowed for more efficient use of fertilizers (Stubbs 2016). The figure shows the decline in total irrigation water despite an increase in total irrigated acres. This is due mainly to the steady increase in pressure-based irrigation technologies replacing gravity-based irrigation technologies. Although on-farm surface water and water delivered to farms in the West for irrigation have declined by 2.5 million acre-feet and 1.2 million acre-feet, respectively since 2003, groundwater withdrawals have risen by 740,000 acre-feet (an acre foot equals approximately 326,000 gallons and 1,235 cubic meters).

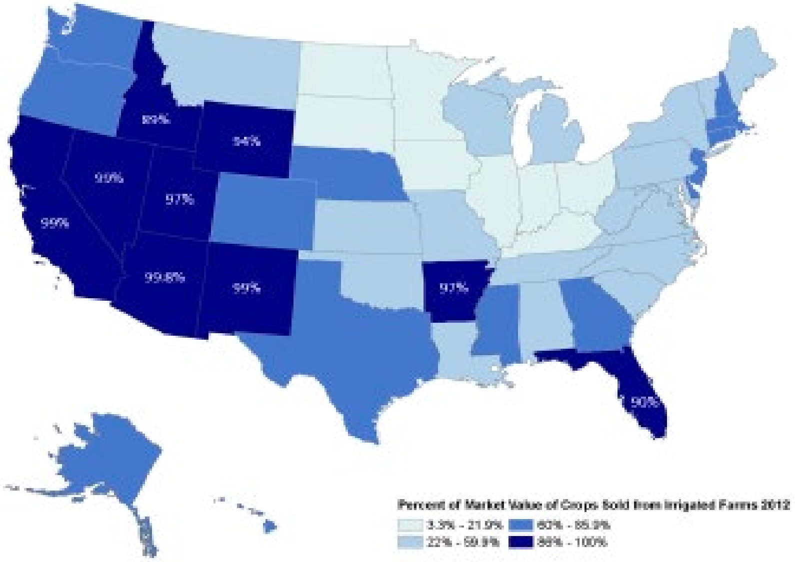
Figure 8: Irrigated Acres and Applied Irrigation Water, Western States 1984-2013.



Source: Stubbs (2016, Figure 3).

Figure 9 shows the percent of market value of crops sold from irrigated farms by state in the US in 2012. Generally, western states have the largest share of crops produced by irrigation to provide water.

Figure 9: Percent of Total Market Value of All Crops from Irrigated Farms, 2012.



Source: Stubbs (2016, Figure 1).

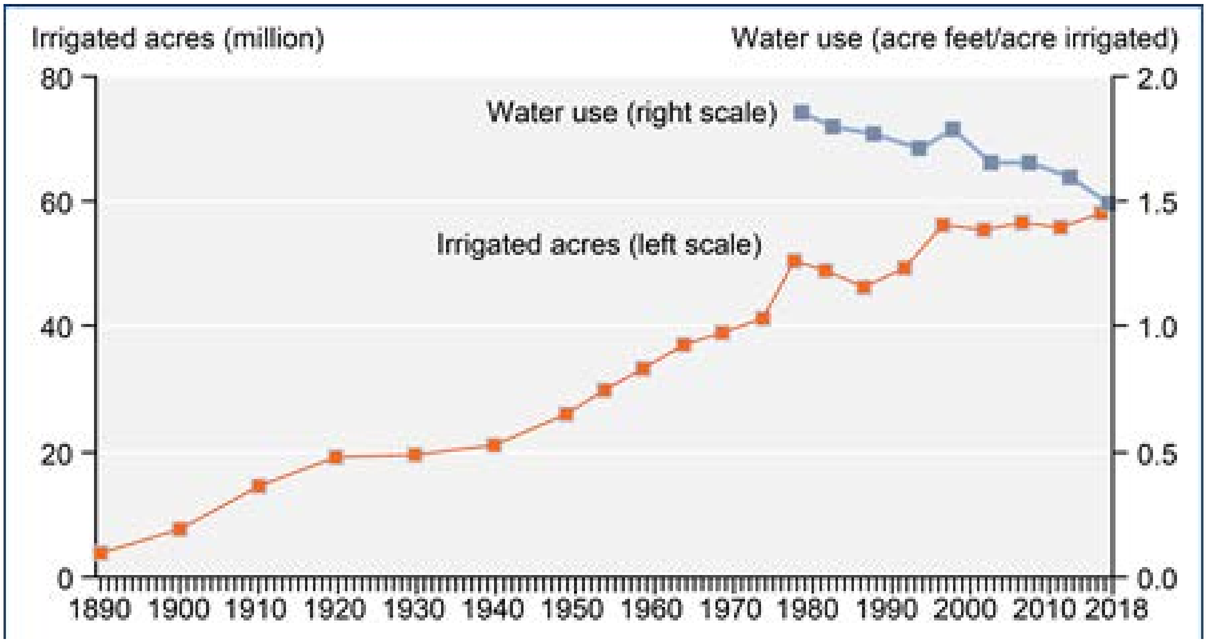
As climate change leads to greater reliance upon irrigation, especially in previously rain-fed agricultural regions, the techniques, institutional responses, and other innovations observed in the drier western US will provide important laboratories for new learning (Schoengold and Zilberman 2007; Libecap 2011; Hornbeck and Keskin 2014).

B. Water Use in Agriculture.

Agriculture is the largest single user of water in the US. It accounts for approximately 80% of the consumptive use of water and of that, irrigation amounts to about 42% (https://www.ers.usda.gov › farm-practices-management). As we have indicated, productivity advances have resulted in declines in water use per irrigated acre, while the area irrigated has increased. These trends likely will continue as water becomes scarcer and more costly, forcing farmers to further adapt.

Figure 10 traces the growing trend in irrigated land in the US over the period 1890-2018 and reductions in water use per acre over the period 1975-2018. There also are noticeable gains in productivity as water use per acre has fallen often with a shift from gravity surface flow onto fields from ditches with an associated extravagant delivery of water.

Figure 10: US Irrigated Acres and Water Use Per Acre, 1890-2018



Source: USDA-ERS, n.d. Irrigation and Water Use https://www.ers.usda.gov/topics/farm-practices-management/irrigation-water-use/

C. Climate Change Projections and Agricultural Water.

For crops to grow and be economically productive several inputs, such as sunlight, water, carbon dioxide, nutrients, and limited weeds, diseases, and insects, have to be present at optimal amount (Mendelsohn and Dinar 2009). An optimal growing process of agricultural crops requires a certain distribution of dry matter across the different plant's organs, especially the reproductive components (in non-weed crops), that lead to yield increases, compared with the green matter components that are non-marketable (Morisson 1996). Climate change as it impacts temperature, CO2, and water availability may alter this distribution and related productivity.

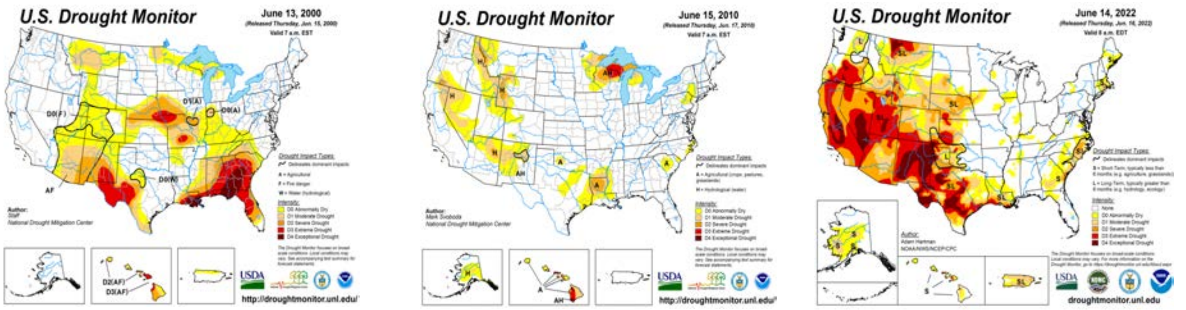
The effect of climate change on US agriculture (with focus on irrigated agriculture) has been examined in multiple studies, and estimation results have varied (Mendelsohn and Dinar 2003; Deschenes and Greenstone 2011; Massetti and Mendelsohn 2011). In part, these differences reflect the underlying uncertainty and complexity of climate change projections as well as the variables examined. Deschenes and Greenstone (2011) estimate that the average present value (in 2005 dollars) of an annual decline in agricultural profit across 2,256 counties in the US is $38.7 Billion. Alternatively, Massetti and Mendelsohn (2011) found that, depending on the severity of climate change, the agricultural sector of the US could benefit (due to CO2 effects on crop yields) from mild impacts.

Mendelsohn and Dinar (2003) used a 1997 census of 2,863 counties in the US and provide estimates of the role of adaptation, specifically, adoption of irrigation technologies, in reducing damage from climate change. They found that the value of irrigated cropland is not sensitive to precipitation changes, and values increase with temperature. They also found that new sprinkler systems are used primarily in wet cool sites, whereas gravity and especially drip irrigation systems, help compensate for higher temperatures. These results underscore the importance of irrigation in adapting to increased water scarcity.

Drought is a major indicator of potential patterns of increased aridity associated with climate change. As indicated in Figure 11, over a 20-year period, drought has become increasingly more intense, covering a larger area, especially in the central and western US. Agriculture is very sensitive to drought as precipitation and water access for irrigation are disrupted. When drought persists, the hydrological cycle can be altered, affecting agricultural productivity (Hays et al 2011).

Figure 11: Drought Intensity Changes in the US 2000-2022

June 2000 June 2010 June 2020



Source: National Drought Mitigation Center, University of Nebraska-Lincoln
https://droughtmonitor.unl.edu/

What is the role of adaptation in securing the agricultural sector's profitability from climate change-induced water scarcity? Gollin (2011) analyzes the role of various science-related technological innovations such as plant breeding for climate adaptation, modifications of farm management practices, water control and improved water use efficiency, mechanical innovations, and chemical use to compensate for yield losses, including the negative effects of pollution externalities from increased intake of chemicals and fertilizers.

Overall, farmer adaptations range from new crops, especially drought-tolerant varieties; intermediate fallowing during dry periods (if climate change results in times of increased water availability followed by drought); permanent withdrawal of marginal production areas; use of cover crops and tillage practice to conserve water; addition of fertilizer and other inputs; greater reliance upon irrigation, particularly in the eastern US, as well as adoption of new irrigation technologies in both regions of the US; greater movement of water from storage sites for irrigation and for drainage; increased reliance of marginal water sources such as recycled wastewater; as well as reliance upon more groundwater pumping. Many of these responses will require institutional arrangements to coordinate groundwater extraction, water movement, and to address other potential externalities associated with fertilizer runoff (Saleth et al 2011). In addition, adjustments in crop insurance programs may assist farmers in responding to uncertainty associated with assessing climatic variability and crop yields (Garrido et al 2011).

D. New Research on Water, Agriculture, and Climate Change.

Agriculture is practiced in the US under a variety of climatic conditions, with wetter and humid climates in the eastern part and drier and semi-arid to arid climates in the western part of the nation. The research outlined below addresses the role of water in irrigated agriculture from snowmelt and groundwater west of the 98th parallel and supplemental water to the east. The effects of too little or too much water resulting from climate change; the adaptations needed to address them; farmer interpretation of past droughts and their responses; adoption of new irrigation practices; institutional adjustments required to promote cooperation; as well as any negative externalities from efforts to maintain yields are examined in the research summarized below.

During the May 12-13, 2022 conference, the authors benefitted from comments provided by Andrew Ayers (Public Policy Institute of California); Tamma Carleton (University of California, Santa Barbara); Zeynep Hansen (Boise State University); Lynne Lewis (Bates College); Prabhu Pingali (Cornell University); and Katrina Schoengold (University of Nebraska, Lincoln).

The first group of research papers refers to agricultural adaptation in the eastern part of the US, dealing with rainfed agriculture and/or supplemental irrigation and the need to remove excess water. Edwards and Thurman analyze the role of drainage under the increasing likelihood of extreme precipitation events across the entire US due to climate change. Alongside with technical innovations to be introduced in drainage tile technologies required for collection and disposal of excess water, the research highlights the relevance of institutional innovation necessary for efficient coordination of drainage reduction, and its associated costs. The chapter begins with the observation that all US regions (even those regions in semi- and arid regions) are projected to see periodic heavier rainfall events under climate change. Poorly drained soils see excess water in the root zone of cultivated crops, leading to waterlogging and salinity, which in turn, create aeration deficits and productivity losses, both of which drastically reduce yields or eliminate production.

The ability of farmers to remove excess water from fields is crucial for ensuring secure and reliable food supply. Legislation for establishing local institutions (drainage districts) has been essential in successful drainage-management adaptation. The analysis suggests that after the enactment of drainage district legislation, poorly drained counties realized a rise in improved-drainage acres, resulting in increase in land value. Estimated increases in the value of land in the worst-drained counties of the eastern United States after adaptation of improved drainage increased by 13.5 percent to 30.3 percent with a combined increase in land value after the enactment of drainage district legislation of between \$7.4B and \$16.6B in 2020 dollars. This finding suggests an important role to adaptation of drainage institutions.

Karwowski adds another adaption angle to climate change in humid regions by analyzing the value of the land easement program. Large agricultural areas in the eastern US exist in regions that were reclaimed on wetlands and floodplains but which now are subject to flooding risks under increased precipitation. Easements might promote removal of some of these areas from production. Approximately 3 million acres of eased wetlands and 185,000 acres of floodplain easements existed in the US in 2020. The easements program impacts agricultural production both directly, by reducing planting on marginal land, and indirectly by changing flood patterns that improve yields on surrounding cropland. The easement program provides payments to farmers who withdraw inundated cropland from production and restore it to its natural condition.

Karwowski analyzes data on crops (corn, soybean, and wheat) in 1,700 rainfed and non-irrigated counties east of the 100th meridian. She finds that easements can be an effective adaptation strategy. For example, a 100 percent increase in wetland easement land share increases county yields by 0.34, 0.77, and 0.46 percent for corn, soybeans, and wheat, respectively. Doubling of wetland easement land share reduces losses by \$3.59, \$6.07, and \$11.23 from excess moisture, heat, and disease for each dollar of soybean liability, respectively. In the case of corn, the same change in easement leads to reduction in insect losses by \$8.50 per dollar of liability. All in all, the results suggest that increasing land share in floodplain and wetland easements leads to reduced risk of loss for all three crops.

Other research addresses the roles of off-farm water conveyance and on-farm irrigation technologies in response to shifting precipitation. Hrozencik, Potter and Wallander focus on the value of water savings in the conveyance of water from the source to farms, as opposed to most water conservation efforts that have focused on farm-level improved irrigation efficiency. Given that more than one-third of the applied agricultural irrigation in the US originated from off-farm sources, improvements in delivery and conveyance efficiency have the potential to significantly reduce water losses. These improvements include lining of canals and converting open canals to pipes.

Using a dataset of irrigation water delivery organizations in the western US the authors estimate the impact of lining and piping of conveyance infrastructure on water losses. The potential resource savings are large. On average, reported conveyance losses are nearly 15 percent of the delivered water in 2019. The findings of the study indicate that at the margin, an increase of one percent in the share of conveyance infrastructure piped leads to an expected 0.16 percent reduction in conveyance losses. Using a simulated water-conservation supply curve, the authors suggest that nearly 2.3 percent of all water delivered to farms could remain in the system, rather than lost through evaporation or leakage at a private capital cost lower than $10,000 per acre foot of delivered water.

Cooley and Smith add to understanding of the role of irrigation technologies in adapting to water scarcity in the US Midwest, a humid region that actually faces relative water scarcity due to climate change. Irrigated agriculture in the state of Illinois saw increased irrigation-equipped cropland by threefold since 1978, mainly by a rise in center pivot irrigation systems (CPIS) a decade later. CPIS adoption came in certain locations with monetary benefits in terms of annual crop yield, greater irrigated acreage, new crop selection, and reduction in drought-related insurance payments. The authors demonstrate the value of CPIS adoption by using a dataset that includes CPIS-locations during drought years and the remaining control variables of crop type, yield levels, and insurance payments. The results of the statistical analysis suggest that in drought years CPIS presence has a significant positive effect on corn yield and a significant negative effect on indemnity payments for both soybeans and corn.

The results provide insights into an emerging trend of irrigation in humid regions, and the role of irrigation in replacing crop insurance. CPIS adoption has reduced drought indemnity for both corn and soybeans. Namely, an increase of 1% in cropland equipped with a CPIS decreases insurance payments for corn by approximately 6.34% and for soybeans by about 2.81%. In addition, CPIS presence during a drought year has a significant effect on corn yield, but no significant effect on soybeans yield. Findings suggest that during a drought year, increase in 1% of cropland equipped with CPIS yields nearly 0.46% increase in corn yield per acre across the state.

Adoption of costly new irrigation technologies and cropping patterns by farmers depends upon their perception of future drought. Blumberg, Goemans, and Manning examine how farmers interpret past droughts in implementation of new irrigation technologies.   Their theoretical framework suggests that farmers facing possible reductions in surface water availability will be more likely to adopt water-efficient irrigation systems. Using data on corn production from one water region in Colorado (corn is considered more sensitive to water stress than are other popular crops) over seven observation years during 1976-2015, the authors identify a change in beliefs arising from past droughts about the reliability of farmers' water supply. Water access is reduced through a curtailment of water supplies through an administrative system of “calls”. Past drought and associated calls on water allow the authors to observe shifts in beliefs and infer their impact on the adoption of water-saving sprinkler Irrigation technology at the field level to replace older flood irrigation. Several important findings include that by the year 2015, there was on average a 11.2 percent increase in land converted from flood to sprinkler irrigation; further, generalizing to the entire water-supply region, the reduction in water availability from increased “calls” brought an increase of over 52,000 sprinkler-irrigated acres; and finally, a reduction in surface water availability led to more groundwater use to augment existing corn irrigation practices.

In addition to on-farm adoption of new irrigation technologies, farmers can also turn to new seed varieties that are more tolerant to drought and related climate-induced effects or they can also introduce new management practices, such as planting cover crops to conserve water. McFadden, Smith, and Wallander investigate the determinants of farmer adoption of drought-tolerant corn varieties in response to an increased frequency of drought in the US. Given that corn is a water-intensive crop and given corn’s economic importance due to its large share in US agricultural value, adaptation of drought tolerant corn might have significant economic benefits. The authors used 2016 data from a survey of corn operations in the US and a sample covering over 73.3 million acres, representing nearly 78 percent of 2016 US corn acreage and where drought-tolerant corn was grown on non-irrigated land in 2016.

Their analysis suggests that the duration and severity of recent droughts do not appear to affect adoption of drought-tolerant seeds, but that higher average temperatures and variability of rainfall instead lead to higher adoption rates, although temperature variability is statistically insignificant. In addition, higher adoption rates occur on lower quality, more highly erodible land. Predictably, increased rainfall leads to lower adoption rates. These findings suggest that irrigation could be increasingly important to support adoption of drought-tolerant corn under changing long-term climate conditions.

Dong investigates adoption of cover cropping to improve resilience to drought. Cover crops include grasses; legumes, including annual cereals, such as rye, wheat, barley, oats; annual or perennial forage grasses, such as ryegrass; and warm-season grasses, such as sorghum. Cover crops can protect and improve soil between periods of regular crop production through erosion, weed, and other pest control; addition and recycling of nutrients; provision of habitat for beneficial organisms; and greater water efficiency by reducing evaporation form bared soil. Tradeoffs associated with cover cropping include incremental costs of soil preparation, seeds, and labor, as well as difficulties in implementation and management of rotating cover crops with major cash crops.

With such background and data available for soybean production in the US, Dong explores factors influencing farmer’s adoption of cover crops and examines the impact of cover crops on soybean yield and risk. She finds regional differences in adoption, likely the result of hedonic effects, such as soil types and quality, landscape, and climate. She also finds that cover crops adoption was affected by farmers' concerns regarding production outcomes. Farmers who had concerns over wind-driven erosion, soil compaction, water quality, or other concerns were more likely to adopt cover crops than were those who did not have such concerns. Still, she finds that the voluntary adoption rate of cover crops is relatively low. Financial support, however, increased cover crop acres enrolled in the government programs from 312.6 thousand acres in 2009 to 2,443.1 thousand acres in 2020.

Greater use of fertilizers along with new cropping patterns can be strategies for farmers to maintain or improve yields under more uncertain water supply conditions. While local agricultural production can benefit from such adaptation practices, downstream costs can be inflicted from runoff. Elbakidze, Xu, Gassman, Arnold, and Yen present a valuable analysis of the unintended consequences of greater use of fertilizers and associated nitrate concentrations in runoff from farmland upstream on water quality downstream. They use a set of models applied to the Mississippi River Basin to estimate the costs of externalities in the Gulf of Mexico. The estimated increase in nitrate runoff to the Gulf is in the range of 0.4-1.58 percent compared to the baseline. The effects vary because changes in production, including nitrate use, are spatially heterogeneous. In some counties, nitrate use will intensify, while in others it will decrease.

Similarly, Metaxoglou and Smith explore the extent of nutrient pollution in US agriculture associated with climate change responses, also using the Mississippi River Basin as their study area. They apply their econometric approach to a long-term dataset and introduce an analytical framework for nutrients, corn production, and precipitation in estimating and interpreting their results. If corn yield is not affected by overapplying nitrate fertilizer, farmers overapply as insurance against yield reduction arising from reduced precipitation, common in many locations in the basin. Any residual nitrogen from overdoses, remains in the soil. With precipitation, the nitrogen leaches into lakes, rivers, and streams as nutrient pollution. Therefore, less rainfall leads to more nitrogen applied by farmers, increasing yields and expanding acreage, whereas more rainfall leads to more nutrient leakage into waterways. Under this framework, increases in corn acreage is expected to increase nitrogen concentration in the soil and downstream waterways.

The authors use data on changes in corn acres planted for counties east of the 100th meridian (excluding Florida), precipitation patterns, Mississippi stream flow for 1970–2017, along with secondary estimates of the median potential damage costs of nitrogen increases in the Gulf of Mexico from declines in fisheries and estuarine/marine life at $15.84 per kg of nitrate disposed to the Gulf (in 2008 values). They estimate that an additional 50,800 metric tons of nitrogen in the Gulf of Mexico yield an estimated damage of nearly $805 million per year.

Increased climate change-induced surface water scarcity will direct more investment in groundwater pumping to support irrigation. Competitive extraction, however, depletes subsurface stocks in a non-optimal manner, raises pumping costs, generates surface land subsidence, and reduces water quality. These effects will be intensified if precipitation and groundwater recharge are reduced following climate change. The assignment of tradable groundwater rights or implementation of other regulatory controls will be required to reduce rent dissipation in such a critical resource. While seemingly obvious, despite their benefits these institutional changes are complex and costly due to heterogeneities across groundwater resources and among the pumpers who draw from them, as well as to the many external constituencies who also seek groundwater claims.

The research by Bruno, Hagerty and Wardle demonstrates the importance of new institutional arrangements to regulate groundwater withdrawal in California with consequences for both long-term water levels and farmland values in the vicinity of the regulated aquifers. The authors use the case of the Sustainable Groundwater Management Act (SGMA) enacted in California in 2014 as an example of the benefits and costs, and hence complexity, of legislative policy intervention. The law identified local groundwater sustainability agencies (GSAs) as key for negotiation and implementation of pumping controls among members to achieve sustainable withdrawals. Despite advertised benefits of locally-higher land values and enhanced groundwater stocks, SGMA adoption has been controversial with opposition from many pumpers and their irrigation districts. Pumpers bear direct costs as they cut back on water extractions. These costs vary. The impact of reductions is immediate and generally predictable, while the benefits are longer-term and more uncertain.

Using data for all 343 groundwater agencies (GSAs) formed following the enactment of SGMA, the authors estimate the gross cost of agricultural groundwater regulation through the changes in land values across GSA boundaries before and after the SGMA enactment. Their findings suggest that although SGMA encouraged a move from the previous *status quo* of open access to a joint management regime, the high costs of reduced pumping are significant. Their estimates suggest that, on average, a reduction of 1 acre-foot per acre of expected future water pumping from an aquifer reduces land values of farms within the borders of the GSA by 55% in the post SGMA period. The study suggests that although institutional changes to address common-pool extraction of critical groundwater resources may have broad public good benefits, localized private net costs may be significant and not be Pareto improving. The implication nationwide is that groundwater extraction controls may be resisted, slow, and incomplete.

In another study in a region with precipitation variability, Kovacs and Rider developed an approach to quantify how the demand for in-situ groundwater can help identify the value of groundwater to farmers who experience climatic change effects. Using detailed field-level data and data from land markets in eastern Arkansas overlaying the Mississippi River Alluvial Aquifer the authors provide empirical evidence of decreases in the value of agricultural land due to increased overdraft of groundwater. Levels fall as farmers use more water from the aquifer to compensate for reduced availability of surface sources.

As part of their analysis, the authors estimate a willingness-to-pay for a foot increase in saturated water thickness of $4.70 and $24.80 for all farms and rice farms, respectively, when current thickness is between 100 to 120 feet. The authors also show that the demand slope for in-situ groundwater is more elastic for rice farmers than for all other farm landowners. The main finding is that in all regional land markets analyzed, a decrease in saturated thickness by 20 feet from 120 feet to 100 feet (as was experienced in the region in the past 30 years) would decrease the per acre property value by $148 for all farms and $296 for rice farms. The analysis in this study demonstrates that declining precipitation patterns and related groundwater withdrawals can have a significant impact on the profitability of the agricultural sector and land values in the presence of interacting natural capital stocks, such as surface and groundwater.

E. Conclusions.

As described, the research summarized here provides valuable insights into how American agriculture responds to changes in water access as climate change unfolds. Fortunately, there is abundant historical and contemporary experience for analyzing farmer reaction to greater drought and intense short-term precipitation. These responses include expanded use of irrigation and related technologies, extensive water transport and drainage, introduction of new drought-tolerant crop types and cover crops, shifts to greater reliance upon groundwater to augment surface water reductions, and intensified application of nutrient fertilizers to maintain yields. At the same time, new institutional arrangements, consistent with local farmer incentives, will be required to mitigate the losses of open access in groundwater, promote use of easements, and reduce downstream negative externalities from upstream fertilizer run offs.

Because climate change is a global process with significant international collective action impediments to mitigation (Libecap 2014), its further unfolding is likely to be inexorable. The research included here, however, indicates that US agriculture and the food stocks, fibers, other outputs and exports, as well as related employment and viability of rural communities are likely to be resilient. There are many margins for adaptation, and farmers have incentives to exploit them.

The studies focus on a subset of adaptation options and provides examples of possible directions available for varying farm types, regions, and water situations. Overall, the research indicates that the responses examined lead to positive changes in the performance of the agricultural sector at the region or state level analyzed either in terms of yield or net revenue. A complete benefit-cost assessment of farmer adaptation strategies, however, would include any external costs associated with new crop and seed varieties, water efficient irrigation technologies, resort to common groundwater, investment in water conveyance systems, and design and implementation of new institutional arrangements.

In the case of groundwater, where property rights are relatively complete, such as with tradable extraction rights to Southern California's Mojave Aquifer (Ayres et al 2021) or where management institutions exist, such as in groundwater management districts in Nebraska (Edwards 2016), the losses may be minimal. Externalities are more significant where these conditions are lacking. Increased fertilizer application and associated downstream runoff is an example, and when costs are not privately internalized, fertilizer use may be excessive within a cost/benefit framework. Alternatively, where farmers adopt easements with downstream benefits, not all gains are privately captured, resulting in under adoption. In these respects, the research can be seen as part of an emerging and critical agenda for analysis of adaptation in the agricultural sector to greater water scarcity resulting from climate change.

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