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Trends in U.S. Irrigated Agriculture: Increasing Resilience Under Water Supply Scarcity

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Abstract

Irrigation contributes significantly to U.S. agricultural output and production value. In 2017, irrigated farms accounted for more than 54 percent of the total value of crop sales. Irrigation allows for agricultural production in arid regions where precipitation is insufficient to meet crop water requirements. In more humid regions with variable rainfall, irrigation supplements available soil moisture and provides a critical buffer against periodic drought during the crop growing season. However, surface water supply shortfalls during prolonged drought are increasingly taxing the ability of regional water systems to meet the demands of the irrigation sector—as well as industry, municipal use, recreation, and environmental needs. The irrigation sector responded by increasing its reliance on groundwater. This response raises sustainability concerns, as groundwater levels in many major aquifers supporting irrigated agriculture are in decline across the United States. The resiliency of irrigated agriculture under projected climate change will depend on how the sector—and the institutions that influence water supply and use—adapts to increasing water scarcity. Regional adaptation to increasingly limited water supplies may involve a combination of measures. These measures include: continued shifts in area irrigated, increased irrigation efficiency through system upgrades, enhanced water management practices, changes in regional cropping patterns, and shifts in water supply sources, including potentially novel sources of irrigation water such as recycled or reclaimed water.

Keywords: agricultural water conservation, drought, irrigated agriculture, irrigation efficiency, resiliency, water conservation policy, water scarcity, water use, water demand, water supply

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Contents

A report summary from the Economic Research Service *December 2021*

Trends in U.S. Irrigated Agriculture: Increasing Resilience Under Water Supply Scarcity

R. Aaron Hrozencik and Marcel Aillery

What Is the Issue?

Growing urban populations and economic development intensify competition for the Nation's water resources. With surface water supplies largely allocated in most river basins of the Western United States and some river basins in the Eastern United States, emerging water demands from non-agricultural sectors must be met in many cases through a reallocation of water initially allocated to agriculture. Meanwhile, changing climate regimes—through increased evaporative losses, seasonal shifts in precipitation patterns, reduced snowpack and snowmelt runoff, and higher frequency and severity of droughts—have reduced water supplies during the crop growing season. At the same time, groundwater pumping in excess of natural recharge has substantially diminished aquifer resources critical to agriculture in regions where, and when, surface water is less abundant. Increasing competition for water, coupled with increasingly constrained water supply trends, have important implications for the viability and resiliency of the irrigated agricultural sector. How the sector adapts to these trends will shape the future of irrigated agriculture and the value it creates for the greater agricultural economy.

What Did the Study Find?

Irrigated agriculture—a critically important component of the U.S. farm economy—expanded significantly over the last century, as public reclamation policy initiatives and technological innovations opened new lands to irrigated production.

- Irrigated agriculture generates substantial value for the broader U.S. agricultural economy. In 2017, irrigated farms accounted for more than 54 percent of the total value of U.S. crop sales, while irrigated cropland constituted less than 17 percent of total harvested cropland.
- Irrigated acreage has expanded rapidly since the onset of the Federal reclamation era, which began with the passage of the Reclamation Act (P.L. 57-161) in 1902. Nationwide, irrigated acreage grew from less than 3 million acres in 1890 to more than 58 million acres in 2017.
- Between 1949 and 2017, the share of U.S. irrigated cropland located within the Mountain and Pacific regions decreased from 77 percent to 44 percent, while the share of irrigated cropland in the Mississippi Delta and Northern Plains regions increased from 8 percent to 34 percent.
- Total U.S. water withdrawals for irrigation decreased by 21 percent between 1980 and 2015, with slightly lesser declines (19 percent) in average withdrawals per acre irrigated. In 2015, irrigation accounted for approximately

64 percent of total U.S. water withdrawals, including both freshwater and treated wastewater and excluding withdrawals for thermoelectric power.

- Since the mid–1900s, the relative predominance of surface and groundwater withdrawals for irrigation shifted. In the Pacific and Mountain regions, more than 60 percent and 72 percent, respectively, of irrigated cropland acres rely on surface water flows. However, reliance on surface water for irrigation is decreasing nationwide. Between 1950 and 2015, the share of irrigated acreage using surface water fell from 77 percent to 52 percent.
- Of crops irrigated in 2017, the largest allocation of irrigated acreage was in corn, with nearly 14 million irrigated acres harvested, or more than 25 percent of irrigated cropland harvested.
- While corn accounted for the largest acreage among irrigated crops during the 2017 growing season, these acres constitute less than 15 percent of total harvested corn acreage. Irrigation is more prevalent among other crops. In 2017, a majority of land planted in vegetables and orchards was irrigated, while 100 percent of land planted in rice was irrigated.
- Use of pressurized irrigation application systems, which are generally more water-use efficient than gravity-flow systems in most field settings, increased significantly in recent decades. Of the total U.S. cropland acres irrigated in 2018, 36 percent used gravity systems, while 67 percent used pressurized systems—including sprinklers and low-flow micro systems. Those systems account for 57 percent and 10 percent, respectively, of total irrigated acreage (approximately 3 percent of acres used some combination of gravity and pressurized systems).
- In the Pacific, Mountain, and Northern and Southern Plains regions,[1] the share of irrigated acres using pressurized systems rose from 37 percent in 1984 to 72 percent in 2018—with innovations focused on improved precision of applied water, reduced pressurization requirements, and system automation.
- Improved irrigation water management practices (e.g., soil moisture sensors, weather tracking, irrigation scheduling tools, flow meters, plant condition monitoring technology, etc.) are essential in achieving maximum water-use efficiency. However, survey data of irrigated producers indicate relatively low adoption rates and potential for further expansion of these improved irrigation water management practices. Both surface water supply shortfalls under multi-year drought and a growing concern for groundwater depletion across major U.S. agricultural regions focus policy attention on vulnerabilities of the irrigation sector. Various Federal efforts have sought to strengthen the resilience of irrigated agriculture to water scarcity and the long-term sustainability of the sector.

How Was the Study Conducted?

This study draws on several Federal data sources to describe historical and emerging trends in irrigation use in the U.S. agricultural sector. Land and water resource use trends were assessed based on: the Censuses of Agriculture, the Irrigation and Water Management Survey (IWMS), and the U.S. Geological Survey's (USGS) water use summaries.[2] IWMS and Farm and Ranch Irrigation Survey (FRIS) data are further leveraged to analyze technology use in irrigated agriculture and highlight recent trends. Federal policy initiatives supporting the resiliency of the irrigated sector are addressed in the closing section.

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[1]In this report, regions refers to USDA Farm Production Regions: Pacific (Oregon, Washington, California), Mountain (Colorado, Utah, Arizona, New Mexico, Nevada, Idaho, Wyoming, Montana), Northern Plains (Kansas, Nebraska, South Dakota, North Dakota), Southern Plains (Texas, Oklahoma), Mississippi Delta (Louisiana, Arkansas, Mississippi), Southeast (Florida, Alabama, Georgia, South Carolina), Appalachia (North Carolina, Tennessee, Kentucky, Virginia, West Virginia), Corn Belt (Missouri, Iowa, Illinois, Ohio, Indiana), Lake (Michigan, Wisconsin, Minnesota), and Northeast (Delaware, Maryland, New Jersey, Pennsylvania, New York, Connecticut, Rhode Island, Massachusetts, New Hampshire, Vermont, Maine). Throughout the report, the West or the Western United States refers to the Pacific, Mountain, and Northern and Southern Plains region, while the East or Eastern United States refers to the Mississippi Delta, Southeast, Appalachia, Corn Belt, Lake, and Northeast regions. See figure 1 for a map of the USDA Farm Production Regions.

[2]The *Censuses of Agriculture* were compiled by the U.S. Bureau of the Census (1890–1992) and USDA's National Agricultural Statistics Service (USDA, NASS) (1997–2017). The Irrigation and Water Management Survey (IWMS) (formerly the Farm and Ranch Irrigation Survey (FRIS) prior to 2018) was compiled by the U.S. Bureau of the Census (1979–1994) and USDA, NASS (1998–2018). The U.S. Geological Survey's (USGS) water use summaries are reported at 5-year intervals between 1950 and 2015. The *Census of Agriculture* is generally collected every 5 years. Between the 1992 and 1997 Censuses, data collection responsibilities were transferred from the U.S. Bureau of the Census to the USDA, National Agricultural Statistics Service. Accordingly, 1992 data were collected by the U.S. Bureau of the Census, and 1997 data were collected by the USDA, National Agricultural Statistics Service.

Trends in U.S. Irrigated Agriculture: Increasing Resilience Under Water Supply Scarcity

Introduction

Irrigation is vital to the U.S. agricultural system, allowing for crop production across arid regions of the Nation while supplementing available soil moisture in wetter regions when growing season rainfall is insufficient. Irrigation has significantly enhanced both the productivity and profitability of the agricultural sector. In 2017, irrigated farms accounted for more than 54 percent of the total value of U.S. crop sales, on less than 30 percent of harvested cropland (USDA, NASS, 2019a). Generally, irrigation increases crop yields and reduces yield risk while providing other potential benefits involving nutrient uptake efficiency, crop quality control, and frost protection (Das and Yaduraju, 1999; Troy et al., 2015; Olszewski et al., 2017). Irrigated crop production supports local rural economies in many areas of the United States and contributes significantly to the U.S. livestock, food processing, transportation, and energy sectors (Wu et al., 2009; Eshel et al., 2014; Edwards and Smith, 2018).

The importance of irrigation for the U.S. agricultural sector grew in the past century since early Federal reclamation policy sought to develop the West through the provision of water supplies for agriculture and other purposes. The Federal reclamation era began with the Reclamation Act (P.L. 57-161) of 1902, which provided funds for irrigation projects in the Western United States.[3] Over the ensuing decades, U.S. irrigated area expanded through additional public investment in water supply infrastructure—as well as technological innovations that opened new lands to production, primarily reliant on groundwater resources. Regional cropping patterns and production systems concurrently evolved in response to the increasing availability of water supplies for irrigation.

By the start of the 21st century, the relative water abundance that defined much of the previous century had waned. Emerging demands for non-agricultural uses started competing increasingly for the same available water supplies. At the same time, the effects of climate change likely began to influence seasonal water availability and agricultural water demand (USGCRP, 2018). Across major river basins of the Western United States and some river basins in the Eastern United States, most river systems were fully appropriated[4] and increasingly less flexible in managing water supply shortfalls during prolonged drought. Meanwhile, Federal budgetary and environmental concerns in the 1960s and 1970s largely curtailed new dam construction for water supply expansion (Billington et al., 2005). At the same time, major groundwater aquifers supporting irrigated agriculture were

[3]The development of irrigation infrastructure and irrigated land in the Western United States predates the advent of the reclamation era. Many of the oldest claims to water rights in States such as Colorado date to the 1850s and 1860s. Additionally, some Federal policy-making efforts related to irrigation infrastructure predated passage of the Reclamation Act, notably the Carey Act of 1894 (43 U.S.C. 641 et seq.), also known as the Federal Desert Land Act, and the Desert Land Act of 1877 (P.L. 85-641). These policy-making efforts differed from the Reclamation Act in that the legislation aimed to encourage private investment in irrigation infrastructure (via land grants and settlement) rather than public investment (Coman, 1911; Lovin, 1987).

[4]A fully appropriated river, stream, or basin is a natural or man-made water system where existing uses and rights to both surface and hydrologically connected groundwater supplies are equal to available water supplies in the long term. An over-appropriated system is a system where existing uses and rights exceed available water supplies in the long term.

being depleted,[5] prompting many states to tighten restrictions on local groundwater withdrawals (Stephenson, 1996; Leahy, 2015; Edwards, 2016). In areas of severe aquifer depletion, the future availability of groundwater as a primary source of irrigation water and a buffer source during drought events became an important policy concern (Scanlon et al., 2012; Haacker et al., 2016).

Agriculture continues to face increasing competition for available water. Population and economic growth have generated water needs for municipal, recreational, and industrial purposes across the United States. Water resources are required to support an expanding energy sector, including commercial oil shale and natural gas development, utility-scale solar power generation, and biofuel processing. At the same time, in-stream flow requirements[6] and water diversions for environmental purposes, reflecting evolving societal values regarding wildlife and ecosystem health, play an increasingly important role among competing water demands. In basins with significant irrigation withdrawals,[7] State minimum-flow provisions and instream-flow requirements for federally listed endangered species have resulted in cutbacks in agricultural water use, particularly during low-flow drought years. In addition, American Indian reservations have existing claims to significant volumes of water under Federal reserved water rights provisions, and the adjudication of these water rights may impact regional allocations of water resources in some Western basins. Meeting competing demands for non-agricultural water uses and environmental purposes has increasingly involved the reallocation of existing agricultural water supplies (Brewer et al., 2008a; Schwabe et al., 2020). Meanwhile, a growing body of scientific research on climate change indicates significant potential impacts on weather patterns and hydrologic systems, with implications for both regional water resources and agricultural water demand (see box, "Climate Change and Irrigated Agriculture").

In an era of heightened water scarcity and motivated by successive severe drought events affecting major U.S. agricultural regions in recent years,[8] policy emphasis has turned increasingly to building drought resiliency within agricultural systems. The National Integrated Drought Information System (NIDIS) program was authorized in 2006 to coordinate drought research through Federal, State, and local partnerships—with the intent of developing a national drought early-warning information system (Brewer et al., 2008b). The National Drought Resilience Partnership (NDRP) was established in 2013 to coordinate Federal activities with State, Tribal, and local efforts to promote long-term drought resilience, including water supply security for irrigated agriculture (Brusberg and Shively, 2015). The increasing incidence and persistence of drought projections under climate change, and related impacts on hydrologic systems and water demand, underscore the importance of developing drought resilience in the agricultural sector (IPCC, 2014; Ault et al., 2014).

[5]The long-term viability of groundwater-fed irrigated agriculture depends on the characteristics of the groundwater resource and the objectives of the irrigators or other entities (e.g., groundwater management district) managing groundwater use. Some aquifers have minimal natural recharge (e.g., confined aquifers—footnote 27), while other aquifers experience relatively high rates of natural recharge. The rate of natural aquifer recharge constrains the sustainable use of groundwater resources, as this rate defines the amount of water that can be extracted without depleting the resource. In addition to the natural recharge rate, characterizing a rate of sustainable groundwater use through time depends on the objective of defining the groundwater use policy and the discount rate. Examples of differing groundwater use policy objectives include maximizing farm profits, minimizing costs to the broader agricultural services sector, maximizing benefits of ecosystem services provided by groundwater stocks, or maintaining the same groundwater level through time. The discount rate represents the time value of money defining how to "discount" future profits or costs compared to profits or costs incurred today. In addition, substantial uncertainty around groundwater resource thresholds may exist, whereby patterns of use may irreversibly change the quality or storage capacity of the aquifer.

[6]In-stream flow requirements refer to the flow of water (e.g., cubic feet per second) necessary to maintain the health of aquatic and riparian ecosystems (Brandes et al., 2009). These flow requirements generally impose a minimum necessary flow but may also place a maximum allowable flow for hydropower dam water releases. Also, flow requirements may be seasonal to reflect the water needs of aquatic species or recreation. In-stream flow requirements are generally imposed in accordance with State or Federal laws (e.g., Endangered Species Act of 1973, P.L. 93-205).

[7]Irrigation withdrawals or diversions refer to water "removed from a groundwater or surface water source for use" for application on crops (Dieter et al., 2018).

[8]Major drought events in the United States over the past 15 years, as identified by the United States Drought Monitor, 2021: California (2007–09, 2012–16), Southwest (2006–07, 2011–15, 2018, 2020), Northwest (2007, 2013–15), Southern Plains (2006, 2011–14, 2018), Northern Plains (2006, 2012–14, 2017), Midwest (2012), Southeast (2006–08, 2011–12).

Climate Change and Irrigated Agriculture

Climate change poses a serious challenge to the future of U.S. irrigated agriculture. While climate projections vary across Global Climate Models and emission scenarios, the modeling assessments reveal significant changes in weather patterns and hydrologic processes that will likely affect future water availability (IPCC, 2014). In the United States, the effects of climate change on water resources are already evident and expected to persist (USGCRP, 2018). Higher temperatures and increasingly variable precipitation are heightening drought concerns and causing significant changes in the quantity, timing, and intensity of seasonal water runoff that may not align with water demand. Shifting precipitation and temperature patterns are expected to directly affect the availability of surface water supplies for agriculture and other uses (Niraula et al., 2017; Smerdon, 2017). Groundwater from confined aquifers is generally less influenced by short-term weather patterns. However, climate change may alter the recharge of unconfined aquifers through shifts in precipitation patterns and runoff, soil evaporative loss, and non-crop vegetative cover (Dettinger and Earman, 2007; Meixner et al., 2016).

The impacts of climate change on water availability and irrigation demand differ across the United States. Some northern regions (e.g., Northeast, Lake) are projected to experience an increase in precipitation (Wolfe et al., 2018). Meanwhile, the Western United States, and specifically the southern regions of the West (e.g., Southern Plains, southern portions of the Mountain region), may face significant decreases in water availability (Foti et al., 2012; Seager et al., 2013; Dettinger et al., 2015). Across the Western States, shifts in the volume and timing of snowmelt runoff are expected to reduce stored surface water reserves in the critical summer season when crop-water demands are greatest (USDI-Reclamation, 2021). In basins with significant reservoir storage capacity, variability in annual and seasonal runoff may be lessened through carryover storage. However, changing patterns of intra-seasonal water availability will challenge dam and reservoir managers to develop new rules and policies governing water releases adapted to evolving climate conditions (USDI-Reclamation, 2015; Jaeger et al., 2019). Projected increases in the frequency and severity of drought events may further heighten competition for limited water supplies in the West, while potentially expanding irrigation use in traditionally rain-fed production areas in the Eastern United States.

Evolving climate conditions may influence future trends in irrigated crops, depending on the relative sensitivity of crops to shifting climate factors and the coincidence of regional climate shifts with geographic patterns of irrigated (and dryland) production (Marshall et al., 2015a). In general, rising temperatures are expected to increase crop evapotranspiration (ET) requirements. Irrigation demand by perennial crops in the West is expected to increase most dramatically as longer growing seasons increase crop ET (Huntington et al., 2014). Increasing concentrations of atmospheric carbon (CO^2) may also influence crop growth patterns by stimulating plant photosynthesis and improving water use efficiency (Marshall et al., 2015a; Urban et al., 2017). Increased atmospheric carbon has the greatest positive yield effect on C3 crops (such as wheat, barley, soybeans, and alfalfa), while effects for C4 crops (such as corn and sorghum) are minimal. Carbon effects on water use efficiency are greatest for dryland production—but are also increased in irrigated production, particularly under deficit irrigation conditions—where water applications do not completely eliminate crop-water stress. Sectoral adaptation can mitigate the effect of a changing climate, as cropping patterns adjust and irrigated land shifts from water scarce regions to areas where water is relatively more abundant.

This report outlines broad national and regional trends relating to water use in the U.S. agricultural sector[9]—including irrigated acreage, water use by source, cropping patterns, and application technologies—and key drivers of change over time. The resiliency of irrigated agriculture is observed through regional adaptations to changing water supply conditions. Drought adaptation is also increasingly reflected at the institutional level through public policies introduced to enhance the flexibility of the irrigated sector's response to shifts in water availability. The report highlights new innovations and policy initiatives intended to enhance the resiliency of irrigated agriculture into the 21st century.

Figure 1
USDA farm production regions

Note: Miss. Delta = Mississippi Delta.

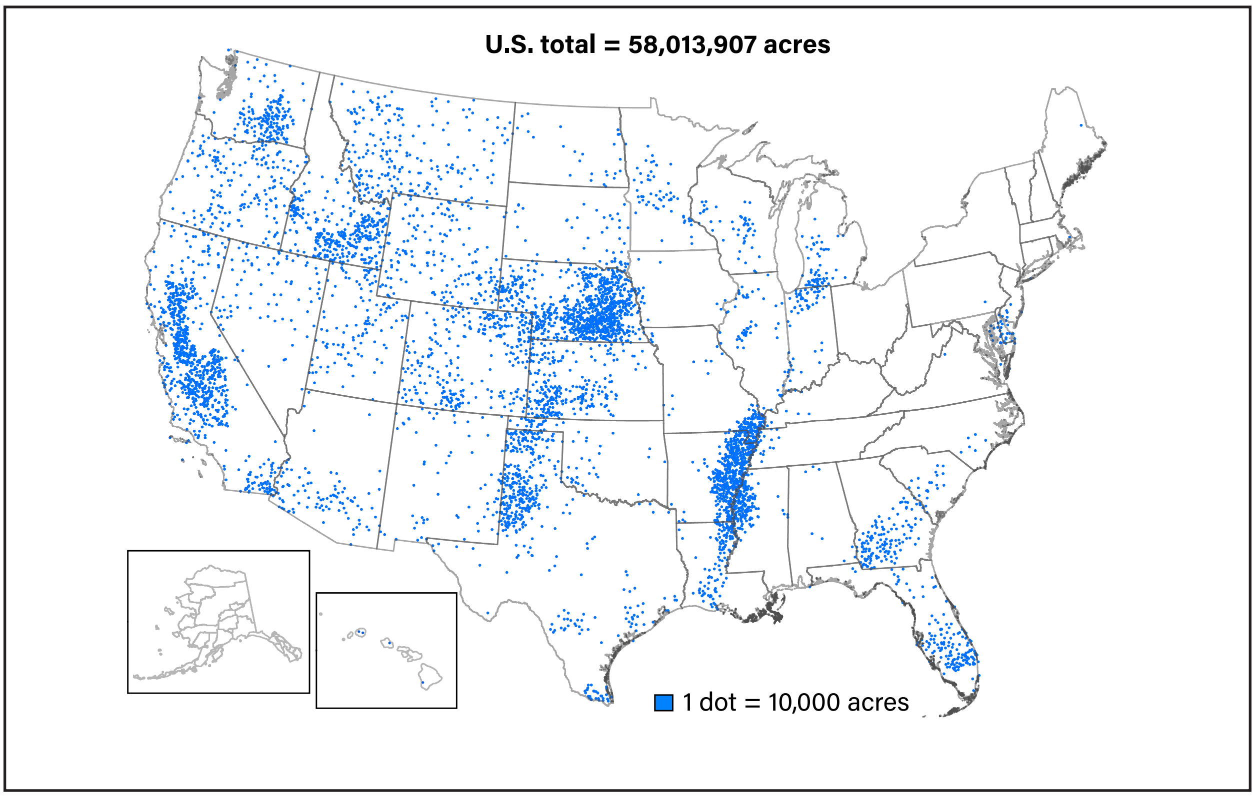
Source: USDA, Economic Research Service.

[9]This report focuses primarily on issues related to water quantity rather than water quality. However, water quality is an important issue facing the U.S. agricultural sector. For example, degraded water quality related to agricultural input use is an issue in many watersheds across the United States, with potentially significant ecological and economic consequences (Ribaudo and Johansson, 2006). In addition, the irrigated agricultural sector also has a host of specific water quality concerns. For example, some coastal, as well as inland aquifers used for irrigation, are threatened by saltwater intrusion—that can be exacerbated by groundwater depletion and sea level rise (Werner and Simmons, 2009; Ferguson and Gleeson, 2012).

Irrigated Acreage

Where crops are irrigated in the United States depends largely on the interaction of regional weather and agricultural production systems, as well as the availability of water resources. Figure 2 presents the spatial distribution of irrigated acreage[10] in 2017, with concentrations in arid regions of the Western United States, as well as in the humid Southeast and Mississippi Delta regions. In many areas of the Pacific, Mountain, and Southern and Northern Plains regions, precipitation is insufficient to meet the water requirements of most crops, and irrigation is a necessity for agricultural production. See figure 1 for a map of the USDA farm production regions referenced in this report. In other more humid regions, annual and seasonal variation in the amount and timing of rainfall drives irrigation adoption decisions. The availability of surface and groundwater is also a primary factor in the spatial distribution of irrigation. Much of the irrigation development in the West was made possible through publicly financed investments in surface water storage and conveyance projects. In the Plains regions, concentrations of irrigated areas largely reflect the availability of groundwater resources, specifically the High Plains Aquifer (Ogallala Aquifer). The water use requirements of specific crops may have also prompted the adoption of irrigation on agricultural land. Flooding requirements of rice in the Mississippi Delta region, for example, help explain the concentration of irrigated acres in a region that generally receives plentiful rainfall.

Figure 2
Spatial distribution of irrigated farmland in acres, 2017



Notes: Figure is based on 2017 county-level estimates of irrigated acreage. The largest concentrations of irrigated acreage occur in the Mississippi Delta region, the Central Valley of Calfornia, and parts of the Northern and Southern Plains regions overlying the High Plains Aquifer.

Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, *2017 Census of Agriculture*.

[10]Irrigated acreage estimates include only crops grown in the open and not crops irrigated in greenhouses or other enclosed structures.

The importance of irrigation for U.S. agricultural production has evolved significantly over the past century. Figure 3 places irrigated land observed in 2017 within the broader context of aggregate trends in U.S. irrigated area and average water use per acre irrigated. Since 1890, irrigated acreage nationwide has grown from less than 3 million acres (less than 1 percent of improved agricultural land) to more than 58 million acres in 2017. Irrigated harvested cropland totaled nearly 54 million acres in 2017, accounting for approximately 17 percent of the 320 million acres of harvested cropland. Irrigated pasture, totaling more than 4 million acres in 2017, made up the remaining irrigated land. The average amount of water applied per acre irrigated declined from more than 2 acre-feet[11] per acre irrigated in 1969 to nearly 1.5 acre-feet per acre irrigated in 2018. The diminishing intensity of water use per acre corresponds to changes in irrigation application and data management technologies, the mix of crops irrigated, and the regional distribution of U.S. irrigated acreage.

Significant expansion in the Nation's irrigated land is attributable, in part, to the water development projects funded and operated by the U.S. Bureau of Reclamation between the Bureau's inception in 1902 and the last authorization for a major project in the late 1960s (Pisani, 2003). Additional publicly financed water projects (providing irrigation supply as a primary or secondary purpose) were also developed by the U.S. Army Corps of Engineers, the State of California, and the Bureau of Indian Affairs (see box, "Irrigated Agriculture on American Indian Reservations"). Meanwhile, post-World War II technical innovations in pressurized irrigation application systems[12] and deep-well groundwater pumping opened new areas to irrigation (Baltensperger, 1993; Hornbeck and Keskin, 2014; Edwards and Smith, 2018). Broader economic conditions also contributed to varying rates of growth over time. The contraction of irrigated land in the early 1980s is likely attributable to the farm crisis of that era (Barnett, 2000). More recently, the national irrigated area remained relatively constant; total acreage increased by approximately 3 percent between 1997 and 2017.

[11]An acre-foot is approximately 325,851 gallons of water.

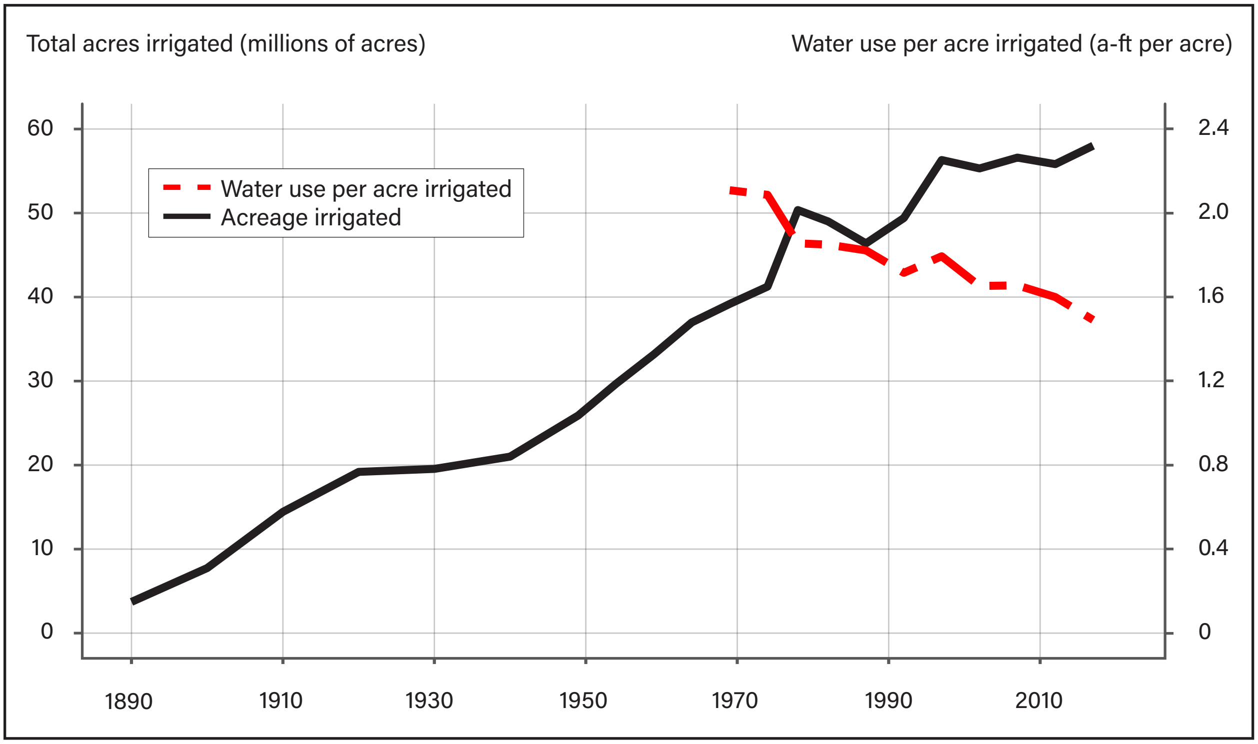
[12]Specifically, the advent of center pivot pressurized irrigation systems allowed for the expansion of irrigation to land previously deemed unsuitable for gravity irrigation systems due to excessive or non-uniform field slope.

Irrigated Agriculture on American Indian Reservations

There are 574 American Indian and Alaska Native tribes and villages in the United States administered as Federal reservations, including public land allotments. Agriculture is an important economic activity on many American Indian reservations, and for the majority of reservations located in the Western United States, irrigation is necessary to grow most crops. Much of the irrigated cropland on reservations is supplied by irrigation projects owned and operated, in full or in part, by the Bureau of Indian Affairs. In 2017, USDA, National Agricultural Statistics Service (NASS) reported 4,496 irrigated farms were on reservations—including Indian and non-Indian operated, and tribal-operated—which irrigated an estimated 840,000 acres (USDA, NASS, 2019b). Much of the irrigation on tribal land relies on federally reserved water rights, dating to the establishment of the reservation. In 1908, the U.S. Supreme Court ruled in Winters versus United States that reservations are entitled to an amount of water sufficient to maintain and survive on the land granted for the reservation (U.S.S.C. 564). The Winters decision vested Tribes with water rights whose priority often supersedes that of other appropriators. Despite the potential value of these rights, only 56 of 226 federally recognized reservations in the Western United States partially settled their Winters claims (Sanchez et al., 2020). Adjudicating Winters claims involves a costly and lengthy negotiation process that potentially hampers the ability of Tribes to receive water rights implicitly granted with the reservation's formation. In 2017, reported irrigated acreage accounted for approximately 18 percent of all harvested cropland on reservation lands (USDA, NASS, 2019b). Further adjudication of Winters claims has the potential to expand the role of irrigation on tribal lands. However, the development of irrigated agriculture on reservations with adjudicated rights may be restricted by limited financial resources for deferred system maintenance (GAO, 2015). Land tenure arrangements may also limit irrigation investment. Reservation land is a patchwork of private property and land held in trust by the Federal government on behalf of Tribes and individual Indians. Recent research by Ge et al. (2020) suggests that land held in trust on reservations is less likely to be irrigated with a capital-intensive irrigation system, as land tenure arrangements may hamper access to capital. While negotiated settlements may support reallocated water rights for irrigation expansion on reservation lands, Tribes may also agree to lease water to off-reservation agricultural users, non-Indian lessees on reservation lands, and nonagricultural users such as municipalities (H.R.4783). To the extent that Tribes accept compensation in lieu of water, the actual reallocation of water from existing agricultural users may be more limited.

Figure 3

Total farmland acres irrigated, 1890–2017, and average water use per acre irrigated, 1969–2018



Notes: An acre-foot (a-ft) is the amount of water needed to cover one acre of land under a foot of water. Water use per acre irrigated in 1969 and 1974 was calculated using data reported in the *Census of Agriculture—Irrigation and Drainage on Farms*, which only reported irrigated acreage for 17 Western States as well as Louisiana and Arkansas. The 1950 *Census of Agriculture* estimated that the irrigated acreage reported in the 1940 Census of Irrigation represented about 99 percent of the Nation's total irrigated acreage. With the exception of a small downturn in the 1980s, irrigated acreage consistently expanded in the United States since 1890. More recent data demonstrated that water use per acre irrigated has steadily diminished.

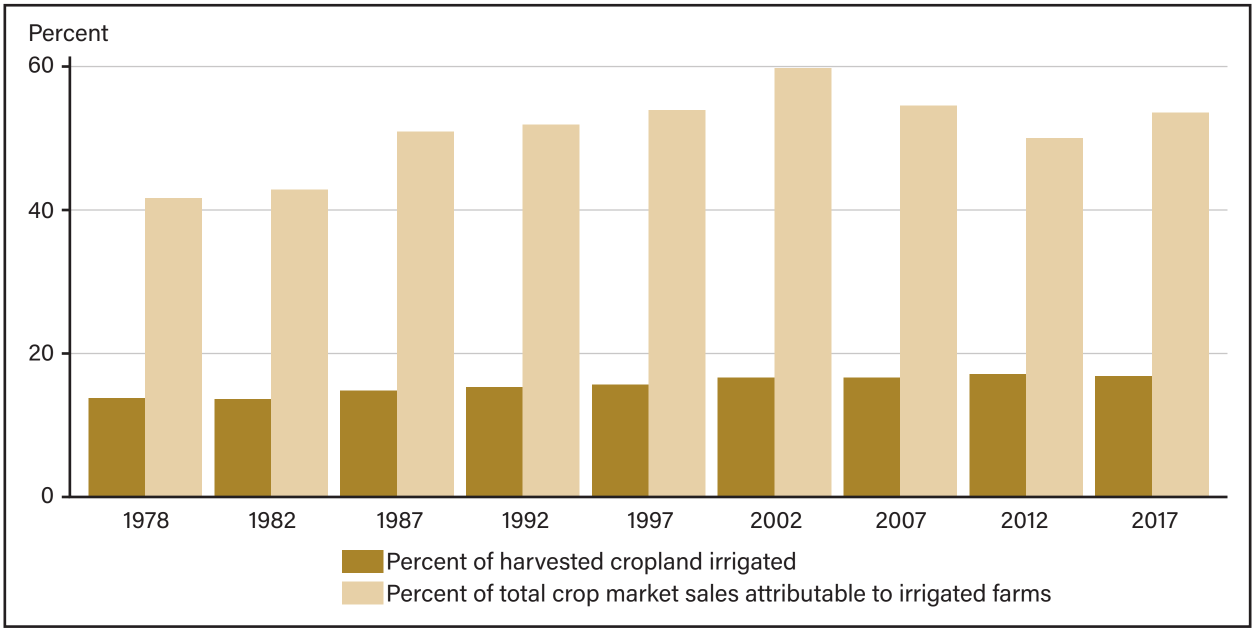
Sources: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service (NASS) (1997–2017) and U.S. Department of Commerce, Bureau of the Census (1890–1992), *Census of Agriculture (1890–2017)*; USDA, NASS (1998–2018) and Census Bureau (1979–94), *Farm and Ranch Irrigation Survey (1979–2013)* and *Irrigation and Water Management Survey (2018)*; and Census Bureau, *Census of Irrigation (1890–1940)*.

The importance of irrigation for the value created by the agricultural sector has also evolved. Figure 4 shows this change by plotting the share of harvested cropland acres irrigated and the share of total crop market sales attributable to farms reporting at least some irrigated cropland. Since 1978, the proportion of total harvested irrigated cropland remained relatively constant. Between 1978 and 2002, the share of total crop-market value created by irrigated farms steadily increased from approximately 40 percent to nearly 60 percent, reflecting in part per acre yield gains from applied water and an increasing concentration of irrigated land area in higher valued crops. Since 2002, the value share generated by irrigated farms ranged from between 60 percent in 2002 and 50 percent in 2012. This share potentially reflects varying production and market effects on irrigated and dryland crop sectors due to several severe regional droughts that occurred during this period.[13]

[13]This report focuses on crops irrigated in the open rather than crops grown in greenhouses and other enclosures. Crops grown in the open include traditional row crops such as corn and soybeans, field crops such as wheat and alfalfa, ornamental and nursery crops, as well as specialty crops such as fruit and nut orchards and vegetables. A sizeable expansion in irrigation for crops grown in enclosed structures occurred in recent decades. From 2008–18, irrigated horticultural production in enclosed spaces expanded from 1.369 to 1.525 billion square feet. This production accounts for only a small portion of total irrigation water use in the United States. According to the 2018 IWMS, water use by horticultural operations on crops under protection accounted for less than 0.06 percent of total water applied by the agricultural sector. However, horticultural production is generally high valued, and continued expansion is anticipated.

Judging the value of irrigation based on crop market sales, or the gross value of production, overlooks the important role of production costs in determining the economic value of crop production. Applying water to crops generally involves additional costs to purchase, pump, or convey water. Irrigation often involves substantially different cropping systems and production inputs relative to dryland production in a given region. Additionally, assessing the share of total value generated by irrigated farms somewhat overstates the value of irrigation as some irrigated farms also produce non-irrigated crops.[14] The extensive consolidation of farms observed in the United States since the 1980s may also overstate the increasing value generated by irrigation (MacDonald, 2020). If previously dryland farms add irrigated land to their acreage, then market sales generated by these consolidated farms would contribute to growth in the value of irrigated farms. Finally, the value generated by irrigated farms reported in figure 4 only considers the market value of crops sold. Irrigated production also generates other values in terms of local employment effects, demand for agricultural services, and increased farmland values. The opportunity costs of water use in agriculture, as well as environmental impacts that may be associated with irrigated production, are notably not reflected.

Figure 4
Percentage of cropland irrigated and share of total crop market sales attributable to irrigated farms, 1978–2017



Notes: Data for 1987 through 2017 are drawn from tables 1 and 10 in the 1987 through 2017 *Census of Agriculture*. Data for 1982 are drawn from tables 2 and 3 in the 1982 *Census of Agriculture*. Data for 1978 are drawn from tables 1, 16, and 17 in the 1978 *Census of Agriculture*. The percent of total crop market sales attributable to irrigated farms was on a mostly upward trajectory since 1978. At the same time, the percent of total cropland acres irrigated also increased, but the magnitude of increases is not as large.

Sources: USDA, Economic Research Service using *Census of Agriculture* (1978–2017) data collected by USDA, National Agricultural Statistics Service between 1997 and 2017, and the U.S. Department of Commerce, Bureau of the Census between 1978 and 1992.

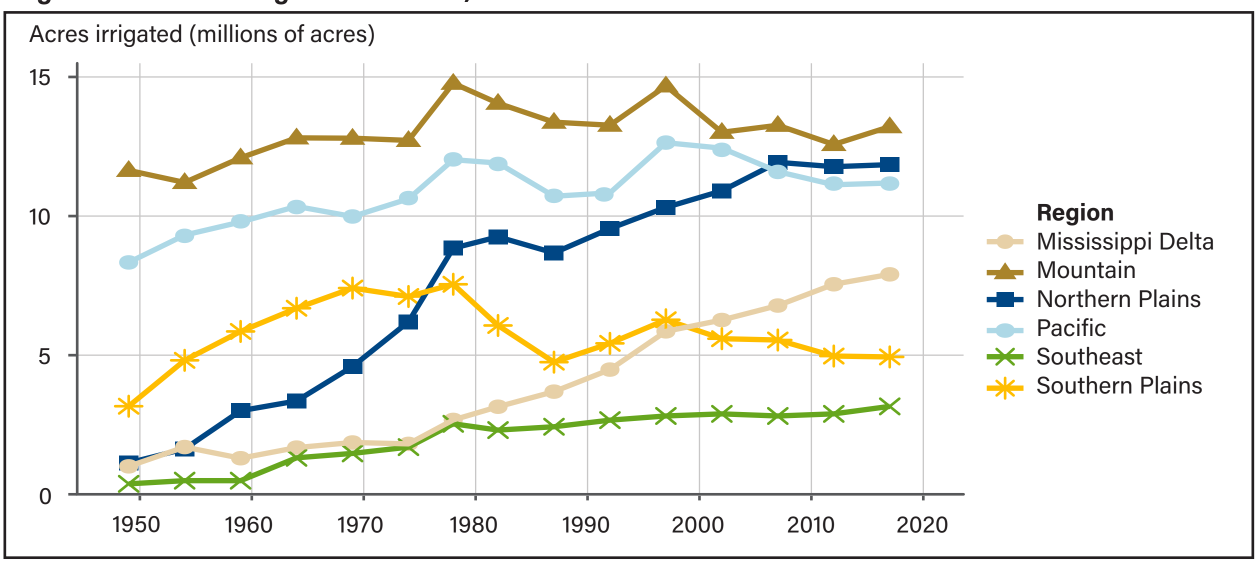
[14]The *Census of Agriculture* reports the market value of crop products sold differentiating across three farm types: 1) farms with any land irrigated, 2) farms with all harvested cropland irrigated, and 3) non-irrigated farms. Note that 2 is a subset of 1 (in farm types defined above). In 2017, 1, 2, and 3 accounted for 54 percent, 30 percent, and 47 percent of the total value of crop products sold, respectively. Figure 4 reports the value attributable to farms with any irrigated cropland (54 percent in 2017), which may somewhat overstate the gross value of irrigated crops as these farms also potentially produce non-irrigated crops. Comparing the value attributable to 1 versus 2 allows inference of a lower bar for the total crop output sales value generated by irrigated land. Specifically, subtracting the value generated by 2 (30 percent) from the value created by 1 (54 percent) yields the percentage of value attributable to farms that produce both irrigated and dryland crops (23 percent). As such, 30 percent can be viewed as a lower bar on the market value generated by irrigated crop production. Data limitations preclude estimating the value attributable to only irrigated crops on farms that produce irrigated and non-irrigated crops.

Regional Acreage Trends

While aggregate irrigated land in the United States was on a steady upward trajectory for most of the past century, the trend in irrigated land area has varied across regions. Figure 5 illustrates irrigated acreage trends for six regions with significant concentrations of irrigated farmland (Mississippi Delta, Mountain, Northern Plains, Southern Plains, Southeast, and Pacific). Between 1949 and 2017, the share of U.S. irrigated cropland located in the Mountain and Pacific regions decreased from 77 percent to 44 percent, while the share of irrigated cropland in the Mississippi Delta and Northern Plains regions increased from 8 percent to 34 percent. Note that the Mountain and Pacific regions, in particular, experienced relatively large spikes in irrigated acreage in both the late 1970s and late 1990s, due in part to ample surface water supplies with generally near-or-above-average precipitation. Relatively high irrigated acreages may also reflect the sector's response to historically high commodity prices and more limited enrollment in Federal cropland idling programs[15] during these periods (Peters et al., 2009; Gollehon and Quinby, 2000).

Several factors explain the relative shift in irrigated area eastward. After the 1950s, rapidly expanding urban centers increasingly competed for land and water resources in the Pacific and Mountain regions of the Western United States (Brewer et al., 2006). Meanwhile, the discontinuation of new authorizations for large-scale Federal water projects after the late 1960s limited significant surface water supply enhancement (Pisani, 2003). At the same time, advances in groundwater pumping and irrigation technologies (e.g., center pivot technology and submersible, high-capacity irrigation pumps) reduced the cost of extracting and applying groundwater. These advancements led to an expansion of irrigation in arid regions without plentiful surface water (e.g., the Southern and Northern Plains), as well as in more humid regions that are still subject to prolonged drought (e.g., the Mississippi Delta and Southeast). The growth of irrigation in the Eastern United States has important implications for agricultural drought mitigation, as producers are more likely to practice supplemental irrigation to replenish soil moisture deficits during critical crop growth stages (Mullen, 2009).

Figure 5
Regional trends in irrigated farmland, 1949–2017



Notes: Between 1949 and 2017, the Mountain region consistently irrigated the most farmland acres. Over the same period, total irrigated farmland acres in the Mississippi Delta and Northern Plains regions increased significantly. Since 2007, the Northern Plains region irrigated the second most farmland acres.

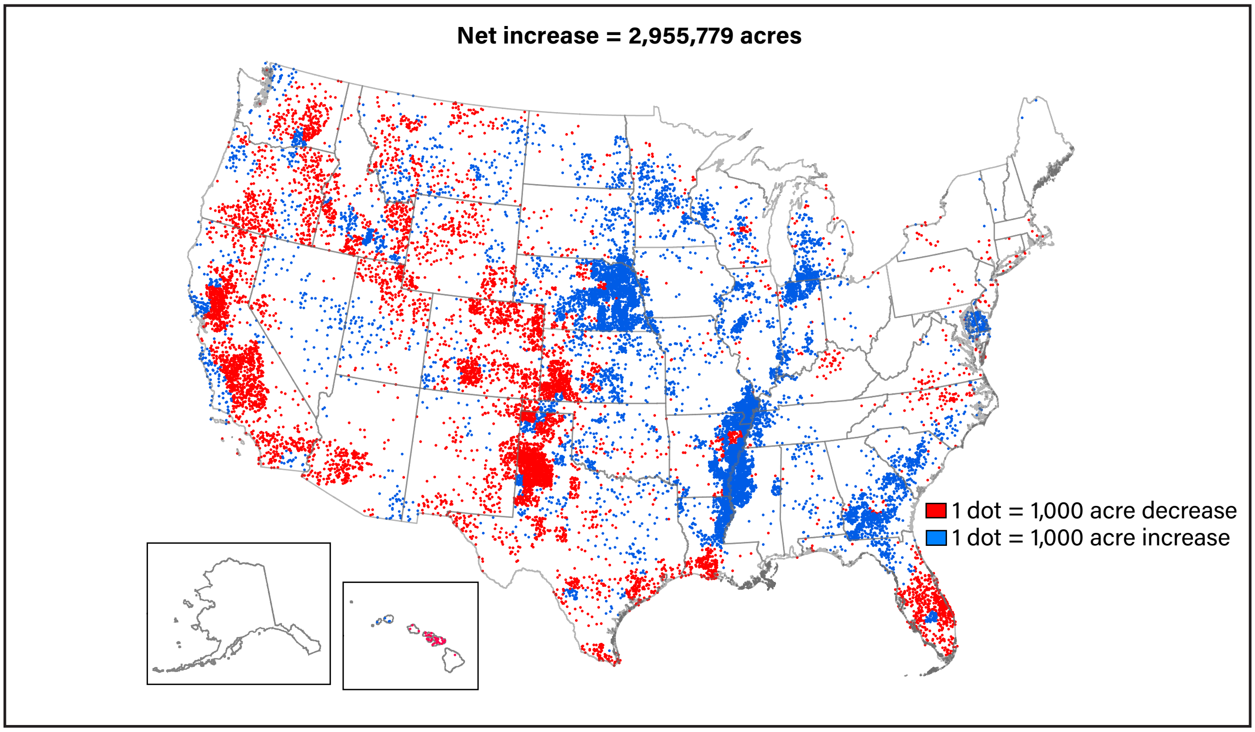
Sources: USDA, Economic Research Service using data from *Censuses of Agriculture* (1949–2017) data collected by the U.S. Department of Commerce, Bureau of the Census between 1949 and 1997, and USDA, National Agricultural Statistics Service between 1997 and 2017.

[15] The history of Federal cropland idling programs in the United States began in the mid-1950s with the USDA's Soil Bank Program (Title I of the Agricultural Act of 1956). More recent examples include the Wetland Reserve Program (WRP) and the Conservation Reserve Program (CRP).

Figure 6 presents a more spatially detailed representation of regional changes in irrigated acreage between 1997 and 2017. The figure highlights the contraction of irrigated land across much of the West and expansion of irrigation in the East, while revealing additional intra-regional acreage shifts. For example, the contraction of irrigated acreage in the Pacific region is concentrated in the Central Valley of California and inland portions of Oregon and Washington. Declining irrigated acreage in the Central Valley is likely related to diminished surface water availability, resulting from successive droughts and decreased snowpack. Specifically, the droughts of 2007–10 and 2012–16 severely curtailed surface water availability in the Central Valley (Famiglietti et al., 2011; Xiao et al., 2017). These droughts, paired with increased water demands due to urbanization and in-stream flow requirements for environmental purposes, explain some of the contraction in irrigated acreage observed in figure 6. Diminishing irrigated acreage in the region was partially tempered by the irrigated agricultural sector's increased reliance on non-surface water resources. Withdrawals for irrigation from the Central Valley aquifer system, the third most intensively pumped aquifer in the United States, increased by 14 percent over the 2000–15 period (Lovelace et al., 2020). This suggests that irrigated producers in the Central Valley adjusted to reductions in surface water availability through an increased reliance on groundwater. With groundwater resources increasingly overdrawn across the State, the passage of California's Sustainable Groundwater Management Act in 2014 (collectively three bills: AB 1739, SB 1168, SB 1319) will likely limit continued expansion of groundwater-fed irrigated agriculture as a response to surface water shortfalls (Leahy, 2015). Note that in both the Mountain and Pacific regions, irrigated acreage spiked considerably in 1997 (figure 5). As such, comparisons between 1997 and 2017 irrigated acreage may somewhat overstate the contraction of irrigation in both regions.

Figure 6

Spatial distribution of changes in irrigated acreage, 1997–2017



Notes: Dots are associated with county-level changes in irrigated acreage between 1997 and 2017, as reported by the 1997 and 2017 *Censuses of Agriculture* (USDA, NASS 1999; 2019a). Changes in county-level irrigated acreage are presented in 1,000-acre increments. The color of the dot denotes a county-level increase or decrease. If a county experienced a change in excess of 2,000 acres, then multiple dots are randomly placed within the geographical extent of the county. Approximately 57 percent of counties did not experience an increase or decrease in irrigated acreage above 1,000 acres between 1997 and 2017. The largest concentrations of increases in irrigated acreage occur in the Mississippi Delta region and the Northern High Plains. The largest concentrations of decreases in irrigated acreage occur in the Central Valley of California and the Southern High Plains region.

Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, *1997 and 2017 Censuses of Agriculture.*

Figure 6 also highlights contrasting acreage trends in the Southern and Northern Plains regions. The High Plains Aquifer, which overlies portions of eight States across the Plains regions, is the most intensively pumped aquifer in the United States (Lovelace et al., 2020). The aquifer contributes approximately $3 billion in gross value annually to the U.S. agricultural sector (García Suárez et al., 2018). Over the 20-year period, the Southern Plains experienced a significant decline in irrigated acreage. The contraction in irrigated area was largely attributable to increasingly scarce groundwater resources, especially in the southern portion of the aquifer overlying the Panhandle of Texas and southwestern Kansas, where depletion was most severe (McGuire, 2017).[16] Meanwhile, irrigated acreage expanded in the Northern Plains region, primarily in clusters of eastern Nebraska, where groundwater resources are most abundant (McGuire, 2017). The growth in irrigation in eastern Nebraska was potentially related to the severe drought experienced throughout the Plains regions in 2011 and 2012. This growth may have prompted a transition from dryland to groundwater-based irrigated production (Hoerling et al., 2014).

Significant expansion of irrigated agriculture in the Mississippi Delta region is concentrated in areas overlying the Mississippi River Valley alluvial aquifer, the second most intensively pumped aquifer in the United States (Lovelace et al., 2020). Withdrawals for irrigation from the aquifer increased by 28 percent between 2000 and 2015 (Lovelace et al., 2020), suggesting that expansion in irrigated acres was attributable, in part, to more intensive groundwater pumping. Figure 6 further highlights irrigation expansions in areas of the Eastern United States historically dominated by rain-fed agriculture—including the southeastern Atlantic Coastal Plain (primarily in southern Georgia), as well as the north-central Corn Belt region, parts of the Mississippi River Valley Alluvial aquifer, and eastern Chesapeake Bay region. Much of this irrigated acreage relies on groundwater withdrawals from relatively shallow aquifers. In contrast, central-southern Florida saw a substantial contraction in irrigated acreage over the period.

Figures 5 and 6 demonstrate the eastward progression of irrigation in the United States. Changes in temperature and in precipitation patterns predicted for the Western United States under climate change may accelerate this transition as water resources become increasingly scarce in much of the region (Huntington et al., 2014). Projected increases in the frequency and severity of drought may also promote irrigation adoption in traditionally rain-fed production regions (USGCRP 2018, Negri et al. 2005). Future patterns of irrigated land in the United States will depend significantly on the impact of climate change, regional water availability, and growing season weather (Paudel and Hatch, 2012).

[16]Since the early 1980s, irrigated acreage in the Southern Plains region has been on a steady downward trajectory. A notable exception was the late 1990s, when higher commodity prices and low enrollment in cropland idling programs caused a temporary spike in the region's irrigated acreage (see figure 5). This increase in Southern Plains irrigated acreage in the late 1990s reduces the irrigated acreage contractions observed in the region in figure 6. However, figure 5 demonstrates these contractions in irrigated acreage are part of a longer-term trend.

Water Use for Irrigation

Water applied to crops constitutes a significant proportion of total U.S. water withdrawals.[17] Figure 7 plots the evolution of water withdrawals for irrigation versus other end uses between 1950 and 2015, excluding withdrawals for thermoelectric power generation, mining, commercial purposes, and aquaculture[18] (Hutson, 2004; Kenny et al., 2009; Maupin et al., 2014; Dieter et al., 2018). From 1950 until 1980, when water withdrawals for irrigation peaked at 168 million acre-feet annually (1 acre-foot = 325,851 gallons), the growth in water use for irrigation generally aligned with the observed expansion in irrigated land. After 1980, this relationship no longer holds, as increases in irrigated acreage nationwide coincided with diminishing levels of water withdrawals for irrigation. The decrease in irrigation withdrawals is potentially attributable to several factors examined in this report: shifts in the regional distribution of irrigated land, regional changes in water source availability and competition from the urban sector, shifts in on-farm irrigation technology and cropping patterns, and improved off-farm water conveyance. These factors together contributed to a 29 percent decrease in average U.S. water withdrawals per acre irrigated over the 1980–2015 reporting period (Solley et al., 1983; Dieter et al., 2018).[19] Over the same period, total withdrawals for irrigation decreased by 21 percent.

Irrigation accounted for 64 percent of freshwater withdrawals in 2015, excluding diversions for thermoelectric power (Dieter et al., 2018). The share of U.S. freshwater withdrawals used for irrigation (excluding diversions for thermoelectric power) remained relatively stable over recent decades. The share increased only slightly from 62.5 percent in 1980, despite the significant decline in irrigation water use nationally. The share of withdrawals that are consumptively used in irrigated production (estimated at 62 percent) is notably higher than for other end uses (Solley et al., 1998; Dieter et al., 2018). For example, just 3 percent of the water diverted for thermoelectric power was consumptively used in 2015 (Dieter et al., 2018). Significant volumes of water consumptively used for irrigated crop production, and effectively removed for other uses, has important implications for overall water availability across sectors of the U.S. economy.

Future trends in water use will depend in part on how climate change influences future water demand by irrigated agriculture and other sectors. Increases in temperature and diminished growing season precipitation (projected under climate change scenarios) may increase irrigation water demand in many areas (Huntington, 2014; USGCRP, 2018). However, increases in water demand may be tempered by changes in cropping patterns, irrigation application technologies, and irrigated areas in response to diminished surface and groundwater availability (Marshall et al., 2015b).

National trends in water withdrawals for irrigation differ somewhat from reported trends in on-field water applied. According to USDA surveys of U.S. producers reporting irrigation in the Agricultural Census, total on-farm applied water remained fairly constant over the 1984–2018 period (Schaible and Aillery, 2012; Schaible and Aillery, 2019; USDA, NASS, 2019c). This disparity can be explained, in part, by differences in

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[17]USGS defines water withdrawals as "water removed from a groundwater or surface water source for use." Consumptive use is the "part of water withdrawn that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment" (Dieter et al., 2018). The USDA's Irrigation and Water Management Survey (previously the Farm and Ranch Irrigation Survey) reports on-farm applied water use based on producer estimates of the amount of water applied to the field (USDA, NASSc, 2019).

[18]Water withdrawals for thermoelectric power generation are primarily used for cooling purposes, with a significant share of withdrawals historically returned to river systems. Data on water withdrawals for mining and aquaculture were not collected before 1985. Jointly, mining and aquaculture accounted for less than 4 percent of total water withdrawals in 2015 (Dieter et al., 2018). Data on water withdrawals for commercial purposes were only collected in 1985, 1990, and 1995. In 1995, withdrawals for commercial purposes accounted for less than 1 percent of total water withdrawals.

[19]After 1980, declining water withdrawals for municipal and industrial uses, particularly for thermoelectric power generation, reflected broad improvements in water use efficiency across sectors of the U.S. economy.

how USDA and USGS[20] report water use data. Most notably, USGS considers conveyance losses occurring prior to application on the field in estimates of water withdrawals for irrigation (Dieter et al., 2018). As such, the observed decline in water withdrawals for irrigation reported in figure 7 may be related to upgrades in off-farm conveyance, where much of the system losses traditionally occurred. These improvements in off-farm conveyance efficiency are not, however, reflected in USDA data on on-field water applied. Further reporting of water supply and use in this report reflects reported data on on-field water applications, based on the more detailed USDA survey estimates for the U.S. farm sector, unless otherwise noted (see box, "Irrigation Water Use Efficiency").[21]

Irrigation Water Use Efficiency

Irrigation water use efficiency measures help to characterize the water conservation potential of irrigation systems and the broader irrigation sector. However, accurately defining irrigation water use efficiency is complicated by multiple scales that can measure efficiency.

- **Irrigation efficiency**: The share of all irrigation water applied to a field that is beneficially used by crops. Beneficial use is predominantly accomplished using evapotranspiration by crops and salt removal to aid soil productivity. Non-beneficial losses may include excess evaporation, field runoff, deep percolation, and weed consumption.

- **Application efficiency**: The ratio of the average depth of irrigation water infiltrated and stored in the root zone for crop consumptive use to the average depth of irrigation water applied.

- **Conveyance efficiency**: The ratio of total water delivered to total water diverted from a surface or groundwater source. Conveyance efficiency may be calculated at the farm, ditch, project, or basin level. Losses related to conveyance are generally related to evaporation, seepage, spills, or water consumption by non-crop plants.

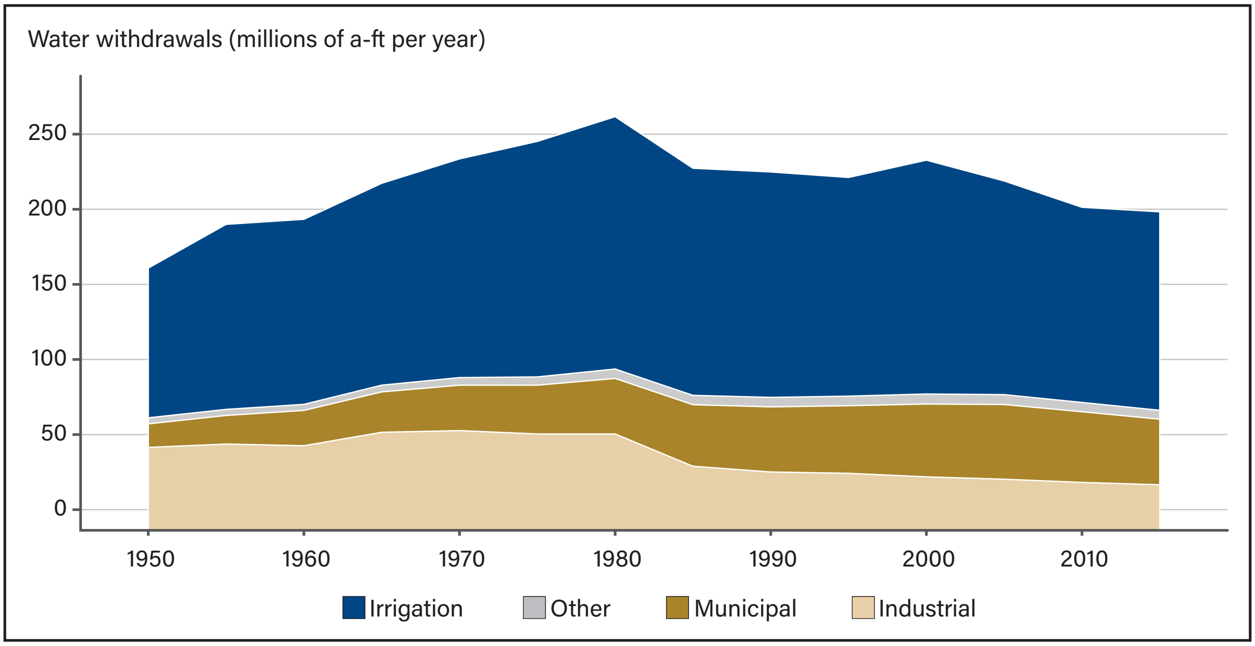
- **Project efficiency:** The share of all water conveyed and applied to a field that is beneficially used by crops. This ratio incorporates both irrigation and on- and off-farm conveyance efficiency and is adjusted for drainage reuse within the project area.

- **Basin efficiency:** The ratio of irrigation water beneficially used, compared to the total volume of freshwater consumed basinwide during the process of conveying and applying the water.

[20]See Bradley (2017) for more information on USGS data collection guidelines.

[21]Water withdrawals, as defined by USGS, refer to the amount of water removed from a ground or surface water source. Potentially, a significant disparity exists between the amount of water withdrawn from a source and the amount of water applied on-field, as conveying water from source to field can incur losses (e.g., seepage, evaporation). Lining and/or covering canals or conversion to pipes can lessen losses by improving conveyance efficiency, reducing water withdrawals required to meet on-field needs.

Figure 7
Freshwater withdrawals for irrigation and other major use categories, 1950–2015



Notes: "Other" excludes withdrawals for thermoelectric power generation—as well as for mining, aquaculture, and commercial purposes. Total water withdrawals—excluding those for thermoelectric power generation, mining, aquaculture, and commercial purposes—have been on a downward trajectory since 1980. Irrigation's share of these withdrawals has also been on a downward trajectory since 1980, but the magnitude of the change is less significant.

Source: USDA, Economic Research Service using data from United States Geological Survey, Water use data, 1950–2015.

Water Sources

Surface water diversions (from reservoirs, ponds, and other watercourses) have historically served as the primary source of water supply for U.S. irrigated production. However, groundwater pumped from aquifers—used as a primary or supplemental/backup supply, particularly during drought years—has become more predominant over time. Nationally, surface water—as a share of total applied irrigation water—declined from 55 percent in 1984 to 50 percent in 2017 (USDA, NASS, 1986; USDA, NASS, 2019c). USGS water withdrawal data since 1950 suggest a more significant long-term trend, with surface water shares declining from 77 percent in 1950 to 52 percent in 2015. The shift away from agricultural diversions of surface water—a largely renewable water source—and the increasing reliance on groundwater (much of it drawn from finite aquifer reserves that cannot be readily recharged) have important implications for the future sustainability of irrigated agriculture—particularly in regions dependent on groundwater extraction. Climate change is expected to significantly affect the timing and quantity of surface water flows—particularly in the Western United States—where water storage relies heavily on snowmelt runoff, further accelerating the transition from surface water use to groundwater (Seager et al., 2013; Dettinger et al., 2015).

Nationally, the majority of irrigated land draws on groundwater as either a primary or secondary water source. In 2018, more than 64 percent of all irrigated acreage relied on groundwater, and nearly 50 percent of all water applied came from groundwater[22] (USDA, NASS, 2019c). However, the predominant water source supplying withdrawals for irrigation varies widely across regions. Figure 8 maps this variation between

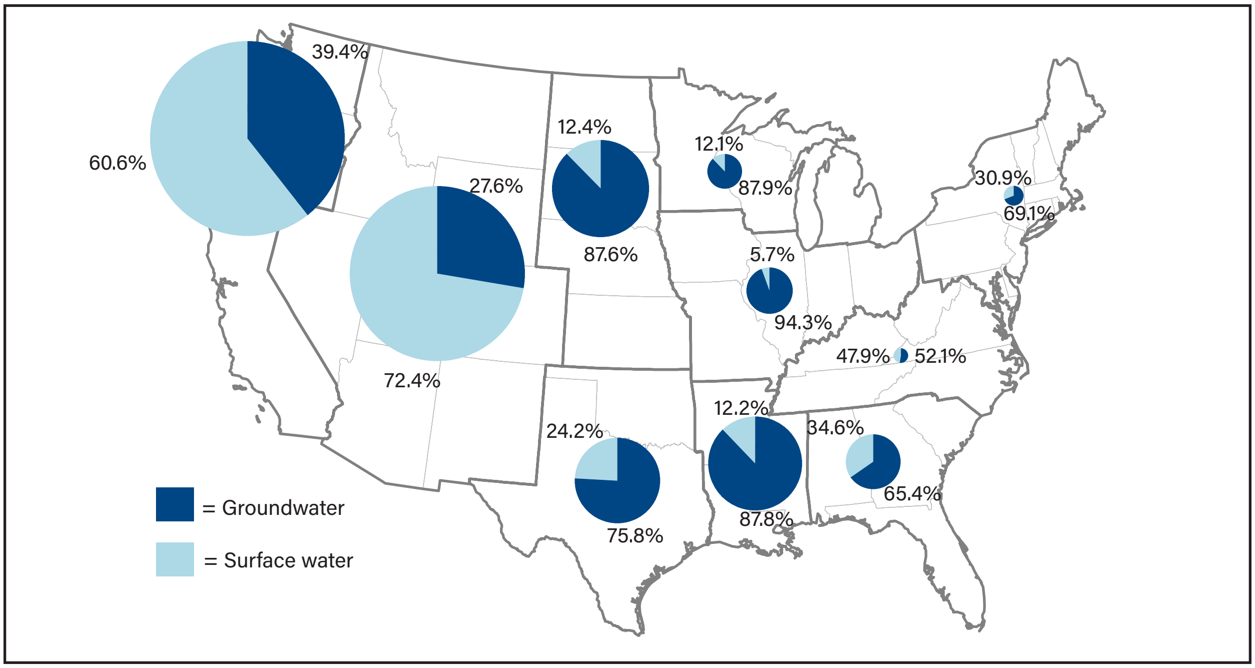
[22]Percentage estimates of irrigated acreage using groundwater and total water applied from a groundwater source are for crops irrigated in the open. Additionally, nearly 3 million acres use a combination of water sources (USDA, NASS, 2019c).

surface water (combining on- and off-farm supplies[23]) and groundwater. The size of each regional pie chart corresponds to the total amount of water applied for irrigation in the region. Groundwater-based irrigation is most prevalent in the Northern Plains, Mississippi Delta, and Southern Plains regions—where 88 percent, 87 percent, and 75 percent, respectively, of all water applied for irrigation comes from groundwater (USDA, NASS, 2019c). Groundwater is also the predominant water source across most of the Eastern United States, where large-scale investment in surface water development for irrigation is limited. Significant use of groundwater as a source for irrigation (notably in the Mississippi Delta, Corn Belt, and Lake regions) reflects regional cropping choices, sporadic growing season precipitation, relatively high water tables for pumped groundwater use, and limited physical and legal capacity for the conveyance of the regions' abundant surface water to non-riparian[24] agricultural land. While the proportion of irrigated land utilizing groundwater is less in the Pacific and Mountain regions, these regions account for the first- and second-most acres irrigated with groundwater, respectively.

Figure 8

Regional use of groundwater and surface water for irrigation, 2018

(Percent of water applied for irrigation by source)



Notes: Size of regional pie charts are proportional to the total amount of water applied for irrigation in the region. Surface water applied includes water from both on and off-farm surface water sources. The Mountain and Pacific regions apply the most water for irrigation, and the majority of this water comes from surface water. The use of groundwater for irrigation is more prevalent in the Southern and Northern Plains regions, as well as the Mississippi Delta region.

Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, *2018 Irrigation and Water Management Survey*.

[23]On-farm surface water refers to "water from a surface source not controlled by a water supply organization. It includes sources such as streams, drainage ditches, lakes, ponds, reservoirs, and on-farm livestock lagoons on or adjacent to the operated land" (USDA, NASS, 2019c). Off-farm surface water is "water from off-farm water suppliers, such as the U.S. Bureau of Reclamation; irrigation districts; mutual, private, cooperative, or neighborhood ditches; commercial companies; or community water systems. It includes reclaimed water from off-farm livestock facilities, municipal, industrial, and other reclaimed water sources" (USDA, NASS, 2019c).

[24]Riparian land refers to land adjacent to creeks, streams, gullies, rivers, and wetlands. Non-riparian land refers to land that is not adjacent to these natural water features.

The use of surface water for irrigation is most prevalent in the Western United States. In the Pacific and Mountain regions, more than 60 percent and 72 percent, respectively, of total water applied as irrigation comes from surface water flows. The pervasiveness of surface water-fed irrigation in the Western United States reflects the significant Federal and State investment in surface water infrastructure and State laws governing surface water use. Investment in water storage and conveyance infrastructure by Federal agencies (such as the U.S. Bureau of Reclamation), as well as State initiatives (such as the California State Water Project), help promote the development of surface water-fed irrigation by moving water from areas (and during seasons) with relatively abundant supplies to those most suitable for agriculture (Autobee, 1993). Additionally, the separation of riparian land ownership from the right to divert water allowed by prior appropriation,[25] the most common form of water law in the Western United States, encouraged the development of privately-owned infrastructure to deliver water from natural streams and rivers to farms.

In 2018, more than 70 percent of all surface water irrigated acreage relied on an off-farm source, while less than 30 percent came from an on-farm source (USDA, NASS, 2019c). The scarcity of water resources, and resulting investment in water conveyance and storage infrastructure, has directly influenced the relative importance of on-farm and off-farm surface water use. Figure 9 demonstrates the relationship between water scarcity and the source of surface water by mapping the proportion of total acres irrigated by surface water source. The size of each region's chart corresponds to the total regional acreage irrigated by surface water. In the Eastern United States—where water is relatively less scarce—the use of on-farm surface water (e.g., on-farm irrigation ponds and surface water diversions) is more common, given lesser public and private incentives to invest in costly water conveyance infrastructure. A notable exception is in the Southeastern United States, where severe drought in the 1950s led to more widespread use of on- and off-farm irrigation ponds (Barber and Stamey, 2000; Paudel et al., 2005). In the Western United States, irrigators are much more reliant on off-farm surface water deliveries from publicly financed water projects. The prior appropriation statutes of Western States also encouraged the development of unique institutions that facilitate the delivery and storage of off-farm surface water: ditch companies, incorporated and unincorporated mutuals, acequias,[26] and irrigation districts. Ditch companies, mutuals, and acequias generally involve a cooperative arrangement between water rights holders to pool resources to build and maintain conveyance and storage infrastructure. Irrigation districts are commonly semi-public entities that operate under the auspices of State law and usually receive water from the U.S. Bureau of Reclamation or State water projects. In many cases, the water delivery institutions (developed under prior appropriation) facilitate markets for water rights, potentially increasing the efficiency of water allocations and the profitability of irrigated agriculture (Ji and Cobourn, 2018).

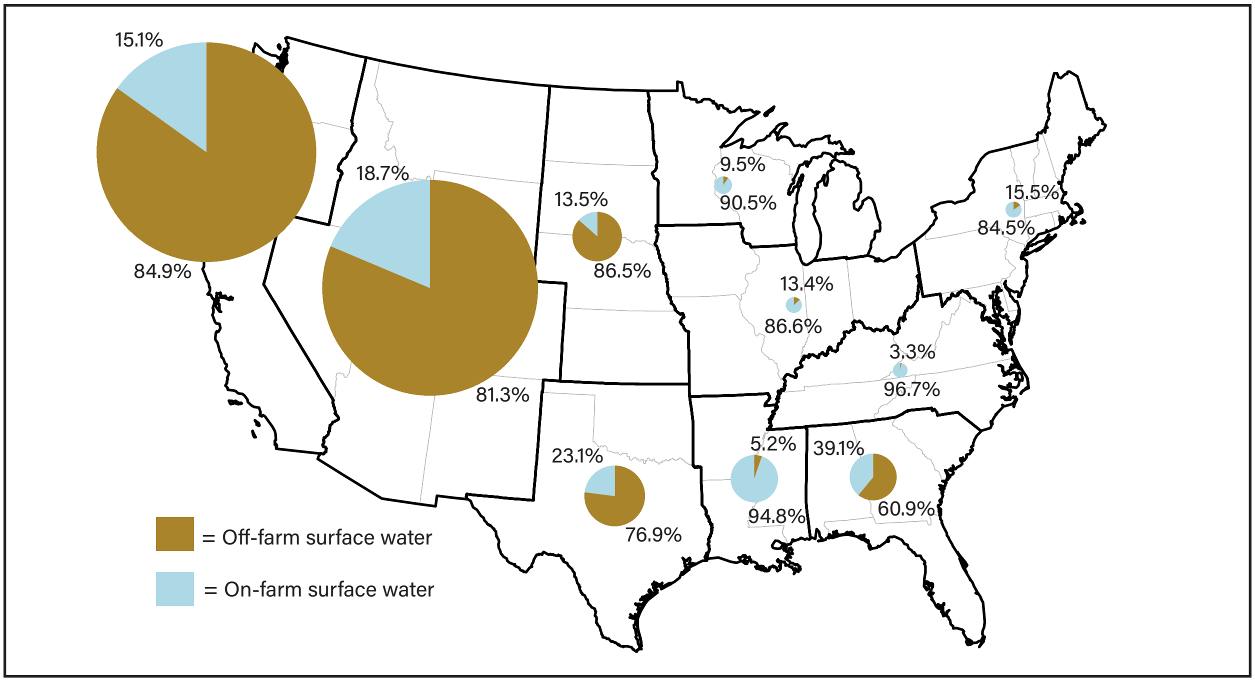
[25]The doctrine of prior appropriation, predominant in the Western United States, assigns water rights based on the beneficial use of water rather than the ownership of riparian land (Haar and Gordon, 1958; Huffaker, Whittlesey et al., 2000). The riparian doctrine, which assigns water rights based on the ownership of riparian land, is most common in the Eastern United States.

[26]Acequias or community acequias are important irrigation institutions unique to the Southwestern United States, primarily New Mexico and Colorado. The history of acequias dates back to interactions between Spain and North African cultures, where community irrigation organizations were and still are common. The word acequia derives from the Arabic word for irrigation ditch. However, irrigation was common in the Southwest before the arrival of European colonists. Specifically, evidence exists of expansive irrigation systems built and used by the Hohokam people in the Salt and Gila River Valleys (Huckleberry, 1992; Hill et al., 2015). The settlement and colonization of the Southwestern United States by Spain brought their irrigation institutions to North America, where they were melded with the irrigation practices of the American Indians to form modern-day acequias (Hutchins, 1928). Acequias differ somewhat from irrigation districts, ditch companies, and mutuals in that most water conveyance infrastructure is commonly owned by the community of acequia users who are expected to adhere to established community rules (Cox and Ross, 2011).

Figure 9

Regional use of on- and off-farm surface irrigation water, 2018

(Percent of surface water-fed irrigated acreage by surface water source)



Notes: Size of regional pie charts are proportional to the total acres irrigated with surface water (both on- and off-farm) in the region. The Mountain and Pacific regions irrigate the most acres with surface water, with the large majority of water coming from off-farm supplies. Acres irrigated with on-farm surface water are more common in the Mississippi Delta and Appalachia regions.

Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, *2018 Irrigation and Water Management Survey*.

The source of irrigation water has important implications for the resiliency and sustainability of irrigated agricultural production. Groundwater applied for irrigation in the United States is pumped from a range of aquifers of varying age and recharge rates. If the rate of groundwater extraction exceeds the recharge of the aquifer, then the stock of groundwater available for irrigation (and other future uses) decreases. Aquifer depletion threatens the future viability of groundwater-fed irrigated agriculture in many regions of the United States (Scanlon et al., 2012; Haacker et al., 2016; Mani et al. 2016; Reba et al., 2017). In response to groundwater depletion, some groundwater users opt to extend wells to access deeper aquifers (Thomas, 2019). However, these groundwater resources suffer from the same depletion concerns that—in some scenarios—may be more severe if the deeper wells draw water from a confined aquifer[27] (Perrone and Jasechko, 2019). Diminishing groundwater stocks can also cause land subsidence, which decreases the future water storage capacity of the aquifer, as well as the dewatering of surface streams that may depend on groundwater for seasonal base flows (Galloway et al., 1999; Konikow and Kendy, 2005; Jasechko et al., 2021).

[27]Confined aquifers have layers of impermeable material both below and above the aquifer (Miller, 1994). The impermeable layer above the aquifer prohibits significant rates of recharge. Unconfined aquifers do not have an impermeable layer above the water table and generally have more significant recharge rates (depending on streamflow, precipitation, or managed aquifer recharge efforts). Notable confined aquifers in the United States include parts of the Central Valley Aquifer system, parts of the Glacial Sand and Gravel Aquifers of the Northern United States, and most of the Floridian Aquifer System (Lovelace et al., 2020).

Generally, surface water flows in the Western United States do not suffer from the same long-term depletion concerns since these flows depend primarily on annual or multi-year precipitation.[28] However, across regions of the United States, surface water availability is sensitive to the effects of prolonged drought, which may drastically reduce water available for irrigation. The increasing incidence and severity of drought expected under global climate change scenarios, coupled with increased competition for available water, may affect the future of irrigated agriculture reliant on surface water flows (USGCRP, 2018). This is particularly true where surface water storage capacity is limited, and access to supplemental groundwater is constrained.

The increasing competition for water derives primarily from increasing demand by urban users (both municipal and industrial), particularly in the Western United States. Between 1987 and 2005, more than 57 percent of water transfers in the Western United States moved water from agricultural to urban use (Brewer et al., 2008a). In many areas, the irrigation sector responded by turning to non-traditional water sources, such as recycled and reclaimed water (see box, "Non-Traditional Water Sources for Irrigation"). The use of novel water sources is a promising development in the sector with the potential to increase the resiliency of irrigated agriculture.

[28]Exceptions to this rule exist, as some streams and rivers rely on groundwater (i.e., springs or subsurface baseflow) for water flows. For example, the flow of the Republican River (whose headwaters lie in eastern Colorado) relies predominantly on springs. This is also the case for many of the streams and rivers in the Eastern United States where baseflow is often more than 50 percent of total flow. As such, subsurface baseflow may be an important source of water for streams and rivers, particularly during drier periods.

Non-Traditional Water Sources for Irrigation

Growing water scarcity in the United States catalyzed efforts to use non-traditional water sources, such as reclaimed and recycled water, for crop irrigation. Reclaimed water is wastewater that has been treated for non-potable reuse purposes, while recycled water refers to the reuse of water previously used for irrigation on the same operation. Desalinated brackish water is another non-traditional irrigation water source. Generally, the cost of desalination is prohibitively high for applications in agriculture, and less than 2 percent of worldwide desalinated water is used for irrigation (Jones et al., 2019). However, increasing water scarcity and rising water prices may increase the use of desalination for irrigation (Caldera and Breyer, 2019). Additionally, the use of saline water for irrigation may increase as more salt tolerant crop varieties are developed (Epstein, 1985).

Recycled water has long been (and continues to be) an important water source for irrigated production. Approximately 1 million acres, distributed across 4,800 agricultural operations, used recycled water to irrigate crops in 2018 (USDA, NASS, 2019c). More recently, the use of reclaimed water for irrigation increased substantially. Between 2013 and 2018, total reclaimed water used for irrigation increased from less than 350,000 acre-feet (on 310,000 acres) to more than 640,000 acre-feet (on 520,000 acres). Similar increases in reclaimed water use were observed for horticultural operations using greenhouses and other enclosed structures. Between 2013 and 2018, the area using reclaimed water grew from less than 7 million to more than 22 million square feet. Reclaimed water comes from varied sources, including industrial, municipal, as well as off-farm and on-farm animal operations. Municipal and on-farm animal operations supplied the largest proportion of irrigated farms in 2018, or 28 percent and 43 percent, respectively, of irrigated farms using reclaimed water. While acres using reclaimed or recycled water account for less than 2 percent of total irrigated acreage, expanding the use of non-traditional water sources is a promising development with the potential to help alleviate water scarcity concerns within the irrigated sector.

The use of reclaimed water for irrigation raises some human health concerns as irrigated crops may uptake pharmaceuticals, heavy metals, and other contaminants found in reused water (Leder et al., 2007; Ayuso-Gabella et al., 2011; Walls, 2015; Wu et al., 2015). Water salinity and nitrogen content in reclaimed water are other sources of risk that may be mitigated by adjusting irrigation practices (Chen et al., 2013). Consumer preferences may also hinder the adoption of reclaimed water for irrigation purposes, as survey research indicates many consumers do not accept foods produced with reclaimed water (Savchenko et al., 2019).

Water Costs

Water costs for U.S. irrigated production vary widely, depending on a range of factors: water source, regional water supply conditions, and the intensity of irrigation. On-farm surface water and groundwater costs include the energy cost required to convey water from the on-farm water body, aquifer, or farm-gate to the field and apply that water to the crop. Off-farm surface water costs reflect the contracted purchase cost of water from local suppliers (e.g., ditch company, irrigation district, mutual, etc.) or the cost of water purchased through market acquisitions, typically charged per unit of water delivered. The purchase cost of off-farm water does not include energy costs incurred in conveying water from the farm-gate to the field, or applying water to the crop. These costs are included in the on-farm surface water costs of conveying and applying water. In 2018, the national average for on-farm water conveyance and application costs paid by farmers per acre irrigated[29] was $36 and $48 for surface and groundwater, respectively (USDA, NASS, 2019c). This compares with average purchase costs for off-farm water deliveries of $96 per acre irrigated, excluding on-farm conveyance and application costs. Some off-farm surface water suppliers charge customers based on the volume of water diverted rather than the amount of land irrigated. This report focuses on average per acre irrigated costs in comparing water costs among different sources.

Water costs reported in this section represent the variable input costs associated with irrigation. They do not reflect the full economic cost of water, as there is an important distinction between the cost of irrigation water and the full cost of irrigation. The full cost includes the cost of irrigation water—as well as labor and capital expenditures to install, operate, and maintain an irrigation system. Operational costs may be significant. For example, in 2018, the average irrigated farm spent more than $25,000 on hired labor for irrigation and an additional $25,000 on irrigation equipment (USDA, NASS, 2019). In addition, irrigation costs borne by producers do not reflect the full public costs associated with the provision of irrigation water supplies—or environmental and societal impacts incurred when removing water from natural water bodies and aquifers.

The cost of irrigation water varies significantly across and within regions. Table 1 presents the average cost of irrigation water across different water sources by region.[30] [31] Differences in the cost of on-farm groundwater are primarily attributable to regional variation in the depth of aquifers, as energy requirements for groundwater pumping increase with pumping lift.[32] Other factors affecting regional costs include: well capacity, pump efficiency, fuel source, and pumping fees imposed by groundwater management organizations. Differences in regional costs help explain patterns in the relative importance by irrigation water source (see figure 8). For example, the predominance of groundwater irrigation in the Mississippi Delta region reflects the relatively low pumping costs, as much of the groundwater is extracted from shallow alluvial aquifers.[33] There is also substantial variation in the regional purchase cost of off-farm surface water. Costs are lowest in the Mountain, Northern Plains, and Southern Plains regions—where off-farm surface water use is dominant. Lower costs may be attributable to publicly financed Federal water project development in the West and economies of scale in water delivery. Many Federal water conveyance and storage projects were completed more than 50 years ago,[34] so the initial capital costs are largely recovered. Current water delivery costs need to cover only system operation and maintenance. However, water delivery costs may increase if storage infrastructure requires corrective action to meet safety protocols.

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[29]Farms and ranches incur water costs at a per acre irrigated level or per unit of water diverted level or both. Generally, on-farm surface and groundwater use incur costs at a per acre irrigated level, while off-farm surface water incurs costs at a per unit of water diverted level, which can then be scaled to generate per acre irrigated costs. As such, USDA, NASS reports energy costs related to irrigation at a per acre irrigated level for farms using groundwater and surface water, where surface water includes both on-farm and off-farm surface water. USDA, NASS also reports water costs for off-farm surface water at both a cost per acre irrigated and at a cost per unit (per acre-foot).

[30]The regional water cost estimates presented in table 1 are drawn from State-level data from tables 13 and 15 of the *2018 Irrigation and Water Management Survey* (USDA, NASS, 2019c). The costs reported in the 2018 survey are variable costs and do not incorporate the fixed costs of installing on-farm water conveyance or irrigation application systems. Regional averages are calculated by dropping State-level costs estimates when these estimates are suppressed due to disclosure concerns.

[31]Note several outliers in costs reported in table 1. Notably, the Appalachia, Lake, and Northeast regions (where irrigation is relatively scarce) have irrigation costs much higher than the national average. These high costs may be attributable to the reliability of estimates as many of the outliers have coefficients of variation indicating low reliability.

[32]Pumping lift or head refers to the amount of pressure that a pump must develop to force water through pipes to a desired elevation. In the context of groundwater extraction, much of the pumping lift required relates to the vertical distance between the water table (top of the aquifer) and the elevation of the field. The greater the vertical distance between the water table and the field, the more pumping lift required and the more energy inputs required to generate that pumping lift.

[33]An alluvial aquifer is an aquifer formed by material deposited by physical processes in a river channel or on a floodplain. Alluvial aquifers are generally located near waterways and interact with streamflow.

[34]Pisani (2003) provides a useful history of the U.S. Bureau of Reclamation's building of water resource infrastructure throughout much of the early 20th century. By 1906, all funds appropriated in the Reclamation Act of 1902 were committed to 28 projects across States and territories of the Western United States. These initial projects include: Garden City Project (Kansas), Salt River Project (Arizona), and Truckee-Carson Project (Nevada) among others.

Table 1

Average cost of irrigation water by region in 2018 (dollars per acre)

	On-farm, groundwater[1]	On-farm, surface water[2]	Off-farm purchased surface water	
	(Coefficient of Variation[3])	(Coefficient of Variation[3])	(Coefficient of Variation[3])	(Coefficient of Variation[3])
	Dollars per acre			Dollars per acre-foot
Appalachia	22.4	19.9	536.5	1,114.4
	(29.5)	(33.9)	(37.2)	(60.0)
Corn Belt	17.7	17.2	130.0	206.9
	(16.9)	(25.0)	(25.3)	(37.6)
Mississippi Delta	26.0	20.7	96.1	146.4
	(8.9)	(28.8)	(56.3)	(49.9)
Lake	24.7	43.5	562.7	518.7
	(7.9)	(44.6)	(14.1)	(58.0)
Mountain	67.3	35.4	43.3	17.8
	(14.1)	(19.7)	(9.6)	(11.5)
Northeast	37.1	40.1	234.3	789.1
	(29.3)	(34.6)	(55.5)	(75.4)
Northern Plains	28.9	25.6	34.9	37.7
	(6.2)	(32.9)	(18.9)	(40.4)
Pacific	84.2	48.4	106.8	43.7
	(8.8)	(11.0)	(6.6)	(7.4)
Southeast	40.0	29.6	135.9	208.7
	(17.2)	(43.9)	(38.1)	(63.7)
Southern Plains	57.5	31.5	59.9	41.6
	(10.5)	(17.9)	(16.7)	(28.2)

Notes: On-farm surface supply is water from a surface source not controlled by a water supply organization. It includes sources such as streams, drainage ditches, lakes, ponds, reservoirs, and on-farm livestock lagoons on or adjacent to the operated land. Off-farm water supply is water from off-farm water suppliers, such as the U.S. Bureau of Reclamation; irrigation districts; mutual, private, cooperative, or neighborhood ditches; commercial companies; or community water systems. It includes reclaimed water from off-farm livestock facilities, municipal, industrial, and other reclaimed water sources. USDA, National Agricultural Statistics Service (NASS) reports off-farm purchased water costs at both the per acre irrigated level and the per acre-foot purchased level. Costs reported only reflect the variable costs of water and do not include the fixed costs associated with irrigation application or conveyance capital. Off-farm surface water is the most expensive source of water for the majority of regions, while groundwater is generally the cheapest source of water. The cost estimates for on-farm surface water are generally the least reliable among the cost estimates presented.

[1] On-farm conveyance and application costs (i.e., energy costs) associated with on-farm groundwater use.

[2] On-farm conveyance and application costs (i.e., energy costs) associated with on-farm surface water use.

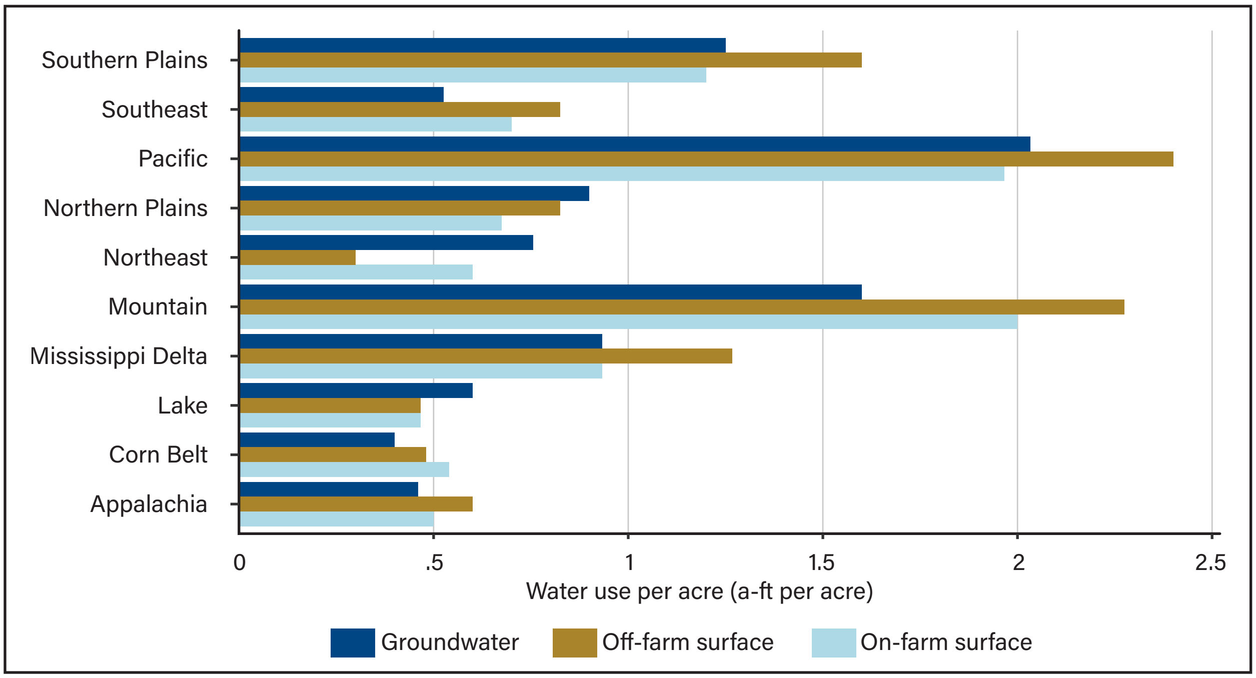
[3] Coefficients of variation (CV) are reported below regional water costs (in parentheses) and provide a measure of the amount of error associated with a cost estimate. Coefficients of variation are calculated by dividing an estimate's standard error by the estimate and multiplying by 100 to report a percentage. These regional coefficients of variation are averages of the State-level coefficients reported by USDA, NASS. Generally, estimates with a coefficient of variation above 30 percent are considered to be of low reliability.

Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, *2018 Irrigation and Water Management Survey*.

Irrigation Intensity

The intensity of irrigation on cropland, or the amount of water applied per acre irrigated, is also an important factor influencing aggregate water scarcity and the profitability of irrigated agriculture. Various climatic, technological, economic, and agronomic factors determine irrigation intensity, which varies significantly across regions and water sources. Figure 10 highlights this variation by plotting average regional irrigation intensities by water sources. The arid regions of the Western United States have relatively higher irrigation intensities than the more humid East, as the dryer western climate requires more applied water to meet crop requirements. In the West, off-farm water sources are associated with more intensive irrigation, likely attributable to incentives created by lower cost off-farm surface water and water law institutions of the region. Similarly, the relatively less intensive irrigation associated with groundwater sources in the Southeast, Mountain, Pacific, Mississippi Delta, and Southern Plains regions may be related to the relatively high cost of groundwater—compared to other water sources, as well as differences in local returns to irrigation.

Figure 10
Water use per acre irrigated in 2018, by source of irrigation water and region



Notes: Across all sources of irrigation water, water use per acre irrigated is highest in the Southern Plains, Pacific, and Mountain regions. In these regions, off-farm surface water is associated with the highest water use per acre irrigated.

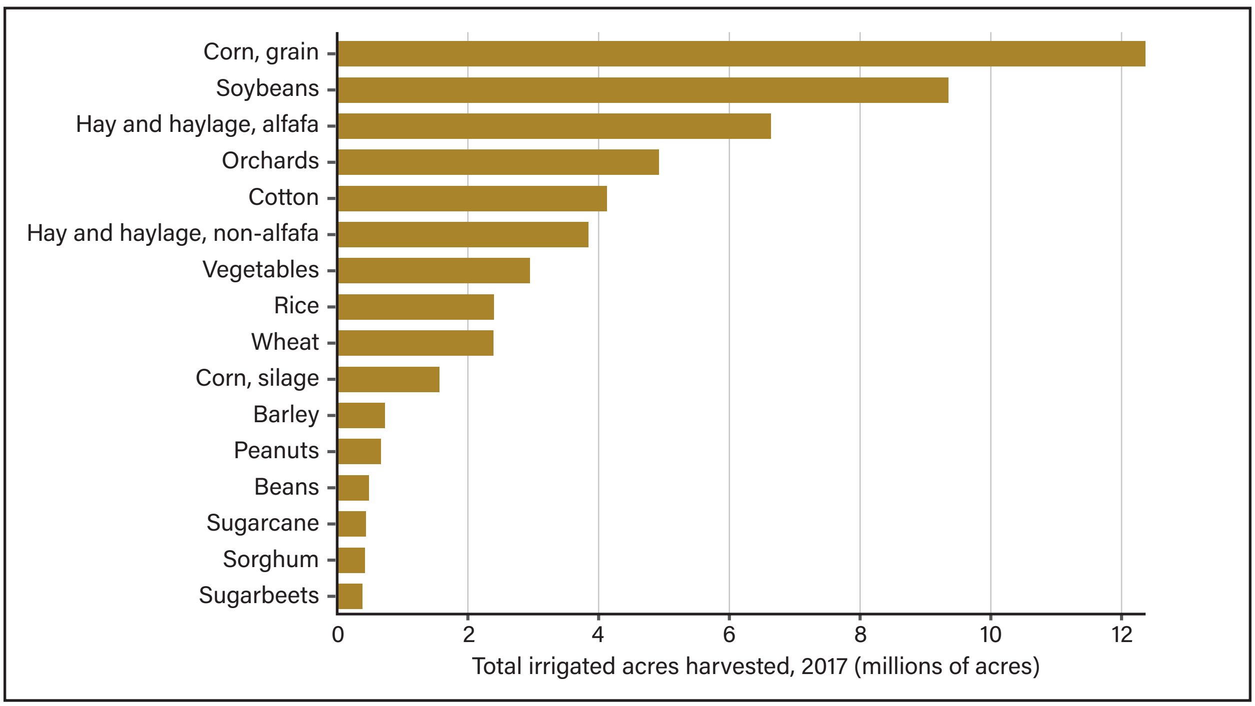
Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, *2018 Irrigation and Water Management Survey*.

Irrigated Crops

This section expands on the review of irrigated acreage and water usage by describing the distribution of irrigated land among crops and shifting cropping patterns over time. Figure 11 presents the distribution of U.S. irrigated land in 2017 by major crops based on irrigated acres harvested. These 16 crops alone account for approximately 98 percent of all irrigated cropland harvested in 2017. The top irrigated crop in 2017 was corn grown for grain, with more than 12 million irrigated acres harvested. Corn for grain and corn for silage together account for more than 25 percent of all irrigated land harvested in 2017. A sizable proportion of the agricultural output produced by the top three irrigated crops—corn for grain, soybeans, and hay and haylage alfalfa—is used as animal feed or exported. This usage demonstrates an important link between irrigated agriculture, the livestock sector, and international commodity markets. In addition, roughly a third of U.S. corn production is dedicated to ethanol production, while soybeans serve as an important biodiesel feedstock—highlighting further linkages between irrigated agriculture and the transportation energy sector (Ash et al., 2018).

Figure 11

Harvested acres irrigated by crop in 2017



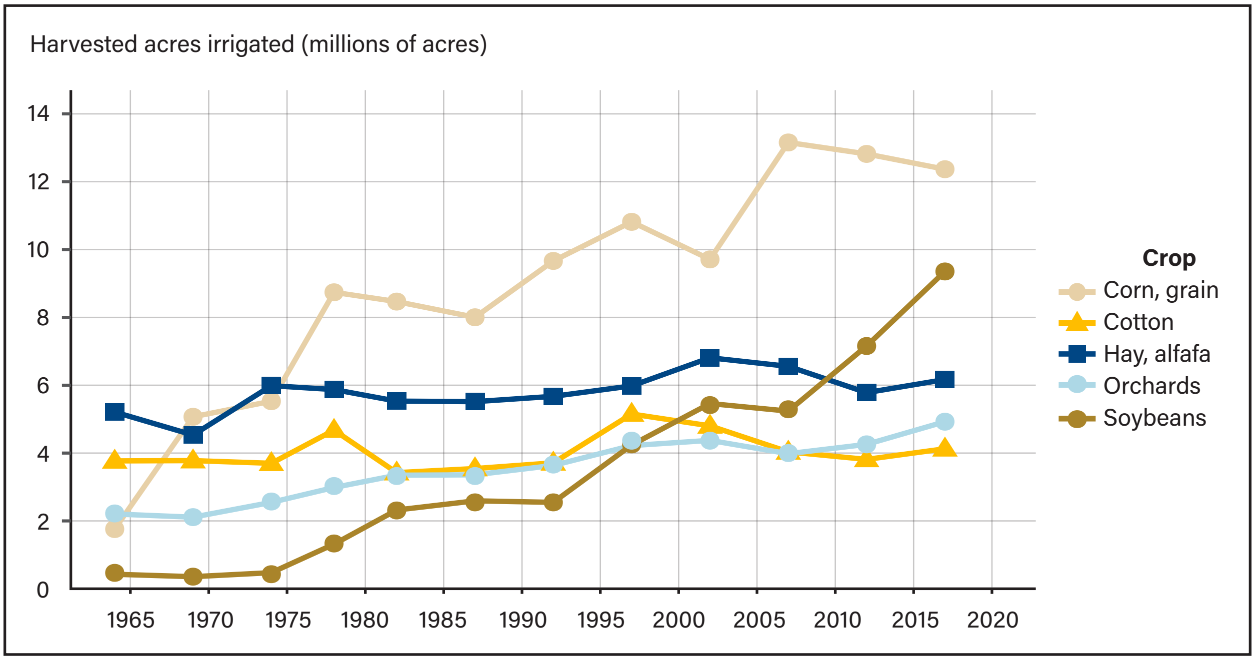
Notes: Beans includes chickpeas, lima, and dry edible beans. Hay and haylage are two methods for storing legume and grass hays, generally for consumption by livestock. Hay and haylage alfalfa refer to alfalfa that is grown, harvested, and then either stored dry (hay) or wet (haylage). Hay and haylage non-alfalfa refer to non-alfalfa crops (e.g., timothy grass, oat grass, clover, etc.) that are grown, harvested, and then stored dry (hay) or wet (haylage). Corn for grain, soybeans, hay and haylage alfalfa are the three most commonly irrigated crops in the United States, as of 2017.

Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, *2017 Census of Agriculture*.

The current crop allocation of irrigated acreage in the United States reflects an important shift in the relative predominance of irrigated crops over the past half century. Figure 12 highlights trends in harvested irrigated acres between 1964 and 2017 for the top five irrigated crops (figure 11), providing additional context for the expansion of irrigated acreage observed in figure 3. In 1964, alfalfa[35] and cotton were the dominant irrigated crops nationwide. Over subsequent decades, irrigated land allocated to alfalfa and cotton remained relatively constant, while land in irrigated corn for grain and soybeans expanded substantially. Thus, a significant proportion of expanded U.S. irrigated land is attributable to the growth of irrigated corn and soybeans. This expansion reflects an increased demand for corn and soybeans, due in part to expanded feedstock use for bioenergy production after 2000 (DOE, 2021). This likely also reflects a structural change in the livestock sector, with the trend away from smaller animal operations employing hay and pasture-based feeding systems to larger confined animal operations more reliant on corn grain and soybean feed products (Gollehon et al., 2016). The expansion of international markets for U.S. agricultural commodities—specifically corn, soybeans and livestock fed on these grains, and oilseeds—also helps explain the increase in irrigated acreage allocated to these crops. Finally, the rise in irrigated corn and soybeans is (to some extent) due to the eastward shift of irrigation. Irrigated acreage has shifted from arid alfalfa- and cotton-producing regions of the Western United States, which face increasing water scarcity, to regions better suited for irrigated corn and soybeans. Evolving climate conditions may influence future trends in irrigated crops, particularly perennial crops such as alfalfa and orchards, as water requirements of these crops are most susceptible to surface water-supply shortfalls associated with climate change (Huntington, 2014). Declining aquifers may also affect irrigated corn, soybean, and cotton production that is heavily reliant on groundwater.

[35]Alfalfa and other legume hays (e.g., timothy, oat, Bermuda, and orchard grasses), as well as grass hays (e.g., fescues, bluegrass, ryegrass, and red top), may be stored as either hay or haylage depending on the moisture content at the time of storage. Legume and grass hays (stored as hay) are allowed to dry, while legume and grass haylage (stored as haylage) are stored with a higher moisture content. Figure 11 presents the total irrigated acreage allocated to hay and haylage alfalfa, as well as hay and haylage non-alfalfa. Unfortunately, exploring past irrigated acreage trends in hay and haylage alfalfa and hay and haylage non-alfalfa is not possible. This is because Censuses of Agriculture (prior to 2002) did not differentiate between alfalfa and non-alfalfa haylage, and prior to 1997, irrigated haylage acres were not reported. As such, later figures (e.g., figure 12) reporting irrigated acreage for differing crops across time focus on hay, alfalfa for which there is complete data from 1964 to 2017.

Figure 12
Trends in harvested acres irrigated by crop, 1964–2017



Notes: The *Census of Agriculture* published before 2002 did not differentiate alfalfa and non-alfalfa haylage, and prior to 1997, irrigated haylage acres were not reported. The figure reports only acreage harvested for hay alfalfa. Between 1964 and 2017, corn for grain rose from the fourth most commonly irrigated crop to the most irrigated crop. Similarly, irrigated acres planted in soybeans increased significantly. As of 2012, soybeans were the second most irrigated crop.

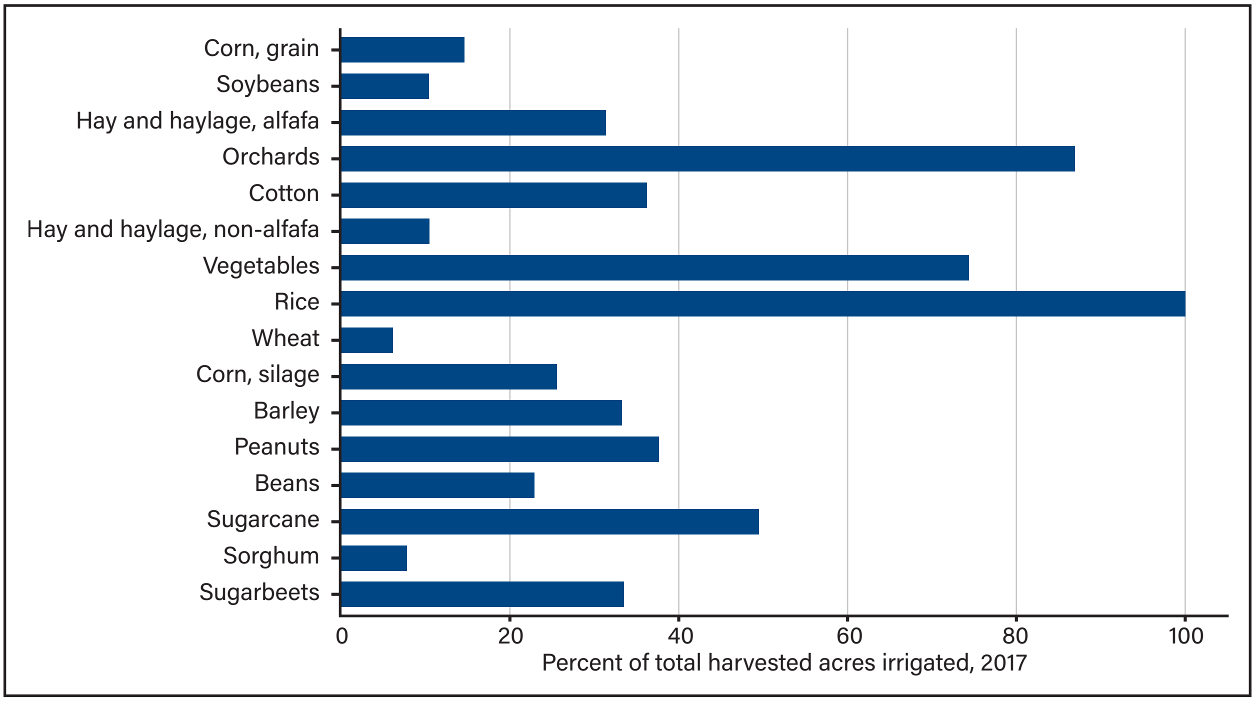
Source: USDA, Economic Research Service using data from *Censuses of Agriculture* (1964–2017) collected by USDA, National Agricultural Statistics Service between 1997 and 2017; and the U.S. Department of Commerce, Bureau of the Census between 1964 and 1992.

Variation in regional climate conditions and irrigation resources influence the prevalence of irrigation among crops. Figure 13 shows the percentage of irrigated acres harvested by crop in 2017. While corn for grain dominates other crops, in terms of irrigated acres harvested, less than 15 percent of total corn acreage is irrigated. Vegetables,[36] orchards,[37] and rice have the largest proportion of harvested acres irrigated. In 2017, nearly all harvested rice acres were irrigated, reflecting agronomic requirements of U.S. commercial rice production (McBride, 2018). More than 80 percent of bearing and non-bearing acres planted in orchards were irrigated in 2017. The prevalence of irrigation on acres planted in orchards is related to the geography and relatively high value of these perennial crops. Orchard production concentrates in the Pacific and Southeast regions (specifically California and Florida), which account for approximately 64 percent and 9 percent of all harvested acres planted in orchards, respectively. Much of the orchard production in California occurs in the arid Central Valley where irrigation is necessary. As such, virtually all acres planted in California orchards are irrigated.

[36]Land planted in vegetables includes: artichokes, asparagus, lima beans, snap beans, beets, broccoli, brussels sprouts, cabbage, carrots, cauliflower, celery, chicory, collards, cucumbers, daikon, eggplant, escarole, garlic, ginger root, ginseng, herbs, horseradish, kale, lettuce, mustard greens, okra, onions, parsley, peas, peppers, pumpkins, radishes, rhubarb, spinach, squash, sweet corn, taro, tomatoes, turnips, watercress, potatoes, and sweet potatoes. It also includes melons (e.g., cantaloupes, muskmelons, honeydew, and watermelon).

[37]Land planted in orchards includes: land planted with pineapples, bearing and nonbearing fruit trees (e.g., apples, pears, cherries, quinces, plums, apricots, peaches, and nectarines), bearing and nonbearing citrus trees (e.g., oranges, lemons, limes, and grapefruits), vineyards, and bearing and nonbearing nut trees (e.g., almonds, pistachios, walnuts, chestnuts, hazelnuts, hickory, macadamia, pecans, and pine nuts).

Figure 13
Irrigated acres as a share of total acres harvested by crop in 2017



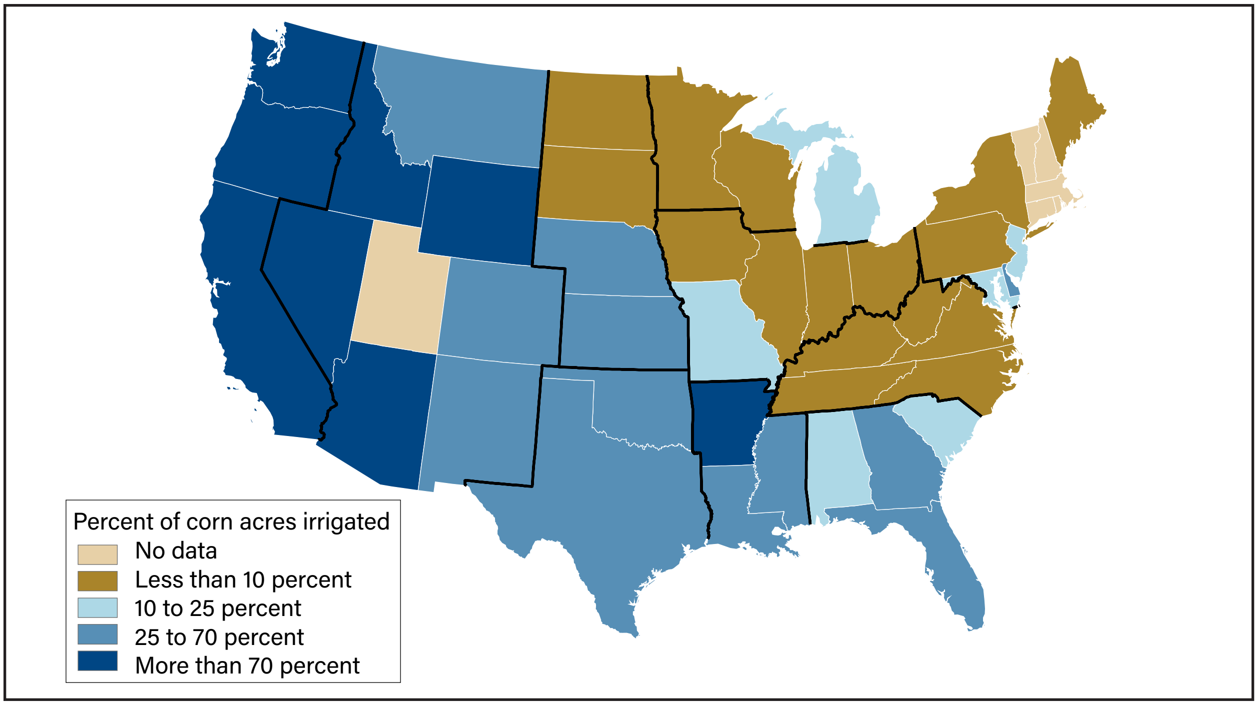
Notes: Beans includes chickpeas, lima, and dry edible beans. Hay and haylage are two methods for storing legume and grass hays, generally for consumption by livestock. Hay and haylage alfalfa refer to alfalfa that is grown, harvested, and then either stored dry (hay) or wet (haylage). Hay and haylage non-alfalfa refer to non-alfalfa crops (e.g., timothy grass, oat grass, clover, etc.) that are grown, harvested, and then stored dry (hay) or wet (haylage). Among the crops presented—rice, orchards, and vegetables have the largest percentage of total harvested acres irrigated in 2017. Wheat and sorghum have the smallest percentage of total harvested acreage irrigated.

Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, *2017 Census of Agriculture*.

The prevalence of irrigation differs across crops, as well as across regions according to climate conditions. Figure 14 demonstrates State-level variations in irrigation versus rain-fed production for harvested acres of corn grown for grain. In the arid Western United States, virtually all corn production is irrigated; in California, Washington, Arizona, Idaho, and Nevada, more than 98 percent of harvested corn acres were irrigated in 2017. In the Eastern United States, where corn production concentrates, the proportion of corn acreage irrigated decreases significantly. For example, the Corn Belt region accounts for more than 42 percent of U.S. harvested acres of corn grown for grain. Less than 4 percent of these acres are irrigated, as growing-season precipitation is generally sufficient to support corn production under normal rainfall conditions. Climate change may induce an increase in irrigated corn in the region, as producers respond to higher temperatures and increasing variability in precipitation.

Figure 14

Prevalence of irrigation in corn production across States



Notes: Disclosure concerns among several Northeastern States and Utah preclude reporting irrigated corn acreages. The prevalence of irrigated corn production concentrates in the relatively arid Pacific and Mountain regions. Irrigated corn production is relatively uncommon in the Corn Belt region.

Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, *2017 Census of Agriculture*.

Irrigation Technology

The increasing scarcity of surface and groundwater supplies for alternative non-agricultural uses, paired with the large volumes of irrigation water withdrawals, motivated efforts to improve the efficiency of on-farm irrigation water use. The technologies and management practices used to apply water to crops jointly determine the efficiency of irrigation (GAO, 2019). Methods for applying irrigation water to crops can be roughly classified into two broad categories: gravity systems and pressurized systems. Pressurized systems are generally more efficient than gravity systems, as less water is lost to evaporation and deep-percolation (Letey et al., 1990; Pitts et al., 1996). However, under certain field conditions, water-supply settings, or cropping systems, gravity irrigation may be more suitable, such as in water-intensive crops on fine-textured soils supplied by open canals or requiring flooding (e.g., rice). Each irrigation system category contains a suite of system modifications and management practices that can substantially enhance water use efficiency.

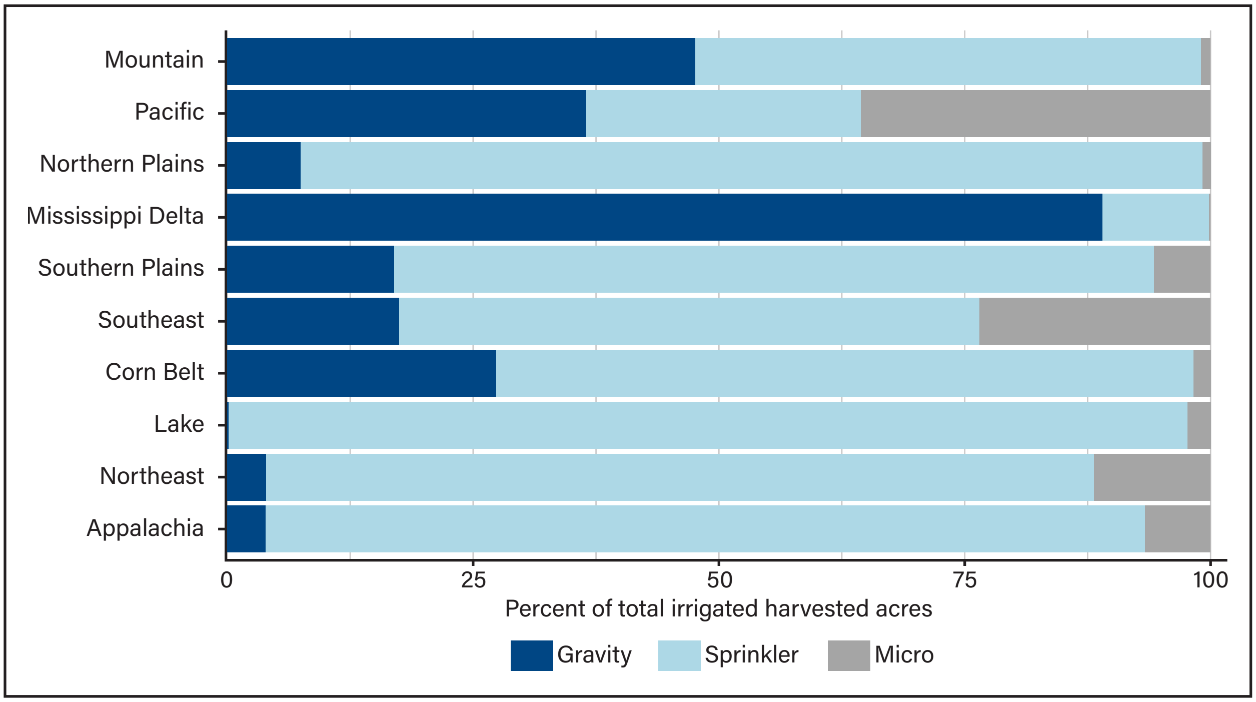
Gravity irrigation systems use field slope to advance water and on-field furrows or basins to control water spread across the field, both through gravity means only. Gravity systems are generally suited to fields with minimal slope, and with clay and silt soils, with higher water-holding capacity. Various system modifications have been implemented to improve the performance of gravity-flow systems. These improvements include: land leveling, reduced field lengths, ditch lining, turnout design, surge irrigation, gated-pipe water delivery, tailwater return, poly-pipe use, and modified furrowing techniques.

Pressurized systems apply water under pressure through pipes or other tubing directly to crops. Pressurized systems may be used on uneven, sloping fields. These systems, while particularly suited to sandy soils with higher infiltration rates, can be adapted for a wide array of soil conditions. Pressurized systems include both sprinkler systems and low-flow micro systems. Sprinkler systems (e.g., center pivot, side roll, big gun) apply water above ground by means of perforated pipes or nozzles operating under varying pressure levels. Low-flow micro systems (e.g., drip, trickle, and micro-sprinklers) deliver high-precision applications, at lower flow rates, at or below the soil surface through emitters or applicators placed along a water delivery line. Technical innovations for pressurized systems have focused on improving the precision of applied water, reducing pressurization requirements, and system automation.

In 2018, of the total acres irrigated in the United States, 36 percent were irrigated with a gravity system, 57 percent used a sprinkler system, and 10 percent used low-flow micro systems. Approximately 3 percent of acres used a combination of irrigation systems. For example, some producers apply water pre-growing season via a gravity system to replenish soil moisture or leach accumulated salts but use a pressurized system during the growing season. The mix of system types varies widely across regions. Figure 15 demonstrates this variation by plotting the proportion of total irrigated acres in each region that use gravity, sprinkler, and low-flow micro-irrigation technologies. Pressurized systems, including sprinkler and low-flow micro-irrigation technologies combined, account for the majority of acreage in all regions except the Mississippi Delta. In the Delta, the prevalence of rice cultivation and low water costs favor the use of gravity systems. Gravity irrigation is also relatively common in the Mountain and Pacific regions. In these regions, gravity irrigation reflects the greater reliance on off-farm surface water delivered through canals and ditches. Water delivered to the farm via canals and ditches is generally not pressurized and requires additional energy inputs and infrastructure (e.g., a pump) to apply using a pressurized system. Of the major irrigation regions, the Southern and Northern Plains have the highest proportion of acres irrigated by pressurized systems. The use of pressurized systems in the Plains reflects the regions' reliance on groundwater, as water pumped from an aquifer is already pressurized and significant additional energy is usually not necessary for pressurized application. The use of low-flow microsystems is most common in the Pacific and Southeast regions, likely attributable to the prevalence of high-value specialty crop cultivation, particularly in California and Florida. Together, the two States account for more than 75 percent of total acres irrigated using low-flow microsystems.

Figure 15

Regional variation in the use of gravity, sprinkler, and micro irrigation technologies, 2018



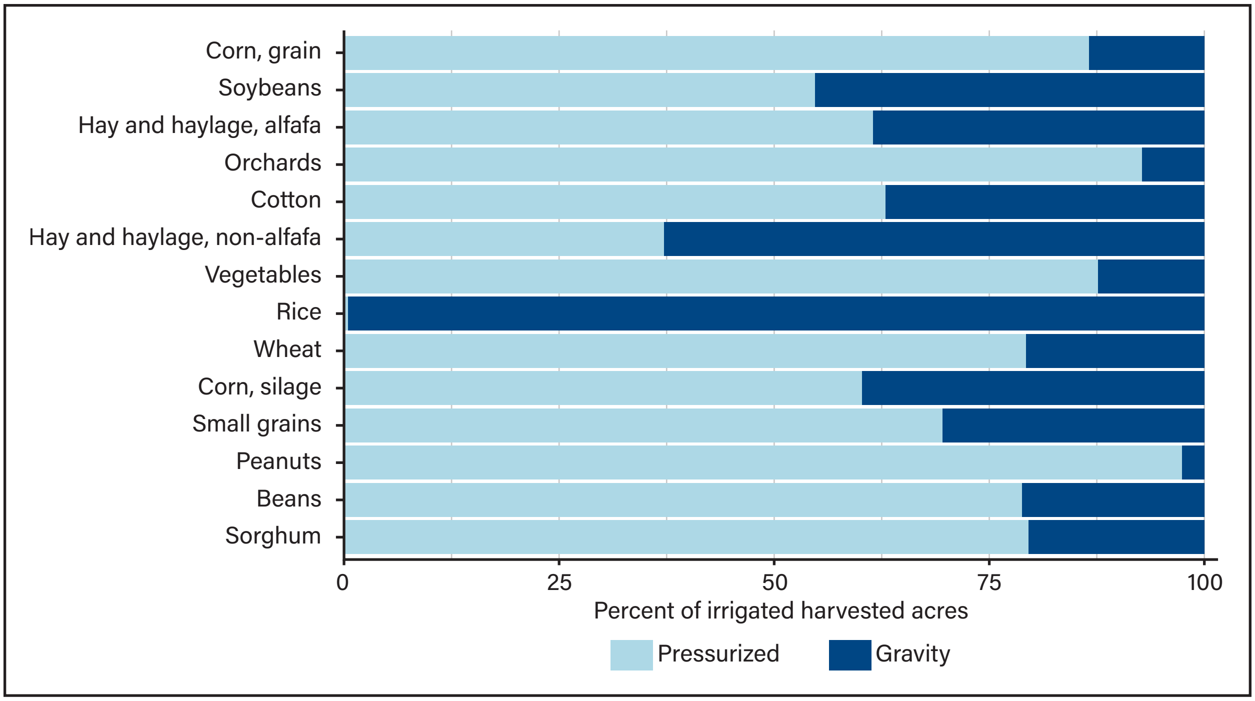
Notes: The largest percentage of total irrigated harvested acres irrigated with a gravity system occurs in the Mississippi Delta region. Micro irrigation systems are most common in the Pacific region.

Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, *2018 Irrigation and Water Management Survey*.

Irrigation Technology and Crop Choice

Crop choice is an important determinant of irrigation system type. For example, the relatively high costs associated with low-flow micro irrigation systems generally preclude their use with many lower-value row and field crops (e.g., corn, soybeans, wheat, etc.). Higher valued perennial orchard crops are most apt to have fixed micro irrigation systems installed. Similarly, many vegetable crops require irrigation water applied below the plant canopy—which is possible with only gravity, low-flow micro, and drop-nozzle sprinkler irrigation systems. Figure 16 demonstrates this variation in irrigation technology, across crops, by plotting the proportion of irrigated acres using gravity versus pressurized irrigation systems for 2018. Crop-specific irrigation technology data only differentiates between sprinkler and low-flow micro systems for cotton, orchards, and vegetables. Among these crops, low-flow micro systems irrigate 2 percent of cotton, 78 percent of orchards, and 30 percent of vegetables in irrigated acres. Rice has the largest share of acres irrigated by a gravity system, reflecting the flooding requirements of most rice production systems in the United States (McBride, 2018). Peanuts have the largest proportion of acres irrigated by pressurized systems. The cultivation of peanuts is concentrated in regions with sandy, well-drained soils. These soils are generally unsuitable for gravity irrigation systems due to water infiltration losses.

Figure 16
Method of irrigation on harvested acres by crop in 2018



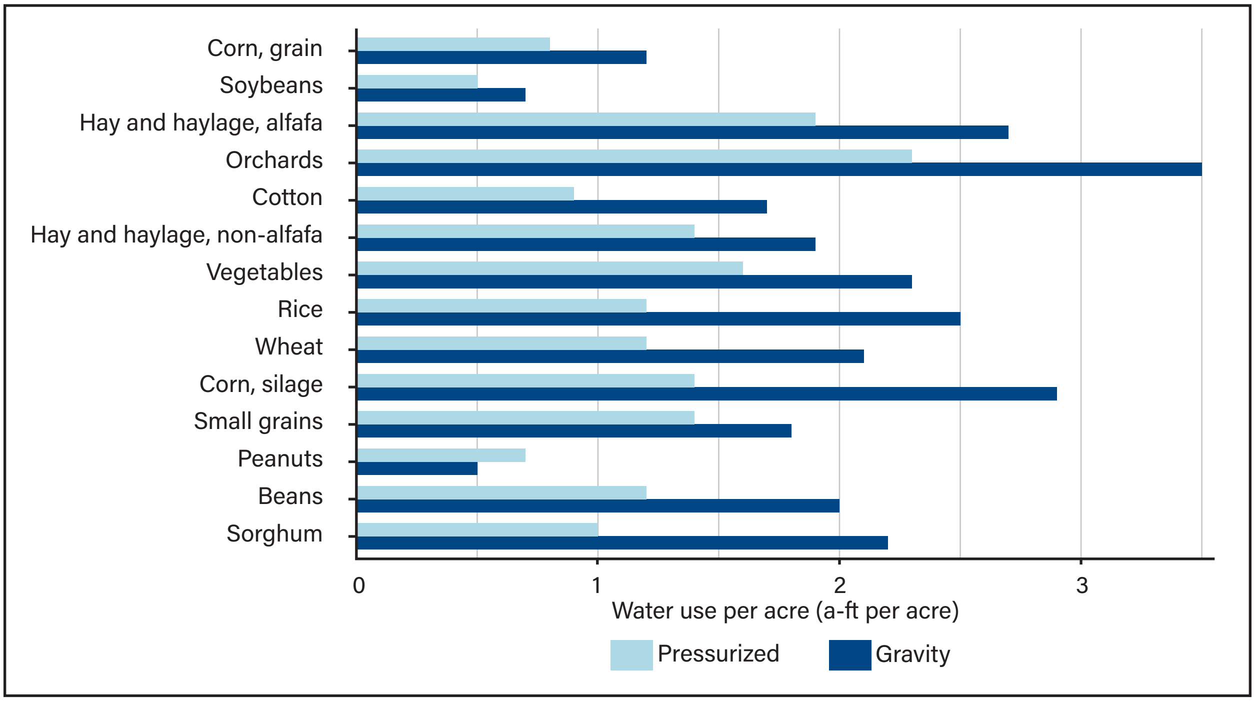
Notes: Small grains refer to rye, barley, and oats. Vegetables represent a total of all acres in production, irrigated in the open. Orchards refers to both bearing and non-bearing acres irrigated. Beans refers to dry edible beans, chickpeas, and lima beans. Hay and haylage are two methods for storing legume and grass hays, generally for consumption by livestock. Hay and haylage alfalfa refer to alfalfa that is grown, harvested, and then either stored dry (hay) or wet (haylage). Hay and haylage non-alfalfa refer to non-alfalfa crops (e.g., timothy grass, oat grass, clover, etc.) that are grown, harvested, and then stored dry (hay) or wet (haylage). Nearly all irrigated harvested acres of rice use a gravity irrigation system. Pressurized systems are most common for orchards, peanuts, and vegetables.

Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, *2018 Irrigation and Water Management Survey*.

The variation in irrigation methods directly influences water applications by crop. Figure 17 explores these differences by charting the average water applied per acre irrigated across crops and irrigation system types nationwide. In virtually all cases, applied water in gravity systems exceeds water applications under pressurized systems. On average, across all crops presented in figure 16, gravity irrigation systems apply 2 acre-feet per acre, while pressurized systems apply 1.25 acre-feet per acre. Corn for silage has the largest difference in water applications per acre when comparing gravity and pressurized systems. On average, corn for silage (using gravity irrigation) applies 1.5 more acre-feet of water per acre. Increased water applications associated with gravity irrigation systems do not necessarily constitute a loss from a basin perspective, however. This water may recharge groundwater resources or be available downstream to provide ecosystem services or meet other demands, although water quality is likely to be compromised if it leaves the field.

The sizeable difference in water applications per acre between gravity and pressurized systems implies that transitioning to pressurized systems has the potential to decrease water applications and alleviate water scarcity concerns. However, transitioning from a gravity to pressurized systems may not be feasible for certain crop or soil types, or may yield only limited water conservation benefits. Additionally, the energy requirements of pressurized systems may constrain adoption among some irrigated farms. In many cases, significant conservation potential may be achieved in upgrading from traditional pressurized and gravity systems to highly efficient pressurized or gravity systems (Schaible and Aillery, 2017). Additionally, irrigators potentially respond to increased water use efficiency by expanding irrigated acreage, adjusting water applied to increase crop yields, or adopting a more water-use intensive crop which may reduce or eliminate potential water savings (Pfeiffer and Lin, 2014).

Figure 17
National average water applications across crops by irrigation system type, 2018



Notes: Small grains refer to water use by rye, barley, and oats. Vegetables refers to water use by acres in production irrigated in the open. Orchards refers water use by both bearing and non-bearing acres. Beans refers to water use by dry edible beans, chickpeas, and lima beans. Hay and haylage are two methods for storing legume and grass hays, generally for consumption by livestock. Hay and haylage alfalfa refer to alfalfa that is grown, harvested, and then either stored dry (hay) or wet (haylage). Hay and haylage non-alfalfa refer to non-alfalfa crops (e.g., timothy grass, oat grass, clover, etc.) that are grown, harvested, and then stored dry (hay) or wet (haylage). Among acres irrigated with a gravity system, orchards, corn for silage, and hay and haylage, alfalfa uses the most water per acre irrigated. Peanuts, soybeans, and corn for grain use relatively less water per acre, with both pressurized and gravity irrigation systems.

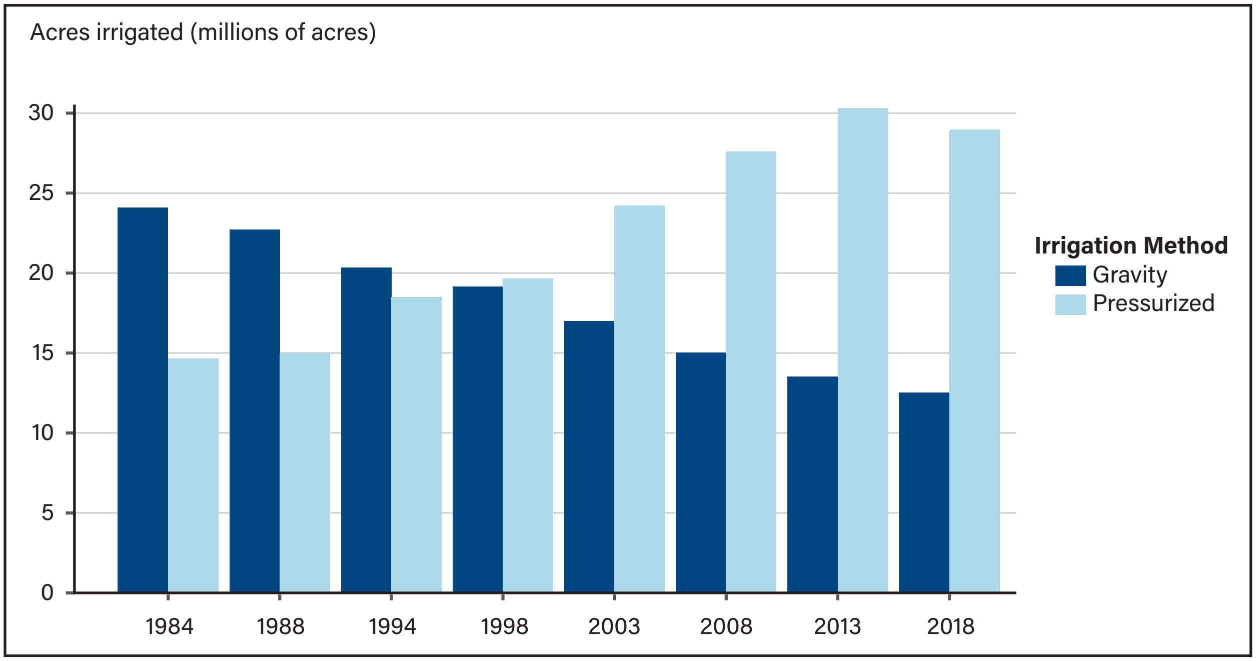
Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, *2018 Irrigation and Water Management Survey*.

Irrigation Technology Trends

The past 30 years saw a significant shift in irrigation technology use, with the decline in gravity systems and concurrent expansion of pressurized systems. Figure 18 shows trends in acres irrigated by gravity and pressurized irrigation systems between 1984 and 2018 for the 17 U.S. Western States.[38] In 1984, 37 percent of all irrigated acres in the West used pressurized irrigation systems, as compared with 72 percent in 2018—roughly doubling over the period. Technical innovations in both gravity and sprinkler systems continued throughout the period. However, the share of irrigated acres using the most efficient types of gravity systems peaked in the late 1990s, before declining thereafter, as farmers turned increasingly to more efficient pressurized sprinklers and micro systems (Schaible and Aillery, 2012; 2019). Trends presented in figure 18 will likely continue as climate change affects water resource availability, driving producers to adopt irrigation technologies and management practices that facilitate the productive use of every drop of water available.

[38]The 17 Western States are: Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, and Wyoming.

Figure 18
Irrigated farmland area in gravity and pressurized systems, 17 Western States, 1984–2018



Notes: Data include only acres irrigated in the open (i.e., does not consider areas in greenhouses and other enclosed structures). Gravity irrigation systems use on-field furrows or basins to advance water across the field surface, through gravity-means only. Pressurized systems (e.g., center pivots) apply water under pressure, through pipes or other tubing directly to crops. Pressurized irrigation includes acres irrigated by sprinkler and micro/drip irrigation systems. The 17 Western States are Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, and Wyoming. Between 1984 and 2018, the number of acres in the Western United States, irrigated using a gravity system, steadily decreased. Over the same period, the number of acres in the Western United States, irrigated using a pressurized system, generally increased.

Source: USDA, Economic Research Service using data from *the Irrigation and Water Management Survey* (2018) and *the Farm and Ranch Irrigation Survey* (1984–2013) collected by USDA, National Agricultural Statistics Service (1998–2018), and the U.S. Department of Commerce, Bureau of the Census (1984–94).

In addition to upgrades in physical irrigation systems used to apply water to crops, developments in on-farm water management technologies and practices can help achieve maximum water use efficiency of the irrigation system while enhancing crop productivity (Schaible and Aillery, 2017; GAO, 2019). These developments include a suite of new and emerging technologies designed to optimize the timing and quantity of applied water to crops. Soil moisture sensors remotely detect moisture at multiple locations on a field to aid irrigation timing decision-making. Leaf sensors measure water deficit stress in plants by monitoring the moisture level of plant leaves. Evapotranspiration reports synthesize local weather conditions with crop development stages to provide detailed information on crop water needs. Remote telemetry data systems coupled with cloud-based irrigation scheduling combine the use of field, crop, soil, and weather data to promote water and energy efficiency while also enhancing plant productivity and health.

Significant developments have occurred in technologies and management tools used to deliver water to crops. Improved seasonal water supply forecasting methods allow producers to allocate cropland more effectively based on projected water supply conditions. More accurate measurement of waterflows and automated adjustments in flow volumes improve water conveyance to fields. Precision irrigation recognizes that crop water requirements are not uniform across a given field. Remote sensing—through global positioning systems (GPS), geographical information systems (GIS), and detailed field-level maps of soil characteristics—help optimize system design and determine variable irrigation application rates based on water requirements within the field (Sadler et al., 2005).

Technical innovations in water management technologies and practices have the potential to reduce agricultural water demands. However, their adoption generally lags, and many irrigators continue to use simple heuristics, such as the visual appearance of the crop and the feel of the soil, to guide irrigation decisions. From 2003–18, the share of irrigated farms using soil moisture sensors for irrigation scheduling increased by 50 percent, from 8 percent to 12 percent. Primary barriers to adopting improved irrigation management practices and technologies include adoption costs, access to capital, and uncertainty about future water availability. In 2018, approximately 28 percent of reporting irrigated farms cited financing as a reason their operation could not invest in water or energy conservation. More than 15 percent of farms indicated that uncertainty about future water supplies was a barrier to the adoption of water conservation technologies and management practices (USDA, NASS, 2019).[39]

A variety of research points to the important role that agricultural extension services play in technology adoption decisions, specifically irrigation technologies (Koundouri and Nauges, 2006; Genius et al., 2014; Krishnan and Patnam, 2014). Insights from this literature suggest that increased extension activities, informing producers of the benefits of water management technologies and practices, may increase adoption.

[39]Exploring the adoption rates of other precision agricultural technologies provides context for the rate of adoption of water management technologies and practices. In 2010, 48 percent of corn farms (representing 70 percent of cropland acres planted in corn) used yield monitoring systems—while 51 percent of soybean farms (representing 69 percent of cropland acres planted in soybeans) used yield monitoring systems (Schimmelpfennig, 2016). Yield monitoring systems instantaneously gather geo-located data on yields during harvest. Guidance systems are global positioning system (GPS) enabled technologies that guide or steer combines or tractors to reduce operator error and gather data. In 2010, 29 percent of corn farms (representing 54 percent of cropland acreage planted in corn) used guidance systems. In 2010, 34 percent of soybean farms (representing 53 percent of cropland acres planted in soybeans) used guidance systems.

Recent Federal Policy Initiatives

Various Federal policy initiatives were initiated within the U.S. agricultural sector in recent years to support resiliency to drought and long-term water scarcity. These initiatives include structural and institutional measures that enhance water supply security through the augmentation of available water supplies from existing and non-traditional sources. Additional measures focus on water-demand management—involving improvements in water use efficiency, water allocation flexibility, and in some cases, land conversion from irrigated production.

Water Supply Security

Recent policy attention has turned toward the need for new capital investment in surface water supply infrastructure serving irrigation and other purposes. The Water Infrastructure Finance and Innovation Act (WIFIA Act, P.L. 113-121) of 2014 grants the U.S. Environmental Protection Agency (EPA) the ability to grant loans to eligible borrowers in support of water infrastructure development. The Water Infrastructure Improvements for the Nation Act (WIIN Act, P.L. 114-322) was signed into law in 2016. The Act has several provisions and appropriations with the potential to affect irrigation infrastructure owned by the U.S. Bureau of Reclamation (Stern and Normand, 2018; Stern et al., 2020). The proposed Drought Resiliency and Water Supply Infrastructure Act (S. 1932) was introduced in the U.S. Senate in 2019. This Act complements the proposed Water Resources Development Act (WRDA) of 2020 (H.R. 7575). The acts would promote drought resilience through critical investments in Bureau of Reclamation water supply projects in the Western United States, as well as water infrastructure and financing mechanisms for non-Federal projects (S 1932, 2019). America's Water Infrastructure Act of 2020 (S. 3591) is another example of proposed legislation focusing specifically on water supplies serving irrigated agriculture in the West. More recently, USDA sought to strengthen its policy focus on investment in irrigation water supply security. The Watershed Protection and Flood Prevention Act (PL-566) authorizes the USDA, Natural Resources Conservation Service (NRCS) to work with local governments to address water resource infrastructure concerns, including potential water supply enhancements, at a watershed scale (USDA, NRCS, 2020b).

Policymakers at the Federal, State, and local levels have also worked to advance policy measures to sustain groundwater resources for irrigation and other uses. Numerous groundwater management organizations—from Nebraska, Colorado, Texas, and other States—implemented groundwater management policies that require well metering and impose fees or quotas on groundwater withdrawals. California's 2014 Sustainable Groundwater Management Act (AB 1739, SB 1168, SB 1319) mandates that groundwater users create local management organizations and develop plans to reach aquifer sustainability (Dickinson, 2014; Pavley, 2014a; 2014b, Hanak et al., 2019). Institutional innovations, such as managed aquifer recharge (MAR) and groundwater banking, are used increasingly across the United States. The NRCS plans to evaluate aquifer and groundwater rechange technologies as part of their fiscal year 2022 conservation program delivery in California. These innovations should slow rates of aquifer decline, through the intentional increase in groundwater recharge and the reallocation of groundwater withdrawals, from surplus water years to drought years (Dillon et al., 2009; Maliva, 2014; Dillon et al., 2019).

While groundwater management is generally the purview of the States, Federal agencies provide critical resources for research on regional groundwater sustainability. USGS is conducting comprehensive groundwater availability assessments for major U.S. aquifers, helping provide foundational data to inform State and local groundwater policy-making (Michelsen et al., 2016; Evenson et al., 2018). USDA, Agricultural Research Service (ARS) conducts applied research on cropping systems and aquifer recharge under the ARS National Program on Water Availability and Water Management. Federal-State research collaborations—intended to enhance the technical design, geographic targeting, and cost efficiency of managed aquifer recharge—hold promise for future groundwater conservation efforts. Recent Federal lawmaking efforts also support the expansion of managed aquifer recharge. Section 2304 of the Agriculture Improvement Act of 2018 (P.L. 115-334), commonly known as the 2018 Farm Bill, amended previous legislation to allow the USDA to provide payments to support "managed aquifer recovery practices." Special targeted USDA regional projects such as the NRCS Ogallala Aquifer Initiative and the USDA, National Institute of Food and Agriculture (NIFA) Ogallala Water Coordinated Agricultural Project have addressed a range of USDA conservation initiatives intended to sustain agricultural production in the High Plains Aquifer region (Gollehon and Winston, 2013; Brauer et al., 2017).

The policy arena also recognized how the use of non-traditional water sources—including reclaimed wastewater and recycled water—can potentially contribute to the resiliency of the irrigation sector. In 2020, the EPA released the National Water Reuse Action Plan (WRAP)—intended to improve the security, sustainability, and resilience of U.S. water resources, through water reuse at the watershed scale (EPA, 2020). USDA identified water reuse as a priority concern under the NRCS Conservation Innovation Grants Program (USDA, NRCS, 2020a), as well as USDA, NIFA's Agriculture and Food Research Initiative (AFRI), Water for Agriculture Challenge Area (USDA, NIFA, 2015).

Water Demand Management

USDA has a long history of supporting the resilience of the irrigated agricultural sector to drought and water scarcity through improvements in irrigation efficiency and other demand management strategies (Wallander et al., 2013). This history encompasses a range of USDA activities—from research on new technological innovations to assessments of local resource conservation needs or technical and financial assistance for technology transfer. USDA, NRCS's Environmental Quality Incentives Program (EQIP) serves as the primary USDA program providing financial assistance for practices that enhance irrigation water use efficiency. Related technical support is provided through USDA, NRCS's Conservation Technical Assistance (CTA) Program. In 2018, EQIP provided irrigation-related funding to more than 2,500 farms, covering more than 500,000 irrigated acres (USDA, NASS, 2019c).

The 2018 Farm Bill extended eligibility for financial assistance under EQIP, historically targeted to farms and ranches, to include water management entities (e.g., irrigation water-delivery and groundwater management organizations). In response to a Congressional research directive, USDA, ERS and USDA, NASS conducted a national survey of these organizations to better understand their operations and their influence on farm-level water allocation decisions and drought resilience (USDA, NASS, 2020).

USDA also provides funding and technical assistance for the voluntary conversion of irrigated land to non-irrigation uses in areas where excessive local water withdrawals may strain available water supplies. USDA, NRCS supports conversion of irrigated production, where feasible, to dryland cropping and grazing systems through EQIP. The 2008 Farm Bill (P.L. 110-246) established funding for USDA, NRCS' Agricultural Water Enhancement Program (AWEP). AWEP coordinated with local stakeholder entities to provide technical and financial assistance to producers supporting water conservation efforts (including voluntary retirement of irrigation water rights on working farmland) (Gollehon and Winston, 2013). Congress appropriated more than $300 million to AWEP between 2009 and 2013. The 2014 Farm Bill (P.L. 113-79) repealed funding for AWEP and created USDA's Regional Conservation Partnership Program (RCPP), which provides funding to promote coordination of USDA conservation activities with local and State stakeholders. Under RCPP, drought resiliency initiatives may be planned at a region or basin scale, with input and financial contributions from multiple stakeholders. Between 2014 and 2019, RCPP distributed nearly $280 million in technical and financial assistance. The 2018 Farm Bill expands RCPP funding to $300 million annually.

The USDA, Farm Service Agency (FSA) also enrolls environmentally sensitive cropland into conservation uses under long-term (10–15 year) land retirement contracts through the Conservation Reserve Program (CRP). While groundwater conservation is not a specific program objective under CRP, significant enrollment involves formerly irrigated acreage in the Southern Plains region, where groundwater reserves are in decline. Additionally, USDA, FSA (in conjunction with State governments) provides funding to permanently retire surface water withdrawals or groundwater pumping rights under the Conservation Reserve Enhancement Program (CREP)[40] (Monger et al., 2018; Rosenberg, 2020). Between 2008 and 2018, Kansas' CREP program enrolled more than 22,000 acres of land and 40,000 acre-feet of associated water rights (Rosenberg, 2020). Through regional conservation initiatives (such as USDA's RCPP), investments in irrigation efficiency can be balanced against conservation initiatives involving irrigated land retirement or conversion to dryland production to effectively achieve basin-level resiliency goals for drought and water scarcity.

In 2013, the USDA, Risk Management Agency (RMA) launched a pilot program in Kansas offering Limited Irrigation crop insurance, with expanded county coverage in 2017 (Manning et al., 2018). The Limited Irrigation policy allows producers to adjust the basis used to calculate indemnity payments, which is tied to crop yield history, to account for yield declines anticipated with reductions in water use. This flexibility facilitates irrigated crop insurance coverage for producers engaging in water conservation efforts, either voluntarily through insurance premium incentives or in response to groundwater management mandates.

The Department of the Interior's Bureau of Reclamation (Reclamation) also invests in water demand management through its WaterSMART Water and Energy Efficiency Grants. These grants offer 50/50 cost sharing funds for water improvement projects. The funds go to irrigation and water districts, States, Tribes, and other entities (that deliver water or power) to support projects aimed at improving water usage. Project objectives include: conserving water, improving water use efficiency, increasing hydropower production, and mitigating water conflict. More than $40 million in Water and Energy Efficiency Grants were awarded to 54 projects throughout the Western United States (USDI-Reclamation, 2020). In many cases, those projects focused on off-farm water supply management, complementing farm-level water conservation efforts, funded by the USDA, NRCS's EQIP program.[41] Since 2011, USDA, NRCS and Reclamation collaborated to coordinate WaterSMART and EQIP investments to improve the cumulative water conservation and drought resilience impacts of both programs (USDA, NRCS, 2021). Under the WaterSMART Initiative, 31 priority areas in 10 States received more than $13 million in EQIP funding in fiscal year 2021. These EQIP funds complement Reclamation WaterSMART projects by helping farmers make improvements that align with WaterSMART project objectives.

Water Market Transfers

Federal policy support for water marketing also expanded in recent years. Water market transfers can potentially aid in addressing water supply shortfalls during periods of prolonged drought through the voluntary reallocation of existing irrigation water supplies to other irrigation users and non-agricultural purposes. This support includes permanent sales of water rights and short-term water leases. The National Drought Resilience Partnership initiative specifically called for market-based approaches to address drought resiliency (NDRP, 2016). Recent trends in water market transactions reflect a substantial increase in both the number of water transactions and the volume transferred from agricultural to urban uses (Brewer et al., 2008a; Schwabe et al., 2020). Short term leases (including contingent market arrangements tied to drought) may

[40]CREP programs retiring groundwater wells from production are active in Colorado, Kansas, Idaho, and Nebraska. Under the Oregon CREP program, landowners who lease water for instream flow purposes receive higher rental rates.

[41]For example, the Dixie Bench Ditch Lateral Association in southeastern Idaho received WaterSMART grant funding to replace earthen canals with pipelines to reduce water seepage.

provide maximum flexibility in meeting critical water needs while preserving water supplies for irrigated production under non-drought conditions.

The U.S. Bureau of Reclamation has facilitated numerous market transfers involving Reclamation project water (USDI-Reclamation, 2016). Under the Bureau of Reclamation's WaterSMART program, the Water Marketing Strategy Grant initiative provides assistance to States, Tribes, and local entities in support of water market planning activities (Bruce, 2012, USDI-Reclamation, 2016). In 2019, the Bureau of Reclamation awarded more than $2 million in Water Marketing Strategy Grants to support the establishment or expansion of water markets in Arizona, California, Colorado, Kansas, Oregon, and Texas (USDI-Reclamation, 2019). USDA is also active in exploring the use of markets to advance resource conservation goals. Following the passage of the 2008 Farm Bill, USDA established the Office of Environmental Markets to address water supply security and agri-environmental objectives with market-based solutions (USDA, OCE, 2008). The 2018 Farm Bill provides specific authority to fund projects (under USDA's Regional Conservation Partnership Program) that help develop environmental markets—including water transfer markets that facilitate the voluntary reallocation of water supplies during drought.

Conclusion

The expansion of irrigation in the United States has fostered the growth of a robust and diverse agricultural crop sector. The sector supports rural livelihoods and provides vital inputs for other sectors of the Nation's economy (e.g., livestock, energy). However, the irrigated sector faces continued increases in water demand from competing users and increasingly constrained water supplies. Where irrigation occurs, what crops are irrigated, and how that water is applied to those crops are issues that continue to adjust to evolving regional water supply and demand conditions. The importance of irrigation for the agricultural economy, and its capacity to adapt, raise critical questions regarding the sustainability and resilience of the irrigation sector. Issues associated with climate change (such as projected changes in temperature, precipitation, and timing of snowmelt run-off) may affect the role that irrigation plays in supporting the continued development of the U.S. agricultural economy (IPCC, 2014; USGCRP, 2018).

Drought adaptation is a defining element of the resilience of irrigated agriculture. The sector's response to recent drought events provides insight into the complex nature of resilience and implications for long-term water resource sustainability. In many cases, the irrigation sector responded to drought-induced surface water restrictions by transitioning to groundwater as a source of irrigation water. The development of groundwater-fed irrigation—while providing a useful short-term response to drought—marks a shift from a largely renewable to an effectively nonrenewable water supply in many regions. An increasing reliance on groundwater led to aquifer depletion and groundwater quality concerns, such as saltwater intrusion in many of the most agriculturally productive aquifers in the United States, with important implications for the future resilience of irrigated agriculture (Scanlon et al., 2012; Mani et al., 2014; Haacker et al., 2016; Lovelace et al., 2020).

Recent trends in irrigation technology suggest overall water use efficiency is increasing. The proportion of acres irrigated using less efficient forms of gravity systems steadily declined, while highly efficient pressurized systems continue to expand. However, less efficient irrigation systems still serve a substantial amount of irrigated land in some regions. The adoption of advanced water management practices remains limited, suggesting that further water use efficiency gains are possible. Efficiency gains may improve crop yields through increased productivity of applied water and nutrients. The effect on irrigation costs will vary, depending on changes in applied water and other inputs (e.g., technology, management, and energy use). Gains in efficiency may also generate off-farm benefits if the conservation gains result in more water remaining in natural streams and rivers (Crossman et al., 2010; Gordon et al., 2010). Improved in-stream flows potentially enhance water quality and support healthier riparian and aquatic ecosystems. However, improved water use efficiency does not always generate water conservation—as producers may respond by increasing irrigated acreage, planting more water-intensive crops, or irrigating more intensively (Ward and Pulido-Velazquez, 2008; Contor and Taylor, 2013; Pfeiffer and Lin, 2014). Consequently, conservation incentives may need to be coupled with water demand management strategies (e.g., irrigated acreage limits, water withdrawal restrictions) that translate efficiency gains into conserved water if water savings for other purposes (e.g., stream replenishment, aquifer management, municipal use) is the policy intent (Grafton et al., 2018).

The irrigation sector demonstrated its capacity to respond to changing water supply conditions over time via observed shifts in acreage, cropping patterns, and technology use. The sector's continued resilience in an age of increasing water demands (and climate change) depends on sustained technological, institutional, and management innovations that promote the greatest benefit from available water resources.

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