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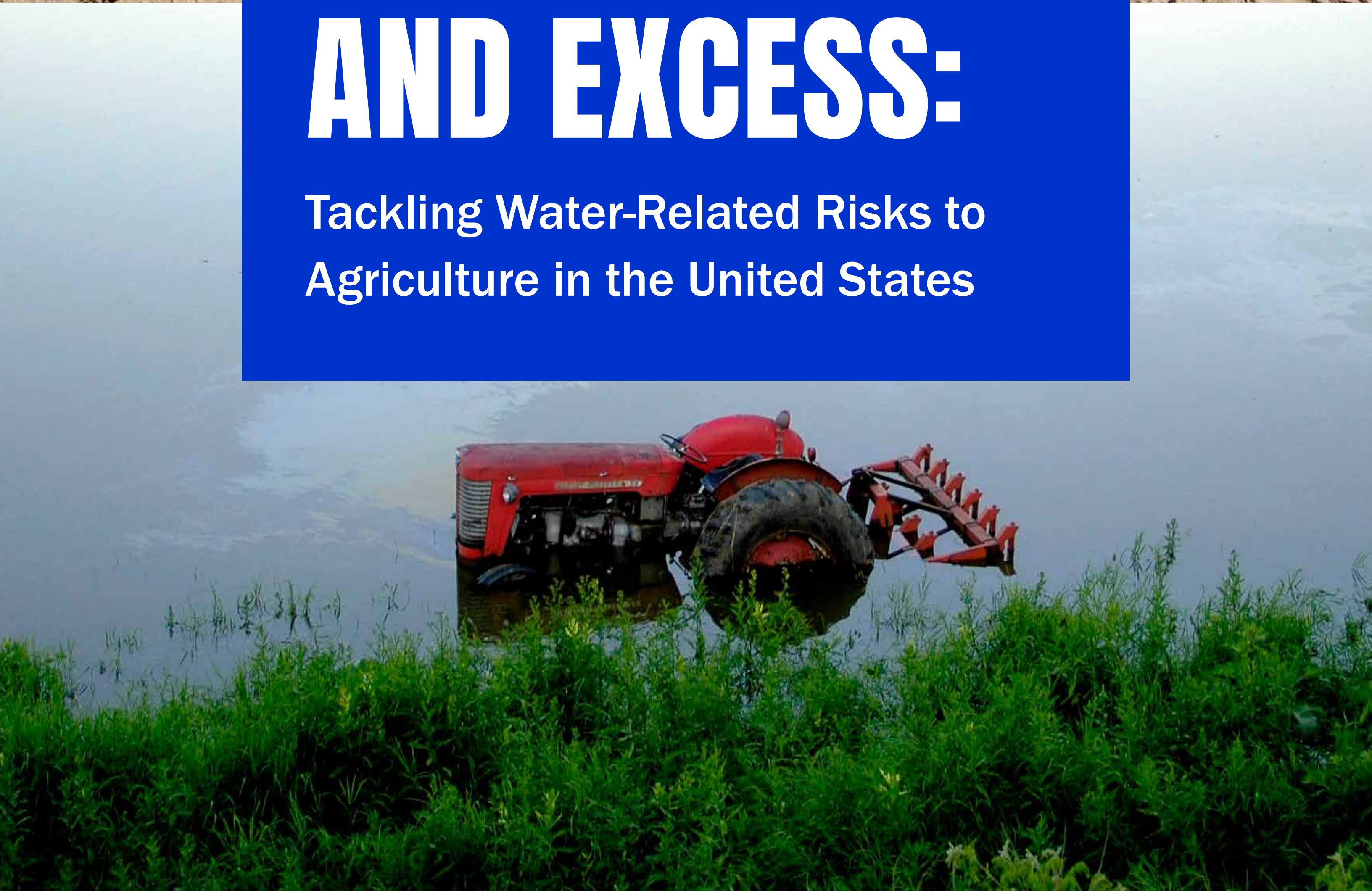
SCARCITY AND EXCESS:

Tackling Water-Related Risks to Agriculture in the United States



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About Environmental Defense Fund

Environmental Defense Fund (**edf.org**) creates transformational solutions to the most serious environmental problems. Guided by science and economics, and committed to climate justice, we work in the places, on the projects and with the people that can make the biggest difference. EDF partners with other organizations — as well as with businesses, governments and communities — to stabilize the climate, strengthen the ability of people and nature to thrive and support people's health.

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OVERVIEW

Water is essential for growing the food and fiber that society depends on. Water availability directly influences agricultural productivity, food security and ecosystem health. Depending on a region's climate, crop water needs may be met by natural precipitation, irrigation, or a combination. Adequate water supply is essential for germination, growth, and development of crops, affecting their yield, nutritional value, and resilience to pests and disease. Furthermore, water plays a vital role in maintaining soil health and optimizing nutrient uptake. The importance of water means agriculture is particularly susceptible to water-related risks of scarcity and excess.

Understanding the inextricable relationship between water and agriculture is paramount to devising effective strategies to mitigate current and future water-related risks. The purpose of this report is to provide an overview of the dual water stressors of too little and too much water, the current and potential future impacts these might have on agriculture, and to highlight emerging adaptation strategies to enhance resilience. While the scope of the risk is global, this report focuses on impacts to agriculture in the western and midwestern U.S.

Report organization

The report begins by characterizing water scarcity and water excess, including physical and climate drivers as well as the legal system for managing water in the western U.S.; these laws have important implications, especially for managing water scarcity. Next, a series of case studies from the Pacific Northwest, California, the Southwest, Kansas and the Midwest illustrate more localized, specific impacts of water-related risks to agriculture. The report concludes by highlighting strategies being developed and tested by EDF and others to promote resilience and help agriculture adapt to scarcity and excess.

Four different types of strategies for adaptation and resilience are discussed:

- Land and crop management changes,
- Technology and decision-support tools,
- Built and natural infrastructure approaches, and
- Policy and funding mechanisms.

Much of EDF's work has been built in partnership with producers, academic researchers, government agencies, communities, water and land managers and other non-profits. This work is part of a broader global effort to support agricultural adaptation and resilience involving a range of entities working on the strategies discussed in this report. EDF hopes that this report will help catalyze innovation, partnerships, funding and other much-needed support for integrated agriculture and water management.

Background

For the purposes of this report, water-related risks are defined as the risks to agriculture associated with water scarcity and excess. Water risk is a broad, context-dependent term that can encompass a wide range of conditions including pollution, poor governance, and infrastructure decay. This report, however, focuses specifically on scarcity and excess.

Water scarcity can be driven or exacerbated by human interventions (e.g., overextraction of available resources) as well as climatic conditions (e.g., drought, warming temperatures, precipitation changes). Governance also impacts how water scarcity affects agriculture. Across much of the western U.S., most crop production is supported by irrigation, and water demand often exceeds the availability of surface and groundwater sources during crop growing season. These conditions even exist in non-drought years because more water has been permitted or allocated for use than is available. As a result, water rights or allocations can be curtailed, physically or administratively, during dry or drought years, constraining agricultural productivity or forcing an early end to the growing season. In other scenarios, agricultural land is permanently taken out of production to address overuse. Climatic conditions can result in changes to the timing and availability of water supply, adverse impacts to water quality and nutritional value and result in pasture losses and crop failure.

Excess water on farmland is caused by heavy and/or prolonged precipitation flooding of nearby water bodies, or adverse soil and land management. Climate changes and land use, together with channelization, levee construction and urban floodplain development along large rivers, have driven worsening problems of excess water over the last century. Excess water can create waterlogging—saturation of the soil—as well as flooding. Both create challenges for crop production. In spring, waterlogging and flooding can prevent farmers from accessing their fields to plant crops. Flooding during the growing season reduces crop growth and may even kill plants by reducing oxygen supply. In either case, overall crop yields are reduced, often dramatically. For example, in the period 1989-2016, excess water caused $10 billion of damage to the U.S. corn crop.[1]

The effects of water-related risks that result from scarcity or excess are only exacerbated by climate change. Climate change is creating more severe weather patterns, yielding more frequent and persistent droughts as well as precipitation events of greater intensity. Further challenges arise from weather whiplash in which there is a rapid transition from drought to floods or from floods to drought; for example, farmland in Iowa saw record flooding in 2011 followed by an extreme drought in 2012, while California went from severe drought from 2020-2022

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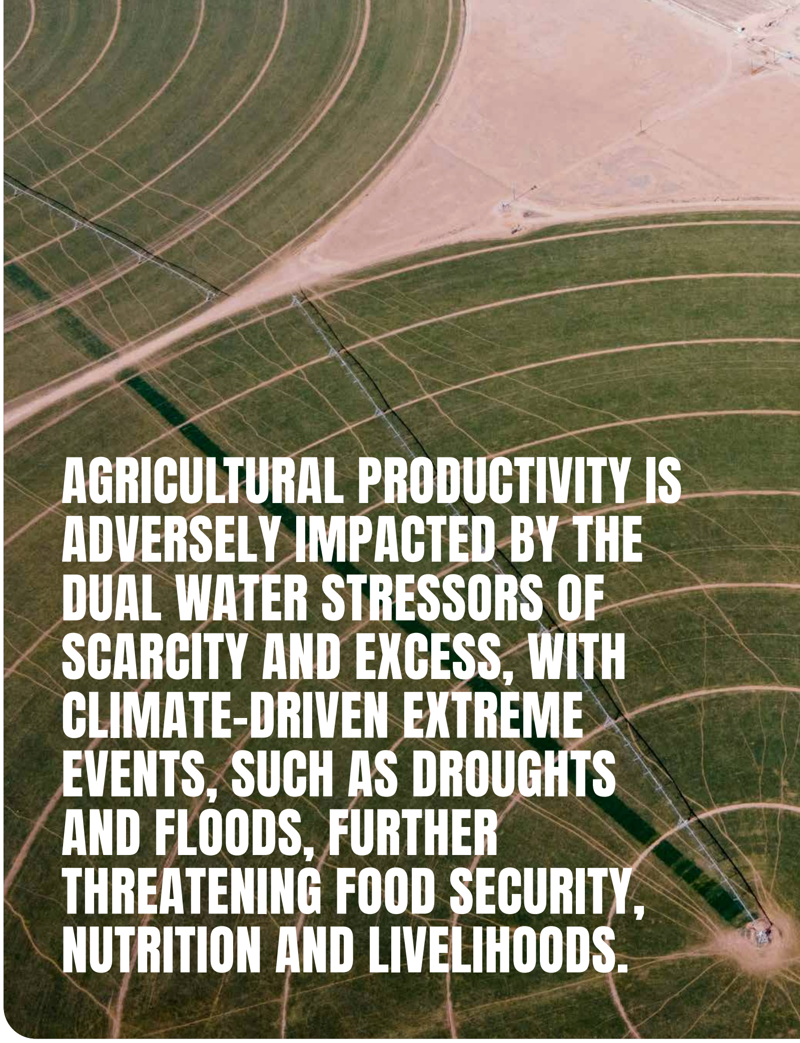
IN DAMAGE COSTS TO THE U.S. CORN CROP FROM 1989-2016 FROM EXCESS WATER.

to record-breaking snowpack and severe flooding in 2022 to 2023.[2] Weather whiplash is expected to become more frequent and extreme because of climate change.[3]

The Federal Emergency Management Agency's National Risk Index estimates combined annual losses for the agriculture sector in the West and Midwest caused by drought and riverine flooding to be close to $2 billion; more than $1.6 billion from drought and $385 million from riverine flooding.[4] Riverine flooding does not capture all the losses incurred from in-field flooding due to heavy precipitation. Crop insurance claims for prevented planting (when the field is too wet to get the crop planted) and for crop losses during the season due to flooding would add significantly to the above annual loss estimates. As water-related risks become more prevalent, new policies, programs and tools are needed to support a transition to agricultural systems that are suited for water scarcity, excess and weather whiplash. Agricultural systems of the future must be both climate-smart (i.e., mitigate climate change) and climate-resilient (i.e., adapt to climate change).



AGRICULTURAL PRODUCTIVITY IS ADVERSELY IMPACTED BY THE DUAL WATER STRESSORS OF SCARCITY AND EXCESS, WITH CLIMATE-DRIVEN EXTREME EVENTS, SUCH AS DROUGHTS AND FLOODS, FURTHER THREATENING FOOD SECURITY, NUTRITION AND LIVELIHOODS.

Key takeaways

Agricultural productivity is adversely impacted by the dual water stressors of scarcity and excess, with climate-driven extreme events, such as droughts and floods, further threatening food security, nutrition and livelihoods.[5] The case studies below illustrate how water-related risks are threatening agricultural economies and communities, with an urgent need for adaptation and mitigation strategies, including both innovative new solutions and scaling traditional agroecological practices.

EDF and partners are working on a range of initiatives to support climate resilient adaptation and mitigation strategies that are economically viable and provide benefits for people and nature. From the high-level review of these initiatives, several conclusions are clear. First, land and crop management changes are necessary in some regions to keep agriculture viable in a changing climate. Second, on-the-ground changes can be supported and bolstered by innovative technological tools. Thirdly, rethinking and upgrading built infrastructure and more proactive utilization of natural infrastructure can help agriculture adapt during periods of water scarcity or excess. Lastly, policy and funding mechanisms need to be in place to drive systems change and sustainability. All solutions need to be created with front line actors, taking into consideration context specific challenges and prioritizing pathways towards sustainable practices and livelihoods.

There is considerable progress toward spreading existing and piloting new tools to address water-related risks to agriculture in the West and Midwest. However, there is still an urgent need for developing and deploying a wide array of approaches to support sustainable agricultural and livelihoods in the face of growing water scarcity and excess.

CHARACTERIZING THE DUAL WATER MANAGEMENT CHALLENGES OF SCARCITY AND EXCESS

This section provides an overview of water scarcity and excess, the drivers behind them and the impacts on agriculture through several different lenses:

- the physical and climate context;
- the growing dependence on groundwater;
- the influence of water law and policy;
- the role of infrastructure; and
- the relationship between water stress, agriculture and the environment.

Physical and climate context for water scarcity

The western and midwestern United States is a vast and diverse region characterized by varied physical landscapes and climate patterns (Figure 1). Much of the landscape in the western U.S. is defined by aridity. Annual precipitation below fifteen inches is common across the region, with topography playing a major role. For example, while the average annual precipitation in Utah is only 13.4 inches, the Wasatch Mountains receive more than 40 inches per year, most of this falling as winter snowpack that stores water and provides streamflow in the spring and summer.[6] In the Midwest, annual precipitation is higher, ranging from 20 inches to over 45 inches.

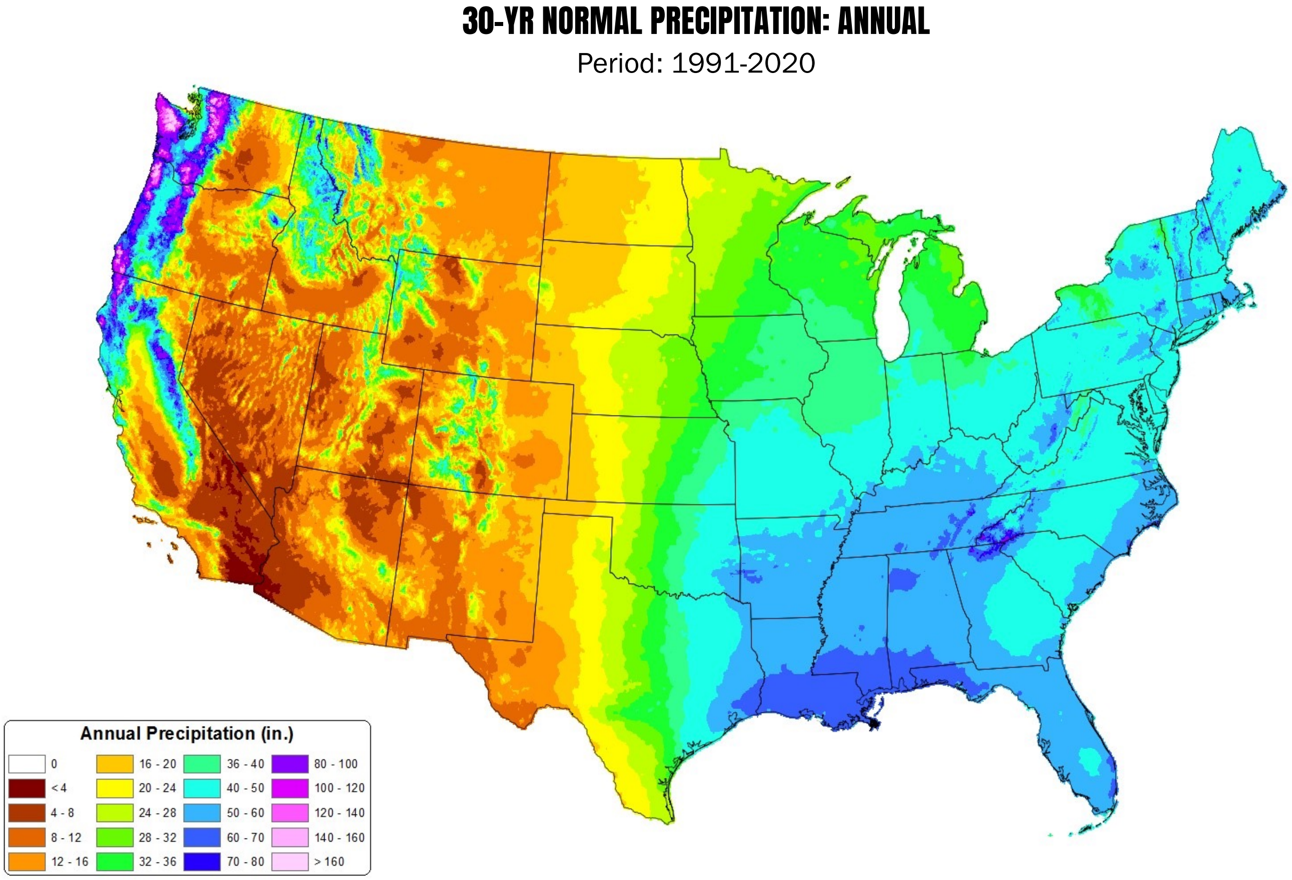
In many regions of the West, a significant portion of the water comes from mountain snowpack. Precipitation falls as snow at higher elevations and then melts over the course of late spring and early summer, providing much of the water flowing in rivers and filling lakes and reservoirs. In coastal and inland temperate valley areas of California and the Pacific Northwest, most precipitation falls as rain with less influence from mountain snowpack. Drought has always been a recurring feature of the West's climate — as evidenced by tree ring and other paleoclimate studies of the region. Climate change research indicates that increasing temperatures will likely increase the frequency, duration, and magnitude of droughts in the West.[7] In addition, climate change is predicted to alter the patterns and timing of precipitation, especially in mid-elevation areas where more winter precipitation will fall as rain, reducing snowpack by potentially significant amounts.[3]

Despite its relative wealth of precipitation compared to the West, water scarcity can also impact the Midwest. Drought is not uncommon in the region; for example, a major drought in 2012 resulted in significant crop losses, while a short-lived but intense drought in 2022 reduced flows on the Mississippi River so much that river barge transportation, a major economic driver in the region, was severely curtailed. There is uncertainty about how climate change will impact drought in the region's future. Some projections show that climate change will impact soil moisture levels, transitioning from excessive levels in the spring to insufficient levels in the summer driven by higher temperatures. In addition to possibly worsening drought, climate change in the Midwest may increase maximum daily temperatures to the point where it negatively impacts crop productivity.[8]

FIGURE 1.

Average annual precipitation in the contiguous U.S for the 1991-2020 period

The vast majority of land in the 11 most western states sees less than 16 inches of precipitation per year, as indicated by the oranges and reds. Notably, the major mountain ranges in these states see the highest rates of precipitation in the contiguous U.S., which typically falls as snow, shown in pink and purple. Moving eastward across the country, precipitation rates increase, as marked by western Kansas receiving 16-20 inches and eastern Kansas receiving 40-50 inches on average.



Source: PRISM Climate Group at Oregon State University.

Physical and climate context for excess water

As with water scarcity, excess water will affect both the West and Midwest, though with some differences based on the two regions' divergent physical and climate contexts. Excess water is a particularly acute problem in the Midwest, where the production of commodity crops (corn, soybean and wheat) often occurs on soils that are slow to drain under heavy or prolonged rainfall. Midwestern farmland is also vulnerable to overbank flooding from the Mississippi and Missouri Rivers and their tributaries. Farmers have understandably taken advantage of high-fertility floodplain soils, but spring snowmelt has triggered large-scale river flooding that often spills onto adjacent agricultural land.[8]

Flooding can also occur in the West, where it is most often driven by atmospheric rivers and rain-on-snow events. Rain-on-snow events occur when unusually warm temperatures, usually during the late winter and early spring, result in rain falling on snow causing rapid melting and runoff into rivers and streams. In California, atmospheric rivers and associated snowmelt runoff resulted in the inundation of thousands of acres of farmland in the Tulare Basin in the spring of 2023, resulting in hundreds of millions of dollars of lost crop production.[9] As with the Midwest, flooding in the West can cause crop losses, property damage and risk to human health and safety.

Influence of law and policy on water scarcity and excess

In addition to physical and climate drivers of water stress, governance — laws, policies and institutional practices for water management — has significant implications for agriculture in managing scarcity and excess. Laws governing water use across the western U.S. primarily follow a template known as the doctrine of prior appropriation.* Water law in the Midwest is less dominated by prior appropriation; while some areas govern water under this doctrine, others follow the riparian doctrine. Across both regions, the use of groundwater is often regulated by different, inconsistent rules. Rarely do the laws governing surface and groundwater appropriately account for their connectedness and interdependencies. Each of these governing frameworks and their implications for managing water under water stress are briefly discussed below.

Prior appropriation doctrine

The primary goal of prior appropriation is to organize water uses among different places and types of use in the face of scarcity.[10] The doctrine has three bedrock principles, including: beneficial use without waste; first in time, first in right; and use it or lose it.

- *Beneficial use* is referred to as the basis and measure of water rights under prior appropriation. The law recognizes that scarce water supplies should be used for purposes that broadly support the public interest. While many of these uses support economic activities like industrial production and irrigated agriculture, the concept has evolved to the point where in most western states it includes the concept of non-economic water uses like instream flow to support aquatic species.[11,12]
- *First in time, first in right* creates a hierarchy of uses within a water source based on the relative times at which different users developed their rights.[13] The earliest users to access a source, referred to as *senior* users, have priority over later developers, called *junior* users. When there is enough water for all, the hierarchy does not apply. During times of the year when water supply is insufficient for all (often mid- to late summer in western, snowmelt-dominated systems), users are *curtailed*, starting with the most junior user and continuing with successively more senior users until demand no longer exceeds supply.[10]
- *Use it or lose it* is expressed in western water codes as a requirement that water rights be actively used or be subject to loss (generally called *forfeiture* when done unintentionally, and *abandonment* when done intentionally).[13] A typical requirement is that a water right be used at least once every five years to avoid forfeiture.

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* In California, water is governed both by the doctrine of prior appropriation and the riparian doctrine which can complicate the administration and management of water rights.

A 1908 Supreme Court case (Winters v. United States) found that native tribes are entitled to water rights as part of the federal government's reservation of lands for tribal homelands.[14]

Tribal water rights, when recognized, are often defined as having a priority date of time immemorial. Despite the seniority, on paper, of tribal water rights, many tribal communities in the arid West continue to confront fundamental issues of daily water access exacerbated by growing municipal and agricultural demand and mounting climate impacts.

Taken together, these three principles, along with myriad complex laws and policies, form the governance context for water use in much of the western U.S. In some ways, prior appropriation is well-suited for water use in the arid landscape — it was designed to be a framework for how water is distributed when there is not enough for everyone to use all they want. In other ways, however, this approach can be maladaptive in the face of water stressors. For example, the use it or lose it principle can encourage water use simply for the purpose of maintaining water right validity, a disincentive to conservation.

Riparian doctrine

Unlike prior appropriation, the riparian doctrine (or riparianism)--which was adapted from medieval English common law--is not designed with scarcity as an organizing focus. The right to use water under a riparian framework is limited to properties that are riparian (adjacent to a river or other water body). Riparian water rights are not specifically quantified like prior appropriation rights, rather they are guided by a reasonable use concept that prevents or limits uses only if they would unreasonably interfere with others' use of water from the same water body.[13] The doctrine is widely used in the Midwest and in some parts of the West.

Riparianism functions well in the absence of scarcity and competition for limited water resources. It is also generally the dominant framework in areas of the U.S. that do not rely heavily on irrigation for crop growth. One potential implication of climate change is an increased need for irrigation in some regions that have not traditionally relied on it. If increasing irrigation use causes greater competition for water supplies in riparian jurisdictions, that could stress the doctrine's ability to effectively organize and manage water supply.

Laws governing groundwater use

The West and Midwest are a patchwork of different laws and policies governing extraction and use of groundwater. In some areas, groundwater is managed under prior appropriation while in other regions it is either un-regulated or is controlled by one of several different approaches. While discussing all groundwater use frameworks is beyond the scope of this report, two examples are illustrative of the variance that exists: 1) the rule of capture (used in parts of Texas) dictates that an owner of land has the right to "capture" any water they can access from beneath their land and pump as much as they want as long as they are not *maliciously* impacting others' water supply; and 2) correlative rights frameworks regulate individual uses within an aquifer in relation to the total pool available (which can either be defined as the actual amount of water in the aquifer, as the amount that can be sustainably annually withdrawn without causing aquifer decline, or some other approach).[10] In many places, existing laws and have done little to prevent overextraction of groundwater supplies and declining groundwater tables.

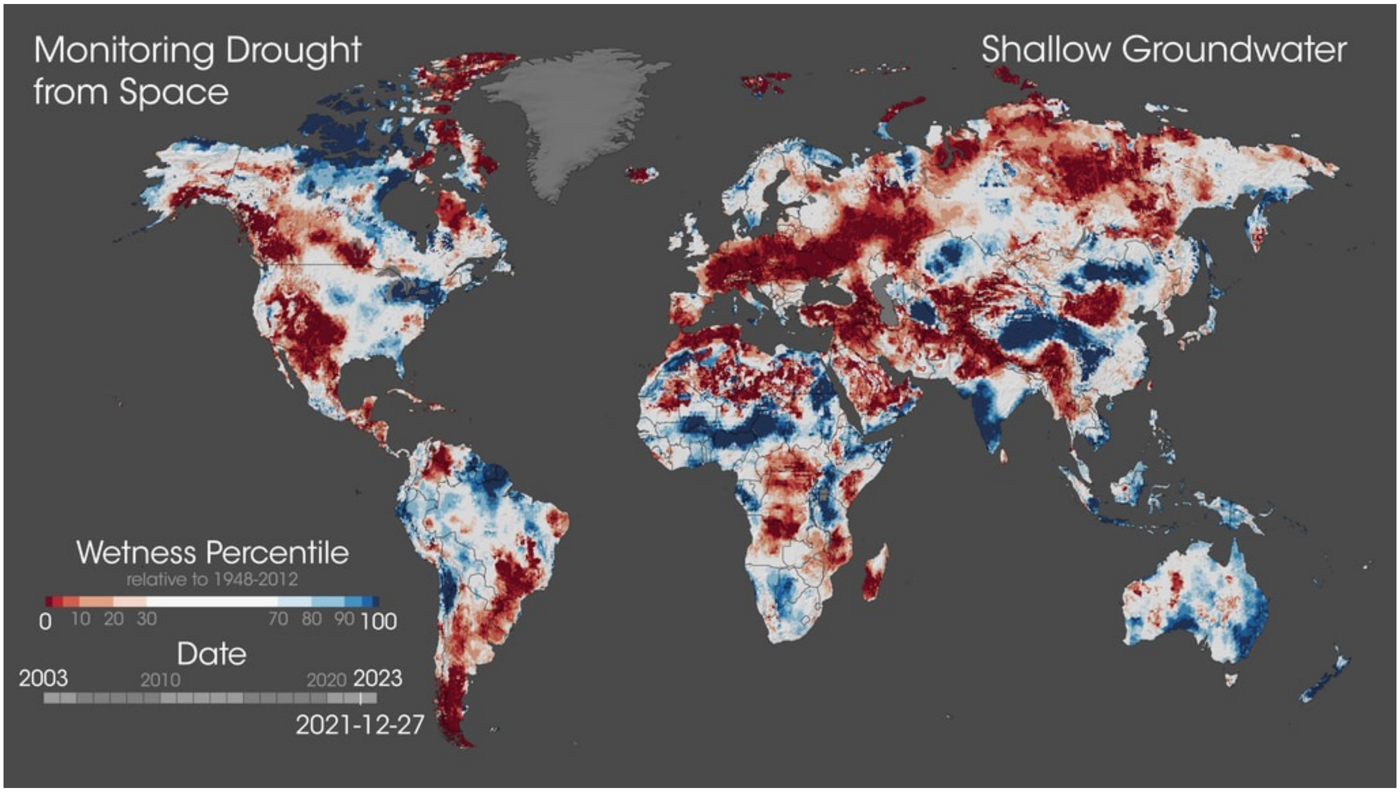
An increasing reliance on groundwater

With surface water supplies deeply impacted by water scarcity, groundwater pumping has increased substantially in recent decades as a supplemental or alternative supply source to surface water in the West; groundwater has long been a major source of water in the Midwest. These extractions exceed the rates of recharge in many basins, resulting in decreasing water availability (Figure 2). In some regions, groundwater has taken thousands of years to accumulate, but is now being extracted at rates that will deplete the accessible water in the aquifer in decades. Agriculture that has grown reliant on these sources faces significant risk.

An influential 2014 study using observations from NASA's Gravity Recovery and Climate Experiment (GRACE) mission, found that groundwater was lost at a rate of approximately 4.5 million acre-feet (MAF) per year in the Colorado River Basin from 2004 to 2013.[15] This phenomenon is not limited to the Colorado River Basin. The USGS found that groundwater storage in the Columbia Plateau region of eastern Oregon, Washington and western Idaho has declined by a volume of more than 10 MAF over time, with local water level declines of over 300 feet in parts of Washington and more than 200 feet in parts of Oregon.[16] The Ogallala Aquifer, a massive underground reservoir underlying vast swaths of the Midwest and Texas has likewise seen varying degrees of decline. According to the Kansas Geological Survey, significant parts of the aquifer under Kansas already lack sufficient water for commercial irrigation needs.[17]

FIGURE 2.

The relative amount of water stored as shallow groundwater compared to the average between 1948 and 2012, with red as below average and blue as above average. The regions in dark red indicate conditions that should only occur about once every 50 years. These maps are compiled by NASA using data from the GRACE and GRACE Follow-On mission, as well as other satellite and ground-based data. During times of drought, groundwater is often used as a supplemental supply source.



Source: NASA, 2023.

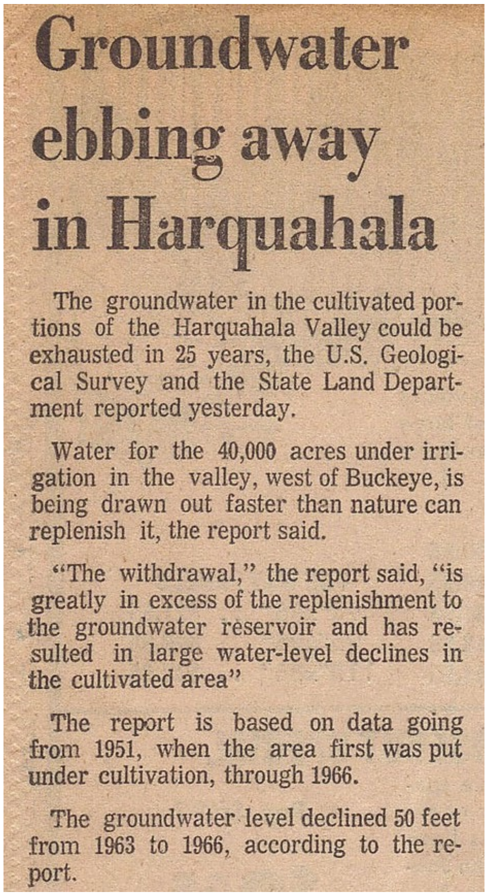
The role of infrastructure

In addition to governance frameworks, infrastructure for water storage and delivery, and for flood protection, has important implications for managing water scarcity and excess water.

While rivers and lakes are a prominent feature of the western landscape, vast swaths of land lie between water sources. The practical implication of this for water management is that water in the West often needs to be moved long distances from its source to the place of use. Another implication of the western landscape is the use of human-made storage reservoirs to help manage water supply alongside flood flows, including managing the timing of water availability. Water management in the West is therefore highly dependent on extensive networks of canals, pipes, reservoirs and other infrastructure to move water where and when it is needed. A prominent example is the Central Arizona Project (CAP) canal (Figure 3), a large canal that moves water over three hundred miles from the Colorado River to central Arizona.[18] The complex network of infrastructure seen across the West has enabled the proliferation of agriculture where water would otherwise be scarce. While these complex storage and delivery systems can provide some measure of water reliability for producers, extended periods of drought can dry up reservoirs and rivers, putting agriculture at risk.

FIGURE 3.

The Central Arizona Project Canal (right) and a newspaper article from the Arizona Republic, May 20, 1971 (left). The 336-mile canal delivers water from the Colorado River to central Arizona, which includes the cities of Phoenix and Tucson. The canal was built in part to augment water supplies in the region, which had relied heavily on groundwater pumping. Pumping rates greatly exceeded the rate at which groundwater was being recharged, causing water accessibility and quality issues. The canal was initially intended to provide water to nearly one million acres of irrigated agricultural land.



Groundwater ebbing away in Harquahala

The groundwater in the cultivated portions of the Harquahala Valley could be exhausted in 25 years, the U.S. Geological Survey and the State Land Department reported yesterday.

Water for the 40,000 acres under irrigation in the valley, west of Buckeye, is being drawn out faster than nature can replenish it, the report said.

"The withdrawal," the report said, "is greatly in excess of the replenishment to the groundwater reservoir and has resulted in large water-level declines in the cultivated area"

The report is based on data going from 1951, when the area first was put under cultivation, through 1966.

The groundwater level declined 50 feet from 1963 to 1966, according to the report.

Source: Bureau of Reclamation (modified).

Aquifers are also an important part of water infrastructure in the west, providing water storage volumes that far surpass that of aboveground reservoirs. However, aquifers have generally not received the same levels of investment to support management and monitoring, leading to overuse and degradation.

Further east, where agriculture is predominantly rainfed, the need to move water rapidly off crop fields has led to the development of a dense network of drainage structures. At the field scale, this often takes the form of subsurface drainage tile — perforated pipe set a few feet below the land surface. Field-scale drain tiles may discharge directly into headwater streams and ditches, or may connect to larger, regional artificial drainage systems maintained by county-level drainage districts. A few figures illustrate the scale of these systems: by 1882, there were over 30,000 miles of drain tiles in Indiana alone,[19] and recent expansion of crop production into North and South Dakota is facilitated by tiling machines which can install nine miles of tile per day. Headwater streams have often been straightened and transformed into drainage ditches to further speed drainage from farmland; by 1884, Ohio had 20,000 miles of drainage ditches.[19] While these changes have helped manage excess water at the field level in spring, they may contribute to downstream flooding and make cropland less resilient to subsequent summer droughts.

In addition, massive engineering works on the main stems of the Ohio and Mississippi Rivers – largely designed to facilitate river transport — have inadvertently increased the frequency and extent of flooding in the river corridors. In an attempt to reduce flood impacts, many hundreds of river miles have been subject to the building of levees (essentially earthen embankments). However, while building a levee may provide some level of flood protection to the community immediately behind the levee and reduce flood risks on agricultural fields, it also diverts flood water downstream, increasing flood risk for downriver communities. An additional concern with levees is that they create a false sense of security for communities behind the levee, which often expand in the belief that they are protected from floods. When levees fail (which is only a matter of time) these communities experience catastrophic flooding.

Water-related risks, agriculture and the environment

Water scarcity and excess also impacts the natural environment. Persistent water scarcity, changes in precipitation patterns and agricultural diversions can reduce the flow of rivers and result in habitat degradation and loss for aquatic and riparian species. Levee construction and floodplain development reduce the ability of watersheds to absorb, store and release flood water; this can impact the productivity of floodplains and wetland habitat and exacerbate low river flows (functioning floodplains are often major contributors to baseflow in many river systems). Flooding also increases the mobilization of fertilizer and other nutrient sources, leading to water quality issues for downstream communities and ecosystems.

These impacts exacerbate the challenges agriculture faces from water-related risks, because competition between agriculture and other water uses is greatly intensified as needs become more urgent. The urgency of environmental water needs is reflected in newly listed endangered species (and additional regulatory hurdles for agricultural water use), higher in-stream flow requirements, more complex requirements for maintaining water temperatures or other water quality parameters in streams and calls for floodplain restoration or other land use changes related to re-establishment of critical habitat or food chain dynamics for fish, bird and other species. Attempts to mitigate and respond to these environmental impacts often require dedicated water and land resources that were previously used for other purposes, such as agriculture. Where endangered species are present or where water quality or other environmental impacts occur, agriculture may face regulatory pressure and the threat of lawsuits layered on top of underlying challenges of scarcity and excess.

REGIONAL CASE STUDIES OF WATER-RELATED RISKS

This section presents five case studies that demonstrate specific regional impacts to agriculture from water scarcity and excess, and how those impacts are influenced by the regions' infrastructure, laws and other competing needs for water.

Each case study provides a high-level description of the subject region including agricultural context, hydrology, expected climate change impacts and specific threats to agriculture from water scarcity and/or excess. Three of the cases focus on the western U.S. (Pacific Northwest, California and the Southwest) while two focus on the Midwest (Kansas and the Corn Belt).

Some water-related risks to agriculture broadly apply to each of the regions. In the western U.S. there are a multitude of factors driving water scarcity that threaten agricultural production, including decreasing snowpack, changes in precipitation patterns, drought, overallocation and overuse, and groundwater depletion. Fundamentally, these factors equate to decreases in water availability during peak agricultural demand, causing localized water shortages with increasing regularity. Irrigated acreage that is dependent on lower-elevation snowfall for summer water supplies is likely to experience elevated levels of water stress more quickly than predominantly rainfed agriculture. These stresses will be exacerbated in areas where rising temperatures or crop mix increases crop water demand, and in areas where other important demands for water increase, such as for fish, hydropower or residential needs.

WATER-RELATED RISKS TO AGRICULTURE:

Pacific Northwest

Agriculture overview

Overall, agriculture in the Pacific Northwest (Oregon, Washington, and Idaho) is both productive and diverse, including over 300 agricultural crops with an estimated value of $22.2 billion in 2017.[20] This diversity is due to variations in climate, soils and geography that support a range of production systems including rainfed and irrigated agriculture, yielding both annual and perennial crops. More specifically, with some important exceptions (e.g., the Snake River Plain of Idaho and the Yakima Basin in Washington), most irrigated agriculture production in the interior Columbia Basin is for livestock forage.

Hydrology

The Pacific Northwest is characterized by cool wet winters and warm dry summers. Mountain ranges strongly influence the spatial distribution of precipitation and create dramatic differences in annual rainfall, with as much as 200 inches along some western slopes of the Coastal Range in Oregon and Olympic Mountains in Washington, but just five or fewer inches annually in areas of central Washington just east of the Cascade Range in Oregon.[21,22]

Across the Pacific Northwest, surface water flows are largely dominated by the temperature-sensitive cycle of snow accumulation and melting. Snowpack in headwater areas act as a natural reservoir for winter precipitation, storing it when demand is relatively low, and then slowly releasing it to streams and rivers during the summer, when demands for water are higher. In most river basins of the region, snow is the most important storage mechanism for shifting water from the wet winter to the dry summer, with man-made storage also playing a role.[23] Surface water plays a predominant role in meeting agricultural needs in the region. Though it varies spatially and reliable data is scarce, surface water provides an estimated 80% of irrigation needs in Washington State, and roughly two thirds of irrigation needs in Idaho and Oregon.[24,25,26]

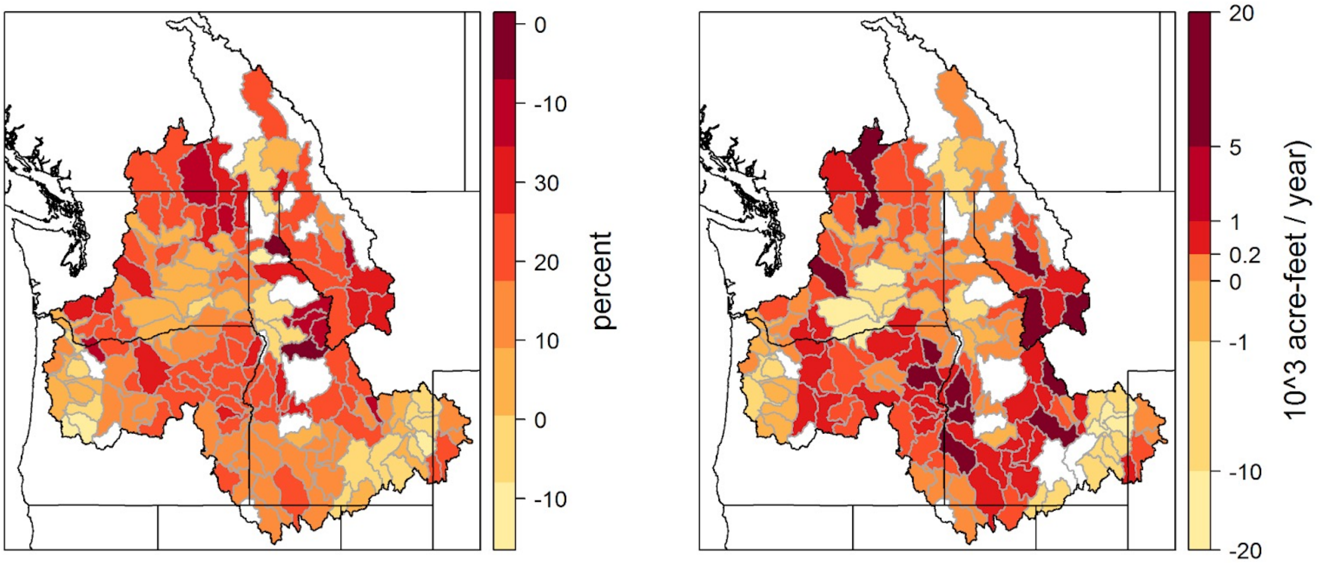
Climate change

Climate projections for the Pacific Northwest suggest continued warming during all seasons and under all future scenarios, although the rate of warming depends on current and future emissions.[23] Projected changes to precipitation patterns are less clear. By the late 21st century, annual precipitation increases of 5-8% are projected, with an 8-14% winter increase

FIGURE 4.

Change in annual irrigation demand between 2040s and historical conditions across the Columbia River Basin expressed as a percentage of historical demand (left panel) and as a magnitude in units of thousand acre-feet per year (right panel). Results are shown by 8-digit Hydrologic Unit Code (HUC) subregion. Warming temperatures coupled with changes in precipitation patterns will increase the demand for water for irrigation across significant portions of the region.

Source: for methodology: Hall et. al, 2021; figure in technical supplement.[24]



and a 4-10% summer decrease.[23] However, more precipitation is projected to fall as rain rather than snow at lower elevations (Figure 4), reducing the amount of natural storage. Climate change will impact the timing of precipitation: hot, dry months will face more drought while cool, wet months see an increase in precipitation. A 14.9% (± 2.5%) increase in water supply is projected for the historically wet months (November through May), paired with a 28.5% (± 2.6%) decrease during the historically dry months (June through October).[24] While storage reservoirs can sometimes help by mimicking the function of the region's historic snowpack, they may not be fully effective at capturing the increased precipitation that falls as rain, and can only hold a fraction of water contained in snowpack.

Climate-induced changes in water supply are expected to vary spatially across the Pacific Northwest (Figure 4), with the most significant changes expected in the snowmelt-dominant basins of the eastern Cascades. A warming climate and decreasing mountain snowpack has already shifted streamflow to earlier in the season, creating a greater mismatch between water supply and demand timing.[3,27,28] For example, in the Yakima Basin of central Washington, a number of studies have suggested that the frequency of years with severe drought impacts is expected to increase.[29–32] The most recent analysis suggests that the probability of significant drought (defined in this case as years with unmet water demands greater than 30%) could increase from 23% over the historical period to ~40% over 2030–2060.[29]

A WARMING CLIMATE AND DECREASING MOUNTAIN SNOWPACK HAS ALREADY SHIFTED STREAMFLOW TO EARLIER IN THE SEASON, CREATING A GREATER MISMATCH BETWEEN WATER SUPPLY AND DEMAND TIMING.

There is also a potential for droughts with unmet demand greater than 65%, more severe than any that have been historically recorded.

Impacts to agriculture

Pasture/hay crops, other annual crops and perennials (e.g., orchards) are all vulnerable to water-related risk, with significant potential reductions in average annual yields. For example, in the Yakima Basin, modelling under a severe warming scenario for the 2060–2090 period indicates that average annual yield of potato, alfalfa, and apple could be reduced 46%, 22% and 48%, respectively.[29] This reduction occurs primarily from the effects of more frequent and severe droughts.

Two recent years provide a glimpse of challenging patterns that are likely to become more frequent. In 2015, a “snow drought” resulted in widespread water shortages the following summer. The Washington State Department of Agriculture carried out a comprehensive effort to document the impacts to agriculture from the drought. Estimated economic damage was somewhere between $633 million to $773 million dollars statewide, even given a variety of efforts to mitigate impacts as the drought unfolded.[33] In 2015 the blueberry industry in Washington lost an estimated $10 million due to heat and insufficient water for irrigation.[34]

Meanwhile, in the summer of 2021, a historic heat dome event—when the atmosphere traps hot ocean air for an extended period of time--occurred across the region during the last week of June, with much of the Pacific Northwest experiencing three consecutive days or more of highs in the triple digits, with lows staying above 65 °F. This event severely stressed a range of crops, notably berries, cherries and even some vegetables, especially those not equipped to use evaporative cooling to mitigate the impact of the heat.[35] Dryland grain crops were also severely impacted by the combination of the heat dome, amid a summer with little to no precipitation. Per-acre yields of winter wheat fell by a third in 2021 compared to 2020, while spring wheat yields fell by more than half.

WATER-RELATED RISKS TO AGRICULTURE:

California

Agriculture overview

California hosts the largest and the most diverse agricultural landscape in the U.S. with gross revenues from farms and ranches exceeding $50 billion—agricultural revenue from California alone makes up 13.52% of total U.S. agricultural cash receipts. Due to the favorable Mediterranean climate, unique regional microclimate zones, a highly engineered and developed water supply system, and a close connection between producers and research and extension institutions, California's agricultural abundance includes more than 400 commodities, some of which are produced nowhere else in the nation.[36,37] The state produces over a third of the USA's vegetables and two-thirds of its fruits and nuts on nearly 1.2% of the nation's farmland.[38] The vast Central Valley is the heart of California's irrigated agricultural economy, extending north-south for some 450 miles and hosting the Sacramento and San Joaquin rivers on their course to the Sacramento San Joaquin Delta which drains both basins to the Pacific Ocean. The state's economy, agricultural production and population have grown largely in pace with the development of its water resources.

Hydrology

California climate and hydrology is primarily influenced by its proximity to the Pacific Ocean (near to which most of the state's residents live) and its two primary mountain ranges, the Coast Range in the west and the higher-elevation Sierra Nevada to the east. Much of California is classified as having a Mediterranean climate, distinguished by mild, wet winters under prevailing westerly winds arriving from the Pacific Ocean and calm, warm and dry summers. Thus, most of California's precipitation typically falls from December to March. This precipitation primarily falls as rain in the Coast Range and snow in the Sierra Nevada.

California receives 75% of its precipitation in the northern third of the state from late fall to early spring. However, 80% of California's water demand comes from the southern two-thirds of the state. Thus, numerous water projects have been built to transport water to Southern California, home to over 60% of the state's population, and the San Joaquin Valley and its 4.5 million acres of irrigated cropland.[39] Irrigation demands further south of the San Joaquin, primarily in the Imperial Valley, and some municipal water use in Southern California, are met with California's sizable allocation of water from the Colorado River with the intrinsic supply risks associated with that source.

Some water from runoff from rain events is captured in reservoirs dotting the coast range. However, most water stored from winter storms is found in the snowpack of the Sierra Nevada and the numerous large reservoirs along the western front of the range that capture snow melt. Substantially less water is captured and stored during periods of drought, imperiling California's water supply and putting agricultural water needs at risk.

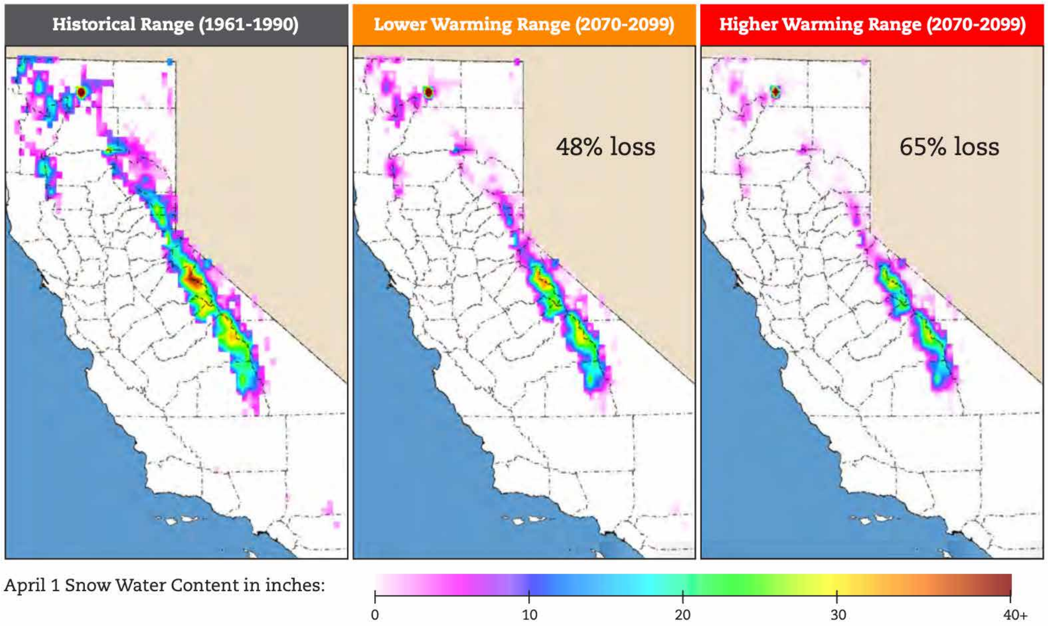
Climate change

The Sierra Region serves as the natural winter snowpack storage for the state's water supply, stretching from about 2,000 feet to above 14,000 feet in elevation. California's climate has increasingly swung on an annual basis between periods of drought interspersed with excessively wet winters. During the latter, precipitation arrives from the Pacific in atmospheric rivers containing large amounts of water vapor that create extreme rainfall and flooding. When bringing moisture from the tropics, these rain-on-snow events deposit rain high into the Sierra Nevada and cause any accumulated snowpack to melt rapidly and flow quickly downstream. In turn, reductions in water stored as snow reduces water availability during the dry, summer season meaning inadequate supply to meet the needs of agricultural and other users.[40]

Further, the rate of increases in the minimum temperatures in the Sierra Nevada is almost three-fold faster than maximum temperatures, resulting in potential decrease in the snowpack, earlier snowmelt, and more water in liquid form as opposed to snow.[41]

According to the California Department of Water Resources, by 2100, the Sierra Nevada snowpack is projected to experience a 48-65% decline from the historical average (Figure 5). Also, given California's reliance on the Colorado River for a portion of its water supply, anticipated climate change impacts will also affect the state's water supply reliability from that interstate basin.

FIGURE 5.



Historical and projected snowpack in the Sierra Nevada region. Modelling suggests that climate change will reduce California's snowpack under both lower warming and higher warming scenarios. Snowpack serves as a storage reservoir, slowly releasing water into rivers and providing flows during summer months. Snowmelt is critical for agriculture during the late summer months when temperatures are warm and there is little precipitation.

Source: California Department of Water Resources.

Impacts to agriculture

California agriculture is vital to the state and nation's economic and food security, yet water-related risks pose many challenges. Increased frequency and intensity of extreme climate events such as heat waves, floods and droughts, increased temperature, variable and uncertain precipitation events and associated increases in weed, pest and disease pressures are already significantly impacting agriculture and the broader economy.[38]

California's 2012-2016 drought led to about 540,000 acres of fallowed farmland in 2015, costing the state's economy $2.7 billion in gross revenue and 21,000 jobs.[42] Abnormally warm winter and spring temperatures in 2015 resulted in more than $240 million in combined crop indemnity payments to almond, cherry, grape, pistachio, peach and walnut growers in California.[43–45]

Typically, irrigated agriculture in California withstands drought conditions by pumping groundwater to replace surface water losses. During the 2021 and 2022 droughts, additional groundwater pumping volumes in the Central Valley were 4.1 MAF and 3.3 MAF, respectively.[46] Increased groundwater pumping during this time combined with lower precipitation had adverse impacts on California's rural communities: over 2,000 domestic wells went dry, cutting off access to drinking water for households in small agricultural communities.[46]

Water scarcity can stress individual plants, making them more susceptible to pests and diseases. A study on pistachios grown in California found that when there was less water available in the soil, the trees became more vulnerable to a fungus that can cause disease, with a connection between the amount of water in the soil and the severity of the disease.[47] Similarly, a study on grapes also found that grapes infected with fungus saw the disease worsen when the plant was stressed by decreased water availability.[48]

CALIFORNIA'S 2012-2016 DROUGHT LED TO ABOUT 540,000 ACRES OF FALLOWED FARMLAND IN 2015, COSTING THE STATE'S ECONOMY $2.7 BILLION IN GROSS REVENUE AND 21,000 JOBS.[42]

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WATER-RELATED RISKS TO AGRICULTURE:

Southwest

Agriculture overview

Agriculture in the Southwest – defined for this report as Nevada, Arizona, Utah and New Mexico – includes a mix of pasture for livestock, annual hay and forage crops like alfalfa, high value grocery crops like lettuces and perennial crops like wine grapes and fruit and nut trees. The leading crops by harvested acres in all four southwest states are hay and alfalfa. According to 2022 statistics from the National Agricultural Statistics Service, Utah (680,000 acres), Nevada (400,000 acres), Arizona (315,000 acres) and New Mexico (225,000 acres) combined harvested over 1.6 million acres of hay and alfalfa.[49] While these are by far the most prolific crops in the region by harvested acres, other valuable crops are grown across the region including pecans, chili peppers and cotton (New Mexico), corn (Nevada) and wheat, corn, barley and cherries (Utah); Arizona has the most diverse cropping of the southwest states growing lettuce, spinach, cotton, pecans and many other fruits and vegetables like broccoli, melons and lemons.[49]

Due to the aridity of the region, irrigation is critical for crop production in all four Southwest states. The main water source in the Southwest is high elevation snowpack runoff, which serves lower elevation farms and communities. While much of this irrigation comes from surface water supplies, the region has seen a growing reliance on groundwater in recent decades. The region relies on groundwater to meet approximately one third of agricultural water demand with more pronounced recent increases in Utah and Nevada and a less pronounced increase in Arizona.[50]

Hydrology

Arizona, Nevada, New Mexico, and Utah have unique climates that impact their hydrology, transitioning from the hot, dry, low elevation Chihuahuan Desert to the cool, wet, high elevation Sierra Nevada. The Mojave, Sonoran, and Chihuahuan deserts have some of the hottest and driest climates in the United States. In Arizona and New Mexico, the North American monsoon season (June 15–September 15) has a major influence over summer precipitation.[51] Precipitation in the region ranges from very low with less than 15 inches of mean annual precipitation, to a surprisingly high mean annual precipitation of over 60 inches at upper elevations.

The southwest is prone to drought, and drought risk is projected to intensify over time. Future droughts are projected to be substantially hotter, and for major river basins such as the Colorado River Basin, drought is projected to become more frequent, more intense and longer lasting than in the historical record.[52] The Colorado River is the largest river in the region, supporting 40 million people and 5.5 million acres of farmland.[53]

Climate change

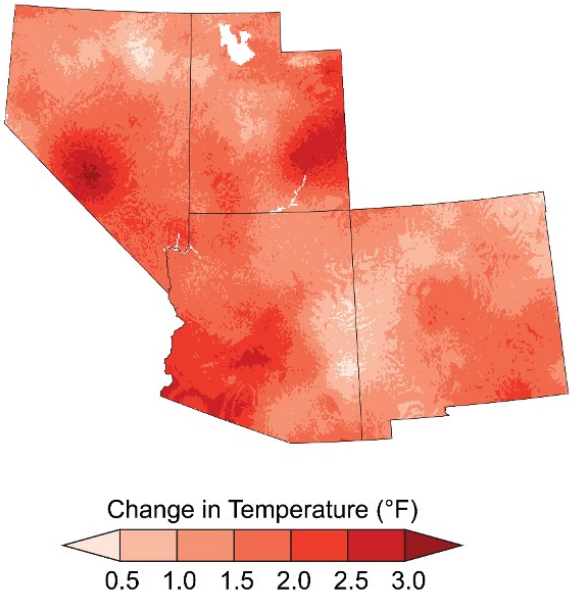
Climate change is already impacting the Southwest in significant ways that are likely to not only increase but magnify in duration and scope. The primary climate change impacts in the region are changes in precipitation patterns and increased temperatures. Temperatures have increased across the southwest region from 1901 to 2016 (Figure 6).[54] In addition, regional average temperatures are projected to rise by 2.5 F to 5.5 F by 2041–2070 and by 5.5F–9.5 F by 2070-2099 with a continued growth in global emissions.[54] As a result of increasing temperatures, the region is seeing proportionately less runoff per unit of snowpack leading to an overall decrease in surface runoff.[52] Summertime heat waves are projected to become longer and hotter, whereas the trend of decreasing wintertime cold air outbreaks is projected to continue.[52]

REGIONAL AVERAGE TEMPERATURES ARE PROJECTED TO RISE BY 2.5 F TO 5.5 F BY 2041-2070 AND BY 5.5 F-9.5 F BY 2070-2099 WITH A CONTINUED GROWTH IN GLOBAL EMISSIONS.[54]

FIGURE 6.

Changes between the 1901–1960 average temperature and the 1986–2016 average temperature. Warming temperatures increase evaporative demands for crops—more water is required to support their growth. This can compound issues of water scarcity as crop water requirements increase while water supplies are diminishing.

Source: USGCRP 2018 (modified).[55]



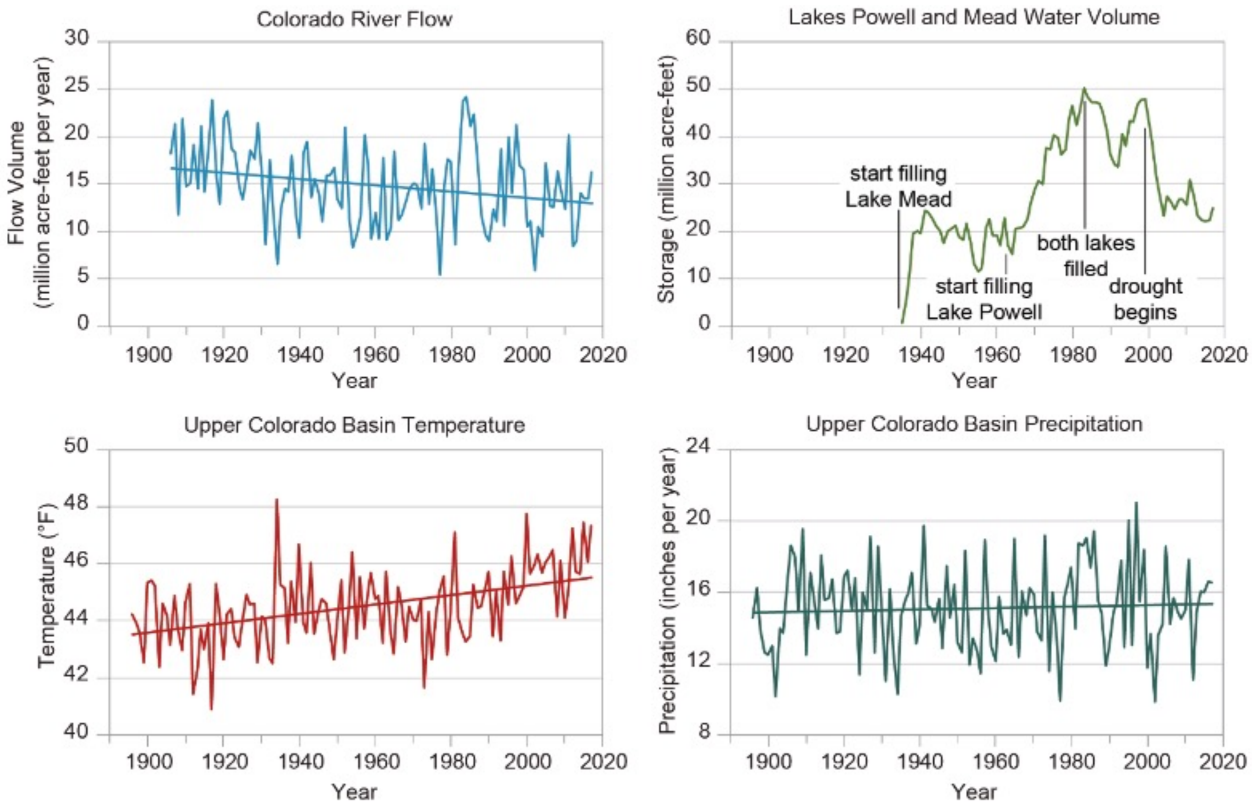
As an example of climate change impacts on the region's hydrology, sustained severe drought has hit water supplies in the Colorado River Basin particularly hard (Figure 7). Since 2000, Lake Mead on the Colorado River has fallen 130 feet (40 m) and lost 60% of its volume because of the ongoing Colorado River Basin drought and continued water withdrawals by cities and agriculture.[54] The increased reduction of snow under climate change has amplified recent hydrological droughts in the Colorado River Basin and other regions of the Southwest like the Rio Grande River Basin. Projected hotter temperatures increase probabilities of decadal to multi-decadal mega droughts, which are droughts of unusually long duration that typically exceed those observed in the instrumental records.[54,56] Increases in temperature can also cause lower soil moisture that could lead to aridification, which is the gradual change of a region from wetter to a drier climate.[57]

In addition to increasing risk of drought and aridification, flood risk is also, counterintuitively, increasing as well. Climate models predict an increase in the frequency of very high precipitation events caused by phenomena like atmospheric rivers and increased atmospheric water vapor resulting from rising temperatures.[54] For example the summer of 2006 was a record monsoon season in New Mexico, with a total of 91 flash flood events.[58] In September 2015, extreme rainfall generated by remnants of Pacific Hurricane Linda flooded Keyhole Canyon in Zion National Park, Utah causing injuries and deaths.[59]

FIGURE 7.

This figure shows on the upper left the Colorado River flow volume, on the upper right the storage of Lake Powell and Mead water volume, on the bottom left the increase in temperature in the Upper Colorado Basin, and the bottom right shows precipitation. Despite the two reservoirs with the greatest capacity in the country on the Colorado River, Lakes Powell and Mead, overallocation combined with persistent drought has reduced reservoir levels so dramatically that there have been significant reductions to water deliveries. In Arizona, some farmers in the central part of the state are the most junior on the system, creating deep uncertainty about the viability of agriculture in that region.

Source: Garfin et. al, 2018.[54]



Impacts to agriculture

Climate change has important implications for agriculture in the Southwest. The predicted reduction in snowmelt runoff will stress agriculture in the region by reducing available water for irrigation. At the same time, crops will need more water because growing seasons and evapotranspiration rates will increase. Evapotranspiration is expected to increase with warming across the Southwest, with projections in parts of the region of an increase of 28% by 2100.[50] One result of this may be an increasing reliance on groundwater. Between 1955 and 2010, groundwater has become a larger portion of the total agricultural water use in parts of the Southwest, primarily Nevada and Utah.[50] Increasing the region's reliance on groundwater will further stress already overtaxed aquifers and the people and ecosystems that depend on them.[53]

Climate change-related warming will also impact crop viability in several different but related ways. Increased heat stress will lead to more crop failures. Water stress will also reduce long-term livestock grazing capacity across the landscape, reduce livestock feed supply and decrease forage quality. It will also likely shift plant hardiness zones northward and upslope; impacting specific crops differently but with the same general result: existing crops might not be viable in some areas while crops like olives, cotton, kiwi and oranges could replace them. Some fruit and nut trees require exposure to cold temperatures for specific amounts of time and reduced crop yields could occur to reduction in the number and duration of cold periods.[54]

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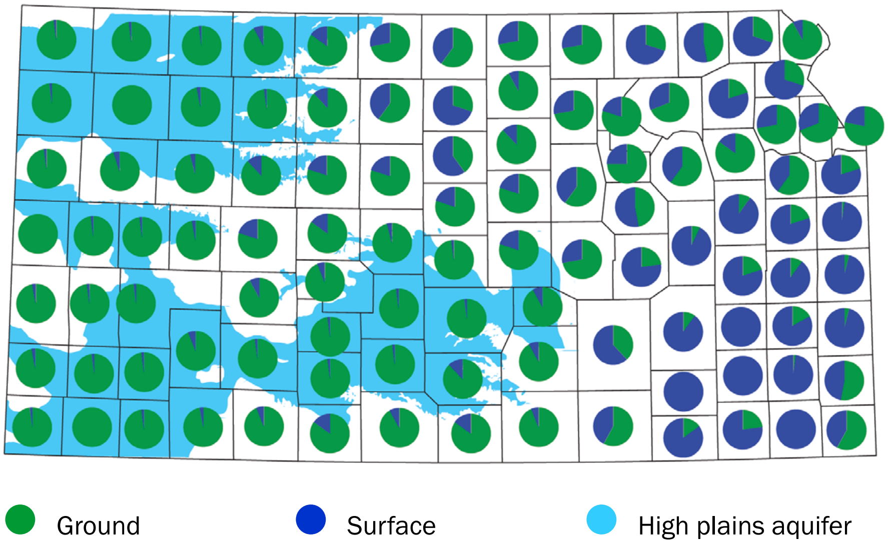
WATER-RELATED RISKS TO AGRICULTURE:

Kansas

Agriculture overview

Moving east to west across the state, agriculture in Kansas transitions from predominantly rainfed to predominantly irrigated (Figure 8). Much of the irrigation that occurs in western Kansas is from groundwater pumping of the Ogallala Aquifer while surface water irrigation comes from sixteen reservoirs in the East and North-central regions. Kansas has a total of 45.7M acres in farmland—over 87% of the state's total land areas--spread across 57,700 farms and is the leading producer in the U.S. of sorghum for grain and winter wheat.[60] Agriculture and agriculture-related sectors support over 256,000 jobs in the state. In 2021, Kansas' exports to 93 foreign markets totaled over $5.3 billion.[61]

FIGURE 8.



When moving from east to west across the state, water rights switch from predominantly surface water to predominantly groundwater. The area that overlies the High Plains aquifer generally contains very few surface-water rights. Groundwater levels in the Ogalla have some of the fastest rates of decline in the world, jeopardizing the accessibility and sustainability of water for agricultural production.

Source: Kansas Geological Survey.[62]

Hydrology

Kansas undergoes notable changes in hydrologic patterns moving east to west—eastern portions of the state can see over 60 inches of precipitation annually, while some parts of the western portion average less than 10 inches per year. As a result, the eastern portion of the state has a significantly more robust network of perennial rivers and streams, which feed into the state's reservoirs. These reservoirs are utilized for maintaining streamflow for diversions, flood protection, drought resiliency, and community water supply—providing drinking water to two-thirds of the state's population. A critical issue facing these reservoirs is sedimentation, which reduces storage capacity.[63]

The central and western portion of the state is characterized by a semi-arid steppe climate with limited precipitation and surface water supplies. The region therefore relies more heavily on groundwater within the High Plains Aquifer which it overlies. The High Plains Aquifer is comprised of interconnected aquifers and, moving from central to western Kansas, includes Equus Beds, Great Bend Prairie and the much larger Ogallala. Agriculture, municipalities, domestic well users and ecosystems are all heavily reliant on groundwater in western Kansas.[62]

Nestled in the center of the continental U.S. and intersected by the 100th meridian, Kansas is subject to dramatic, widely-varying weather patterns—including extreme temperature gradients from winter to summer, as well as oscillations between flooding and drought, sometimes within the same year.

Climate change

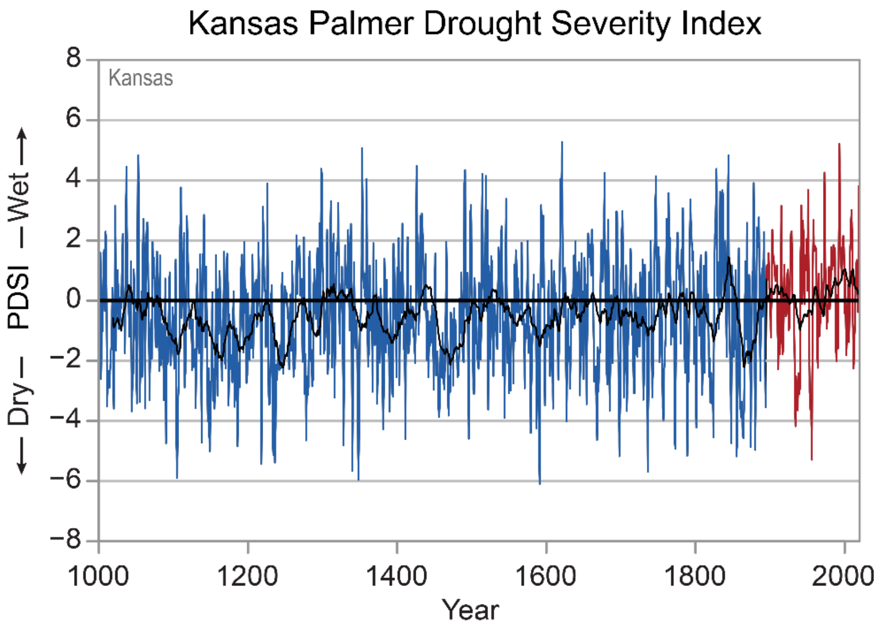
Climate change is expected to increase average temperatures in Kansas, as evidenced by the 1.5 °F of warming that has occurred since the early 1900s.[64] Warmer temperatures will drive increases in evaporative demand, putting additional strain on water supplies in areas facing water scarcity as crops require more water to grow.

Though Kansas has historically been prone to extreme weather events, warmer temperatures will exacerbate these events, leading to increased frequency, duration, and severity.[64] In eastern Kansas, the shift of precipitation to less frequency but greater severity negatively impacts soil moisture as soils have less time to capture and retain moisture and longer periods of drying out. Prolonged drought, such as that experienced in Kansas from 2010 to 2015 (Figure 9), can also have negative implications for agriculture, resulting in early harvests, crop stress, and crop losses.

FIGURE 9.

Time series of the Palmer Drought Severity Index for Kansas from the year 1000 to 2020. Values for 1895 to 2020 (red) are based on measured temperature and precipitation. Values prior to 1895 (blue) are estimated from indirect measures such as tree rings. The fluctuating black line is a running 20-year average. In the modern era, the wet periods of the early 1900s and the dry period of the 1930s to 1940s are evident. With the exception of the 2010–2015 drought, Kansas has experienced overall wet conditions since the 1980s. The extended record indicates periodic occurrences of similar extended wet and dry periods.

Source: Frankson et. al, 2022.[64]



Groundwater is expected to decline in Kansas by as much as 25% from 2010 to 2060 due to climate change driven decreases in precipitation and increased groundwater withdrawals.[65] Similarly, surface water reservoirs are projected to decline by 50% between 2007 and 2050 due to reduced precipitation and rising evaporative losses.[66] These reductions in water availability will significantly alter crop production in the state. Increased irrigation will not offer a true solution to rising water scarcity, because both groundwater and surface water reserves will be depleted.

Impacts to agriculture

Modeling studies predict that Kansas corn yields would fall by 18-33% and winter wheat yields would decrease by 17% under future climate scenarios.[67,68] Higher yield reductions are predicted for both crops under the worst case climate scenarios. **A previous EDF study** reported an increasing climate burden (a climate change-induced drag on yields) is anticipated in northwest Kansas.[69] That report also projected a meaningful decrease in the protein content for winter wheat that could affect the price. A small climate boost--a climate change-induced uplift on yields--is anticipated elsewhere. Despite the possibility of a boost in some locations, such a benefit may not be large enough to counteract the long-term yield declines in irrigation-dependent Western Kansas.

Research has shown that irrigated crops in the Southern Plains are vulnerable to climate change and researchers project that groundwater pumping costs will begin to limit irrigated agriculture by 2030.[70] Other modeling suggests a forced shift to dryland farming in the Central High Plains by 2099, with irrigated corn acreage reduced by 60% and irrigated wheat acreage by 50%.[71] Another study considers how devastating a forced transition to dryland agriculture would be for the twelve million acres of irrigated cropland dependent on the High Plains Aquifer.[72]

According to the Kansas Department of Agriculture, the 2011 drought caused nearly $1.8 billion in crop losses and in 2012 the losses were $3 billion. Additionally in 2012 the insurers paid out over $1.3 billion to Kansas farmers in crop insurance indemnity payment for failed commodity crops.

Kansas farmers will increasingly be faced with water management decisions in the warmer and drier climate. The Kansas Water Office released the Kansas Water Plan in 2022, which outlines a water management and conservation strategy for the state with an emphasis on local solutions.[63] Regional Advisory Committees are required to identify local goals and develop action plans to address water needs and respond to urgent water depletion. Water in the future will need to be managed with precision just like seed or fertilizer inputs.

WATER IN THE FUTURE WILL NEED TO BE MANAGED WITH PRECISION JUST LIKE SEED OR FERTILIZER INPUTS.

Environmental Defense Fund

WATER-RELATED RISKS TO AGRICULTURE:

Midwest/Corn Belt

Agriculture overview

The Midwestern States (Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio and Wisconsin) represent some of the most intensive crop production in the world. The area is often referred to as the Corn Belt, as the region produces one-third of the global production of corn. Corn and soybeans are grown on 75% of the arable land, but the region also produces wheat, oats, fruits, vegetables, tree nuts and nursery stock. Some of the corn and soybean production is used to support the production of livestock (cattle, hogs and chickens) and related products, with Iowa leading the nation in hog production. Much of the corn and soybeans is exported overseas after being shipped down the Mississippi River on barges; floods and droughts both can cause multi-billion-dollar disruptions to barge traffic. According to the 2017 Census of Agriculture, the annual value of agricultural products from the region exceeds $100 billion.

Corn and soy are typically grown on the deep, organic-rich soils of the former tallgrass prairies. Many of these soils are slow-draining and have been modified to support crop production through the installation of subsurface (tile) drainage. The Midwest region is the most intensively tiled region in the U.S., with the 2017 Census of Agriculture reporting that over 50% of Iowa farmland is underlain by tile. Across the Midwest, 19.2 million hectares of cropland are tile-drained (Figure 10).[73] In contrast, specialty crops are more commonly grown on sandier soils in central Wisconsin, central Illinois and southern Michigan; most of these specialty crops are irrigated.

Although rainfed production dominates, there has been an increase in irrigated acreage in recent years, with a near-doubling of irrigated acreage between 1981 and 2015.[75] This includes irrigation of corn destined for biofuel refineries and irrigation of sweetcorn; in both cases the end-users need for steady supply drives contract requirements for stable yields facilitated by irrigation.

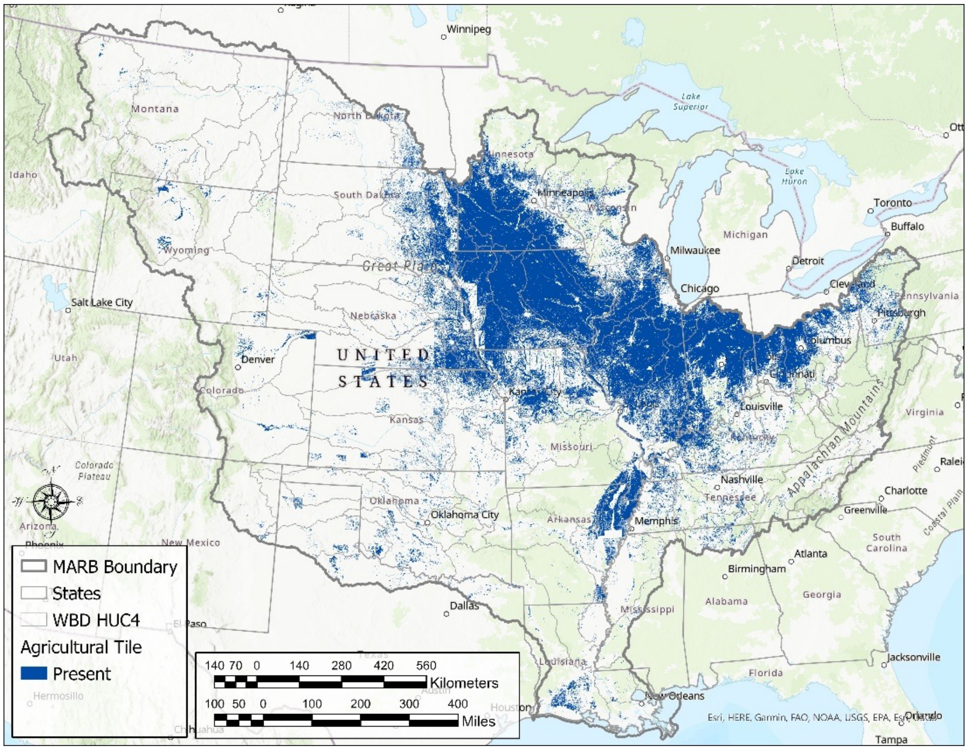
Hydrology

The Midwest experiences cold and usually snowy winters and hot, humid summers. Annual precipitation increases from northwest to southeast across the region, ranging from about 20 inches in northwest Minnesota to 47 inches along the Ohio River, while snowfall ranges from 20 inches in southern Ohio to

FIGURE 10.

Map showing presence of tile drains in the Mississippi-Atchafalaya River Basin (MARB). Many crops do not grow well in overly saturated soils–tile drains can be used to support the development and growth of healthy roots. However, there is a risk that increased drainage will reduce flood risk at the level of the individual agricultural field at the expense of increased flood risk for downstream communities.

Source: Shilling et al. 2023.[74]



over 60 inches in Michigan. Although there is evidence that decadal scale climate variability such as El Niño-Southern Oscillation events drive regional precipitation patterns, transport of moisture from the Gulf of Mexico by mid-level atmospheric disturbances also plays a role in regional hydrology.[76]

Land use change – the conversion of perennial prairie vegetation to annual crops, the widespread use of tile drainage, and the more recent shift from oats and other small grains to soybeans – has contributed to hydrologic shifts across the region, although it is often difficult to separate the impacts of land use change and climate change.[77–79] Over the past 30 years, there has been a well-documented increase in spring rainfall and runoff, with increased frequency of days of heavy precipitation.[80] The region suffered a series of large floods in 1993, 2008, 2011, 2013, 2014 and 2019 which impacted both agricultural production and urban communities. These regional flooding events are due to a combination of increased precipitation and wet ground conditions due to rapid snowmelt.[81] The 2019 floods on the Mississippi and Missouri Rivers caused over $20 billion in damage, including payments to farmers for prevented planting on over 19 million acres of cropland. More localized summer floods are associated with thunderstorms fueled by moisture from the Gulf of Mexico.

The region has also experienced extraordinary droughts, most notably in 2012 when the U.S. lost almost 25% of its corn production.[82] In 2022 a flash drought due to lack of rain across the Upper Mississippi and Ohio Rivers led to near-record low flows on the Mississippi River. This in turn led to the stranding of river barges transporting grain downriver, with associated impacts to the region's economy.

Climate change

The Midwest is expected to become warmer and wetter because of climate change. Warm-season temperatures are expected to increase more in the Midwest than in any other region of the country, with mean annual temperature increasing up to 11.7°F by 2100.[83,84] There is broad agreement that winter and spring precipitation will increase, with increases of up to 30% by the end of this century, much of this occurring as intense precipitation events, continuing a trend seen over the past 30 years.[80,84]

As a result of increased precipitation, peak daily streamflow will increase by 10-30%.[85] For the Cedar River basin in Iowa, river flows corresponding to the 100-year flood in the early years of this century are projected to become much more common, corresponding to the 25-year flood by the end of the century.[8] There is much less agreement on potential changes to droughts, though some models suggest that summers will be drier, increasing drought risk.[86] It is suggested that rapid wet-to-dry transitions, as experienced in the region in 2011-2012 and in 2019, will become more frequent.[87]

Impacts to agriculture

Changes in climate will affect both crop yields and yield variability. Using historical data from the region, one study showed that inter-annual variability in temperature and precipitation explained 42% of the inter-annual variability in crop yields.[88] A related study demonstrated that nearly half of this variability was tied to extreme events (heat waves, extreme rainfall, prolonged drought) which have largely been ignored in climate and crop models to date.[89] This study also identified the Corn Belt as a region that is particularly susceptible to the impacts of extreme events.

The projected higher mean temperatures will affect crop production, especially for corn and especially in the south of the region. High temperatures directly affect yield by shortening the all-important grain-filling stage of crop growth, which leads to reduced yields. In addition, a warmer growing season translates to more days of high heat stress, which slow down crop growth and can result in crop reproductive failure and even death, again affecting yields. Increased precipitation is likewise expected to lead yield declines; waterlogged soils prevent the plant from absorbing needed oxygen, leading to reduced growth or plant death.

The interaction of temperature and precipitation creates still more challenges for crop production. Increased temperatures will lead to increased vapor pressure deficit in the atmosphere, meaning greater evapotranspiration and water consumption by crops. If the needed extra water is not available (in the form of increased precipitation, or provision of irrigation water), then yield will decline. Irrigated acreage may need to expand by 300% to maintain current corn yields in a warmer climate, and higher yields projected in response to technological improvement may not materialize due to this “water ceiling.”[90]

Some rainfed crop acreage is already transitioning to irrigation due to supply chain demands for yield stability. Broader transition to irrigation is likely to be limited due to limited water supplies. The Cambro-Ordovician aquifer which underlies northern Illinois, and portions of Michigan, Minnesota and Wisconsin, is already widely used to support drinking water and industry. In southern Illinois and Indiana, no near-surface aquifers are available, and irrigation would need to use surface water, with consequences for aquatic ecosystems.

Extreme events are likely to have dramatic impacts on crop yields. Excessive rainfall could cause yield declines of as much as 34%, comparable to the impacts of severe drought (32%).[1] Higher precipitation in spring may even prevent farmers from planting their fields; if they are able to plant later than usual, crop yields will suffer, and in many cases, farmers may simply leave fields fallow, impacting overall crop production. Heavy spring rains in 2019 affected timely planting on 11 million acres of corn alone, and farmers are increasingly interested in installing or intensifying tile drainage systems to reduce the risk of delayed planting.[91]

THE RISKS OF MALADAPTATION

As agriculture across different regions works to mitigate and adapt to water-related risks, maladaptation poses a threat to the success and durability of different approaches. Adapted from the Inter-Governmental Panel on Climate Change (IPCC), maladaptation for the purposes of this report can be defined as "any changes in natural or human systems that inadvertently increase vulnerability; an adaptation that does not succeed in reducing vulnerability but increases it instead."[92] Identifying the risks of maladaptation can inform more inclusive, holistic and robust planning and decision-making processes. To avoid maladaptation, the development and implementation of policies and programs must be grounded in community participation with two-way learning as well as evaluate the socioeconomic impacts of adaptation strategies across different groups. The maladaptation risks are significant for both water scarcity and excess, threatening food security and livelihoods.

The risks of maladaptation to scarcity

Some responses to water scarcity may provide either only temporary relief or may only provide the appearance of relief while causing additional or potential future harm. Several such responses are briefly discussed here including: over-extracting groundwater, increasing consumptive use via increased water use efficiency, seeking alternative supply sources with exceedingly high costs and large-scale fallowing without proper planning and safeguards.

Tapping groundwater as a supplemental or alternative source of water has been occurring for decades, resulting in severe declines in aquifer levels in many places.[17] Groundwater law is inconsistent across the West and Midwest. This patchwork of different laws means many regions lack protections for aquifers. Declining aquifers can have serious impacts not only on agricultural users, but also on groundwater dependent ecosystems and communities, especially low-income rural communities with high proportions of families that rely on private wells for domestic water. For example, in the Harney Basin in southeast Oregon, rapidly declining groundwater levels threaten more than 1,000 households that rely on private wells; one study estimated that it could cost between 12 and 25 million dollars.[93]

Increased water scarcity naturally increases calls for greater water use efficiency in agriculture. While greater efficiency is much needed and should be encouraged, in some instances it can result in negative consequences. Specifically, efficiency gains can mean water that formerly seeped into shallow aquifers and helped boost baseflows in connected surface water sources, seeped into deep aquifers, or returned to a surface water source via overland flow, is instead used to irrigate new land or provide for municipal or industrial demands.

The net result of this can be an increase in consumptive use rather than an overall reduction, exacerbating the risk and impact of water scarcity.[94]

Aside from tapping local groundwater, other alternative water sources are sometimes proposed to augment or replace declining water supplies. In 2021, the Arizona Legislature requested funding for a feasibility study of building a diversion dam and pipeline to harvest floodwater from the Mississippi River and transport it to the Colorado River. Such a pipeline would likely need to be 700-900 miles long, and in 2012 had an estimated cost of $9-$14 billion.[95] Though this proposal is one of the more far-reaching, water supply augmentation projects can lead to maladaptation if the full impacts of the project are not wholly considered. Augmentation projects that transport water create vulnerabilities for the exporting region, potentially creating conflict between communities and water users in the respective importing and exporting regions.

A final example of maladaptation is fallowing agricultural land without regard to economic, social, environmental and other potential negative impacts. While strategically reducing the footprint of irrigated agriculture may be part of the solution to growing water scarcity, fallowing land without proper planning and without putting safeguards in place to mitigate negative impacts can have consequences in the form of weed or dust problems, community decline and economic impacts, and at larger scales can impact national or global food security. One of the most famous examples of large-scale fallowing of farms occurred in the Owens Valley in southern California where, in the early 1900s and again in the 1970s, Los Angeles purchased water from farms, resulting in significant impact to ecosystems, the cultural and economic resources of tribes in the region, and the local agricultural economy.[96]

> **“GOVERNANCE MECHANISMS HAVE EMERGED THAT CONSIDER FOOD SECURITY, SOCIO-CULTURAL FACTORS, AND LAND AND WATER RIGHTS, USING PARTICIPATORY, INCLUSIVE ‘TWO-WAY LEARNING’ METHODS THAT INVOLVE VULNERABLE PEOPLE ALONGSIDE GOVERNMENT.”[5]**

While there is no clear delineation of what actions are maladaptive, several hallmarks are helpful. First, actions that harden water demand – such as major investments of public money in expensive alternative sources or in expanding irrigated acreage using water savings from existing systems – can cause greater problems than they solve, especially over medium- and long-term horizons. Similarly, failure to fully consider secondary or less-obvious impacts, for example impacts to distant but connected groundwater-dependent ecosystems from excessive groundwater pumping, is another pitfall that can lead to maladaptation. Tradeoffs are a reality in almost all potential responses to water-related risks, however, focusing on approaches that prioritize flexibility and resilience can lead to positive outcomes and avoid unintended negative consequences.

The risks of maladaptation to excess

Many Midwestern farmers are expanding and intensifying agricultural drainage. A 2020 survey showed that 42% of Iowa farmers intend to invest in new drainage infrastructure to prepare for increased rainfall associated with climate change.[97] There is a risk, however, that this increase in drainage will prove to be maladaptive at both the field and regional scales. While rapid drainage of water in the spring allows equipment into the field for crop planting and management, it also means that this water becomes unavailable for use later in the growing season if the crop needs additional water beyond that supplied by precipitation. A more systemic approach to drainage water management could address this challenge, as we discuss in section four of this report.

Increased use of tile drainage, at least in the Midwest, also risks draining some of the few remaining wetlands in agricultural landscapes. These wetlands are valuable as wildlife habitat and provide important flood retention service at the broader landscape scale. There is therefore a risk that increased drainage will reduce flood risk at the level of the individual agricultural field but increase flood risk for downstream communities at the larger scale. Tile drainage is also associated with increased losses of nitrogen from farm fields and increased nitrogen loads in downstream waterbodies. Nitrogen impairments to drinking water supplies and the occurrence of an oxygen-depleted dead zone in the Gulf of Mexico both result at least in part from nitrogen losses in tile drainage. Climate change, by increasing spring precipitation, will make these problems worse; increasing the use of tile drainage can only exacerbate these problems. Thus, as noted by Edwards and Thurman, while the use of tile drainage makes economic sense for the farmer, it creates economic burdens for larger society.[98,99,100,101]

While tile drainage is perceived as a solution to inland flooding, the construction of levees is perceived as a solution to river flooding. In the U.S., land that lies behind a levee certified to provide protection against a 100-year flood is exempt from various restrictions on development, including the need to purchase flood insurance. This leads to the “levee effect”, in which the construction of levees serves as a perverse incentive for development behind the levee, thereby increasing exposure to flood risk in extreme events. As quoted in Pinter et al.: “…there are two kinds of levees,..[t]hose that have failed and those that will fail,” as currently only 2% of surveyed levees meet “acceptable” standards.[102] Climate change is likely to further downgrade levee stability, increasing the risks of levee failure and catastrophic flooding.[103] A further problem is that construction of levees serves to direct floodwaters downstream, thereby increasing the risk for unprotected communities. This can lead to a vicious spiral in which failure of a levee leads to replacement with a taller levee, which increases downstream flooding, in turn prompting more levee construction and elevation downstream. While levees are recognized as being maladaptive, institutional support for levee construction may be difficult to overcome.[104]

TRADEOFFS ARE A REALITY IN ALMOST ALL POTENTIAL RESPONSES TO WATER-RELATED RISKS, HOWEVER, FOCUSING ON APPROACHES THAT PRIORITIZE FLEXIBILITY AND RESILIENCE CAN LEAD TO POSITIVE OUTCOMES AND AVOID UNINTENDED NEGATIVE CONSEQUENCES.

DEVELOPING POLICIES, PROGRAMS, AND TOOLS FOR AGRICULTURAL RESILIENCE

In the face of the dual stressors of water scarcity and water excess, each of which will be exacerbated by population growth and climate change, it is critical to consider the building blocks essential for resilient agriculture. As demonstrated in the case studies above, both water scarcity and excess can have widespread implications for crop production specifically and agriculture generally over short and long timescales.

Policies and programs that foster adaptation and resilience are needed at the nexus of agriculture and water to ensure there are sufficient water resources to meet human and ecosystem needs for future generations. This will include critically evaluating agroecological tradeoffs such as which crop types and water management practices are most suitable in a given geography in light of population growth and climate change.

An "all-of-the-above" approach will be necessary to address the challenge at hand. Within this broad and global effort, EDF is working with partners and stakeholders to advance science, develop tools, and implement policies and programs that build climate resilient agricultural and water systems and support the livelihoods that depend on them. This section introduces this work with the intention to spark ideas, dialogue and opportunities for further innovation and collaboration. EDF's efforts can be grouped into four categories: land and crop management changes; technology and decision-support tools; natural and built infrastructure approaches; and policy and funding mechanisms.

More specifically, the efforts highlighted in this report include:

Land and crop management changes:

- Land repurposing;
- Climate resilient crop production; and
- Soil health practices.

Technology and decision-support tools:

- OpenET; and
- Groundwater Accounting Platform

Built and natural infrastructure approaches:

- On-farm water recycling; and
- Natural infrastructure for flood resilience.

Policy and funding mechanisms:

- Smart groundwater governance; and
- Financing solutions to support climate-smart agriculture investments

Each of these specific efforts are discussed briefly on the following pages.

Land and crop management changes

Land repurposing

Land repurposing is a strategy to coordinate multibenefit land use transitions in regions where water supplies are insufficient to irrigate the current agriculture footprint. Strategic planning, dedicated funding, and incentive payments to voluntarily participating growers can enable regions to repurpose formerly irrigated farmland to new uses that create benefits such as restored species habitat, renewable energy generation, floodplain restoration, well-managed rangeland and community recreation opportunities in a spatially coordinated manner. While multibenefit land repurposing is a tool that may be needed and used across the West and perhaps in some areas of the Midwest, EDF is currently working to develop and test strategies for land repurposing in California, where the 2014 Sustainable Groundwater Management Act (SGMA) has mandated a transition to sustainable use of groundwater over the next two decades in the state's major agricultural regions.

Balancing California's groundwater demand and supply will require shifting to less water-intensive agriculture or taking land out of production. It is estimated that up to 900,000 acres, nearly 20% of farmland in the San Joaquin Valley, may need to be taken out of production by 2040 to meet the sustainability mandate of SGMA and address greater water scarcity exacerbated by climate change.

In late 2021, Governor Gavin Newsom signed legislation that created the Multibenefit Land Repurposing Program to provide farmers with options to voluntarily repurpose farmland that can no longer be irrigated due to groundwater conservation to other uses that deliver new benefits for people and ecosystems, including wildlife habitat, parks and low-impact solar projects.

The program has awarded over $75 million in block grants to local agencies, tribes and local nonprofits, and provides incentive payments to landowners who repurpose some of their fields to these new uses. Grant recipients must develop a regional agricultural land repurposing plan and strategically distribute funding for land repurposing projects. To ensure the plans reflect diverse stakeholder priorities and preferences, the grant recipients must also meaningfully engage low-income communities and socially disadvantaged farmers and ranchers and prioritize projects that benefit these groups.

By strategically repurposing previously irrigated land to create new uses and value, the San Joaquin Valley can transform into a region with a thriving agricultural economy, sustainable groundwater supplies, vibrant wildlife habitat, outdoor recreation and jobs, and healthy air and soil.

Climate resilient crop production

Several case studies above noted changes in crop suitability that may occur due to increasing temperature and other impacts of climate change.

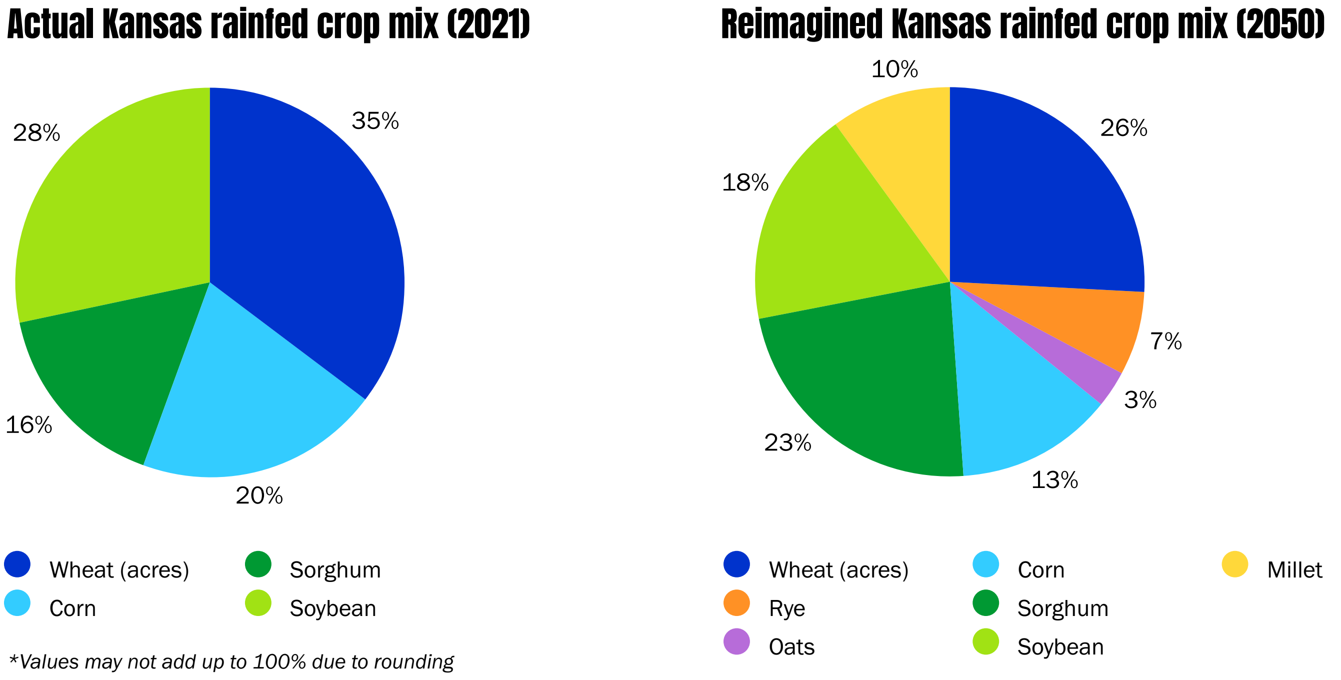
Some of the crops currently grown in the West and Midwest may not be commercially or otherwise viable in the predicted future climate, which may result in negative impacts on water resilience, food security and sustainable livelihoods. Another adaptation strategy EDF and others are investigating, therefore, is how to support more resilient food production, including the incorporation of more climate smart agricultural practices such as transitioning to growing crops that will be a better fit for the future climate. Often times, these transitions result in more biodiversity at farm level and include the incorporation of food varietals that are more adapted, or native, to the climate they are grown in, and thus require less land intensive practices to maintain production levels.

For example, **EDF's latest research** explores alternative crops that Kansas farmers could grow to respond to decreased water availability and higher temperatures, while still growing nutrient-rich food for an expanding global population.[105] The analysis evaluates the potential resilience benefits at a county level of growing sorghum instead of corn, winter rye or winter oats instead of winter wheat, and millet instead of soybeans. Interviews with Kansas farmers helped identify these as feasible crop switching options. EDF's research suggests that by 2050 a substantial proportion of current rainfed crop acres would need to shift to alternative crops to meet constraints related to nutritional value and less available water. The results show that the alternative climate-resilient crops could increase from 16% of acreage in 2021 to 43% of acreage in 2050 resulting in a crop water use reduction of 12% (Figure 11). This crop water use reduction would be concentrated in parts of the state that will experience the greatest change in water needs between today and mid-century.

Some of the crop switching envisioned in EDF's future scenario (e.g., corn to sorghum) is already

FIGURE 11.

Pie charts showing actual 2021 and projected 2050 rainfed row crop mix for Kansas. In 2021 the crop mix is predominantly wheat and soybeans (63% of rainfed crops) and alternative crops make up only 16%. In the reimagined crop mix of 2050, alternative crops (sorghum, millet, rye and oats) could grow to 43% of the acreage while wheat and soybeans shrink to less than half.



Actual Kansas rainfed crop mix (2021)

Reimagined Kansas rainfed crop mix (2050)

**Values may not add up to 100% due to rounding* underway and could be accelerated. However, other types of crop switching – for example, winter wheat to winter rye – are not yet underway. EDF's analysis has shown that it is biophysically possible for future crop production in Kansas to be more resilient to climate change. However, achieving this vision on the ground will require major shifts and tradeoffs in the broader agricultural system and market. Private-public partnerships, including those between food companies, agricultural lenders, and policymakers, will need to play a fundamental role in creating an enabling environment for these critical agricultural systems transformations.

Climate resilient crop production in regions outside of Kansas is also a viable alternative. Crop suitability is a site and climate-specific issue. Because of this, expanding this tool to other regions will require site-specific studies to identify future climate parameters and the best-fit crops for the region considering those parameters.

Soil health practices – possible field-scale benefits for droughts and floods

Anecdotal evidence (a survey of farmers following the 2012 drought in the Midwest) suggests that cover-cropped fields are more resilient to drought than fields without cover crops in the Midwest. For example, one study found that long-term improvements can be made in soil water storage following long-term use of cover crops in Iowa, which might be anticipated to provide crop benefits in drought years.[106] However, it's unclear whether the increase in soil water is sufficient to provide a significant benefit, as another study saw no increased resilience to drought (as measured by yield) despite increased soil water storage.[107] In contrast, in the Canadian prairies (an extension of the U.S. Corn Belt) another soil health practice, extended rotations, reduced plant water stress while building soil organic matter, which has been shown to confer resilience to drought.[108,109]

Increased soil water storage might provide some resilience to floods as well as to droughts. A survey of Midwestern farmers following the 2019 floods in the region reported that fields with cover crops were less likely to experience flooding sufficient to prevent planting of the following year's cash crop.[110] A number of soil health practices appear to improve soil water infiltration and other hydrologic properties, potentially allowing soils to absorb more rainfall before becoming saturated.[111,112] There are, however, no peer-reviewed studies that demonstrate improved flood resilience (expressed as reduced extent or duration of flooding) from the use of soil health practices.

A number of plot-scale studies have examined the impact of cover crops on runoff, with inconsistent results. A potential concern with many studies is that they focus only on surface runoff and do not consider changes in subsurface drainage (which might be expected because of increased infiltration). An exception is a study in the Canadian prairies, that found that decreases in surface runoff were offset by increased infiltration and subsurface drainage.[113] While the reduction in surface runoff might confer field-level benefits, it could potentially increase downstream flood risk. Likewise, few studies have examined the impact of soil health practices at small watershed scale, and those which have showed no consistent impact of cover crops on total volume of water at the watershed outlet.[114–116] Despite inconsistent results, the potential for soil health practices to have benefits for both water scarcity and excess makes them a worthy target of future investment and effort.

Technology and decision-support tools

OpenET: publicly accessible, scientifically robust evapotranspiration data

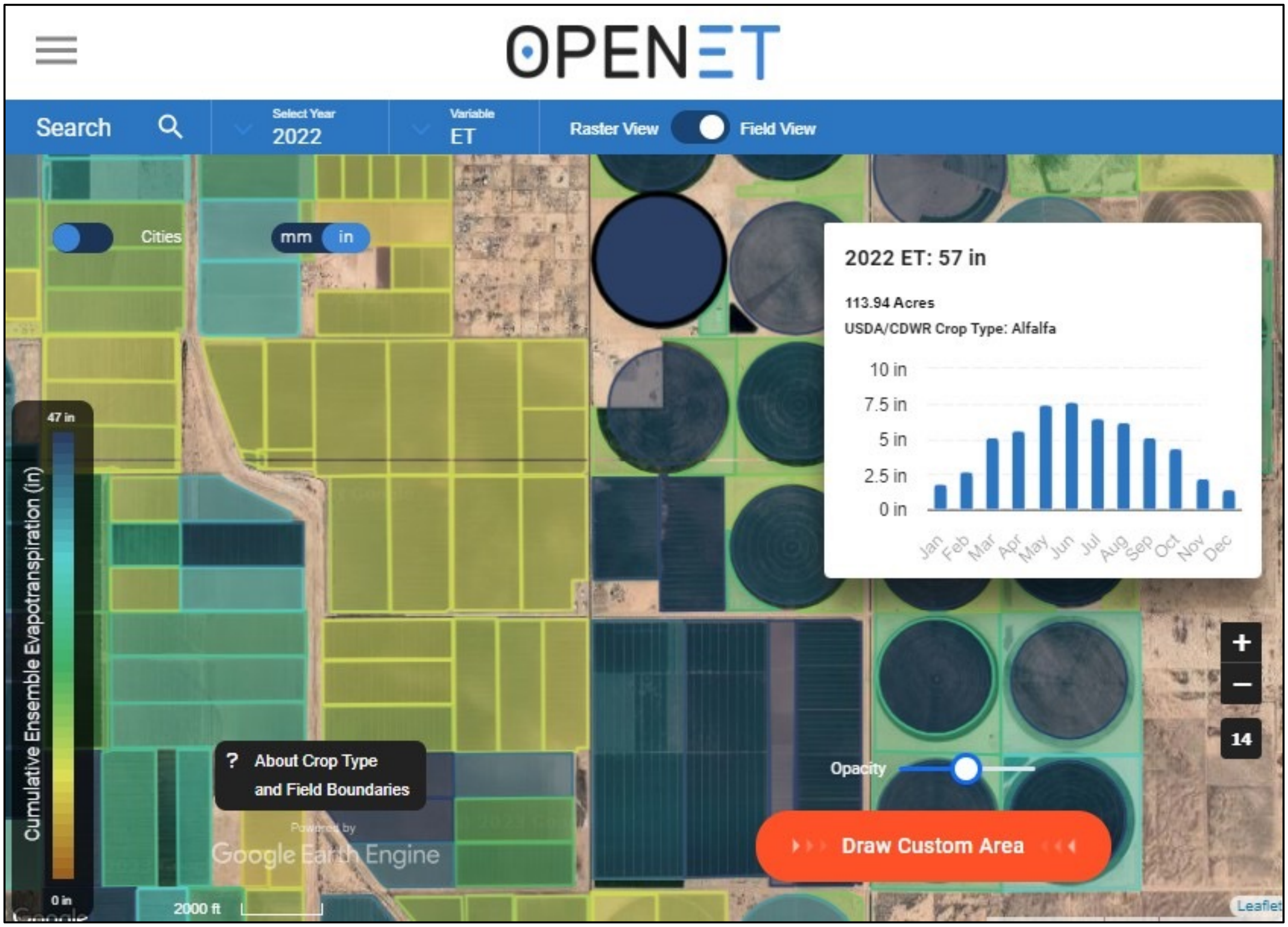
Sustainable water management requires careful measurement of water availability and use. In arid regions, evapotranspiration (ET)—the water that evaporates from the soil and transpires from crops as they grow—is often the second largest piece of the water budget after precipitation. Climate-driven water scarcity and declining aquifers necessitate more precise measurement and efficient use of water to continue producing the same amount of food, yet

ET data has historically been fragmented, expensive, inconsistent and difficult to access. To help close this gap, a public-private partnership—including EDF, NASA, Desert Research Institute, Google Earth Engine, scientists across several universities, and government agencies—was formed to develop OpenET (www.openetdata.org).

OpenET is an online platform providing publicly accessible ET data at the field scale for the 23 westernmost states in the US (Figure 12). OpenET uses an ensemble of well-established satellite-based ET models to provide a shared basis for decision making as agricultural producers work with local, state, federal and tribal water management agencies to respond to record setting drought events and longer-term imbalances between water supply and demand. One way OpenET can help agriculture adapt to climate stress is by helping growers and communities track and better understand the ET demands of low-water-use crops or alternate cropping strategies/patterns like deficit irrigation; this data can be compared to ET of current crops to estimate potential water savings and help communities determine the strategies that work best for them in meeting their water conservation goals and needs.

FIGURE 12.

OpenET web platform available at www.openetdata.org. OpenET was developed in partnership with EDF, NASA, Desert Research Institute, Google, and dozens of researchers and scientists across several universities. The platform provides evapotranspiration data in raster and vector form for part of the U.S., bringing together some of the most-widely used satellite-based ET models. The data is publicly accessible, supporting water management efforts and enabling shared decision-making.



Select Year 2022

Variable ET

2022 ET: 57 in

113.94 Acres

USDA/CDWR Crop Type: Alfalfa

Source: Melton et. al, 2021.[117]

One example of an ongoing OpenET study is occurring in northern Colorado near the headwaters of the Colorado River. EDF, along with other partners within the OpenET consortium, private landowners, university researchers and other non-profit groups, is testing the ability of OpenET to detect changes in consumptive water use of high-altitude hay crops in response to different irrigation patterns that could be used to promote water conservation. In the study, irrigated parcels were "treated" with partial season irrigation in year one (i.e. they were irrigated normally but for a shorter portion of the irrigation season than normal). Other parcels were not irrigated at all. OpenET was used to estimate changes in consumptive use for treatment parcels compared to parcels in the same area that received normal irrigation; this information is critical in determining whether the partial season irrigation strategy can help conserve water during droughts and more generally in the face of growing water scarcity. In each subsequent year, OpenET and other tools are being used to analyze how the crops on treated parcels respond when normal irrigation is resumed.[118]

Water accounting and budgeting for sustainable management

As water resources become more scarce, water managers and agricultural water users should have access to the best possible tools to effectively balance supply and demand. The Groundwater Accounting Platform, built in partnership by Environmental Defense Fund, California Water Data Consortium, Olsson and ESA, enables water managers, landowners, and water users to track water budgets and usage in near real-time. The Platform accepts water supply data from a variety of sources including satellites, flow meters and sensor networks, combining it with water use data. The Platform includes two views: the Landowner Dashboard to track water budgets at the field scale for water users, and the Water Manager Dashboard to track and account for water across a district or region, which informs management decisions such as billing and allocation planning.

The Groundwater Accounting Platform was built using open-source code, providing a springboard for water districts everywhere to launch and customize their own software solutions. Many public agencies see an advantage to open source because they avoid vendor lock-in and are available for anyone to modify, enhance, and update over time. Open-source software additionally encourages users to participate in an open user-community to guide platform roadmap and feature implementation.

In 2014, the California Legislature passed the Sustainable Groundwater Management Act (SGMA) establishing a statewide framework to protect groundwater resources over the long-term. It requires local agencies to form groundwater sustainability agencies (GSAs) in priority basins and to develop and implement groundwater sustainability plans (GSPs). The Groundwater Accounting Platform is currently being piloted in five GSAs in California, customized to suit the needs of each individual GSA. Technological solutions, such as the Platform, provide an accurate, timely and efficient way to track water budgets and evaluate progress toward management goals.

Built and natural infrastructure approaches

On-farm water recycling – turning two problems into a solution

Climate change is predicted to increase the frequency and intensity of wet-to-dry and dry-to-wet transitions, meaning that farms may experience drought and flooding in rapid succession. In the Midwest, this is most likely to be in the form of spring flooding followed by summer drought. Current approaches focus on rapidly draining water from farm fields in the Spring, which makes this water unavailable to the crop later in the growing season, worsening the impact of drought.

There is growing interest in on-farm water recycling, also called drainage water recycling. This approach involves constructing a reservoir (often a farm pond or wetland) at the outlet of field-scale tile drains and connecting the reservoir to a subsurface irrigation system (Figure 13). In Spring, water drains through the tiles into the reservoir, lowering water levels and allowing farm equipment to access the field for planting. During dry spells, water from the reservoir is pumped into the subsurface irrigation system to support crop growth. Studies in the Midwest suggest that this approach confers benefits to crop yield and – if the reservoir is designed to function as a wetland – also provide benefits to downstream water quality. Several recent studies suggest there are significant opportunities to use drainage water recycling in the Midwest, and that if extensively implemented, such systems could reduce current irrigation withdrawals by 48%.[119,120]

This approach potentially offers a solution to two problems likely to worsen under climate change – increased spring flooding and summer drought – in a way that avoids unsustainable expansion or intensification of irrigation, if managed properly.

FIGURE 13.

Image of drainage water recycling from Transforming Drainage. Subsurface tile drains are shown draining a field into a reservoir where there are pipes to pump the water back into subsurface irrigation.

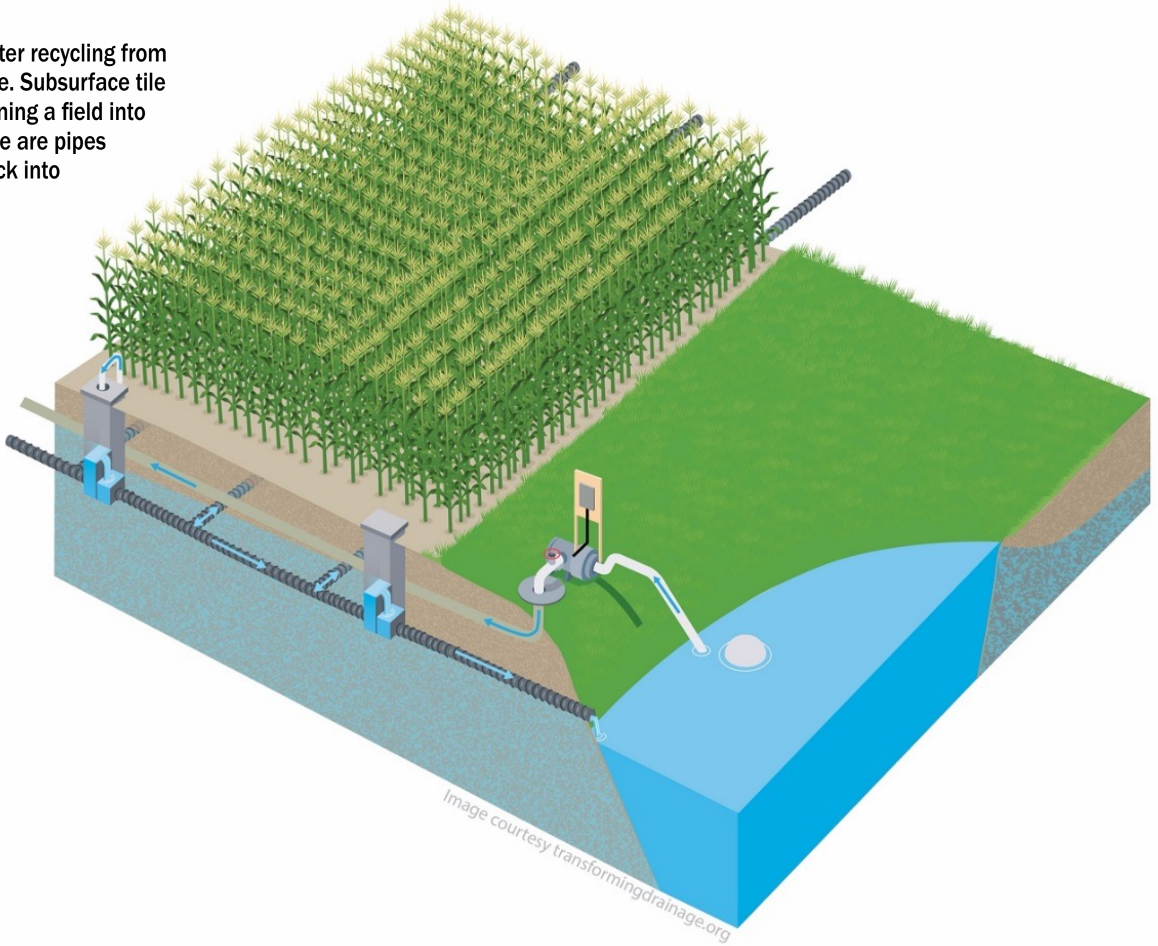


Image courtesy transformingdrainage.org

Natural infrastructure for flood resilience – increasing the resilience of landscapes and communities

Natural infrastructure practices within agricultural landscapes can enhance both the storage and slow release of water that help mitigate flooding and support surface water flow. Natural infrastructure practices include a range of approaches that: (1) reduce runoff generation, (2) increase water storage, and/or (3) attenuate flow.[121] These features are typically edge-of-field practices that would also minimize the loss of productive agricultural land. EDF scientists reviewed the scientific literature describing the use of natural infrastructure in agricultural landscapes and aggregated data on the effectiveness of these practices in mitigating floods and the strength of the evidence for such benefits.

The research concluded that four natural infrastructure practices were highly effective for flood mitigation and had strong evidence for their efficacy as reported in peak flow reduction in the literature.[121] These practices were farm ponds, conversion of cropland to forest, depressional wetland restoration, and floodplain restoration and each had an average peak flow reduction of 38%, 27%, 26% and 17%, respectively. The conversion of cropland to forest, while a beneficial flood reduction practice, is unlikely to be used in an agricultural setting, because too much land would be required. The other practices use a much smaller area to achieve similar peak flow reductions compared to land use conversion practices.

The researchers reviewed another six practices (engineered wetlands, riparian forest buffers, runoff attenuation features, stream restoration, two-stage ditches and vegetated ditches) that warrant further study for their potential flood mitigation benefits. Two-stage ditches, for example, have design features that potentially provide water storage and flow attenuation, yet research so far has only focused on their water quality benefits. Runoff attenuation features and stream restoration both show promise for higher flood mitigation in more recent studies.[122,123]

Natural infrastructure is thought to be most effective for storms that are smaller and more frequent (higher annual exceedance probabilities like 20-99%) and less is known about whether they can be as effective for larger, less frequent storms (lower annual exceedance probabilities like 1 or 5%). However, some practices like floodplain restoration require the less frequent storms for the river to overtop its banks onto the floodplain. Therefore, EDF recommends a full suite of practices installed strategically throughout a watershed (Figure 14).

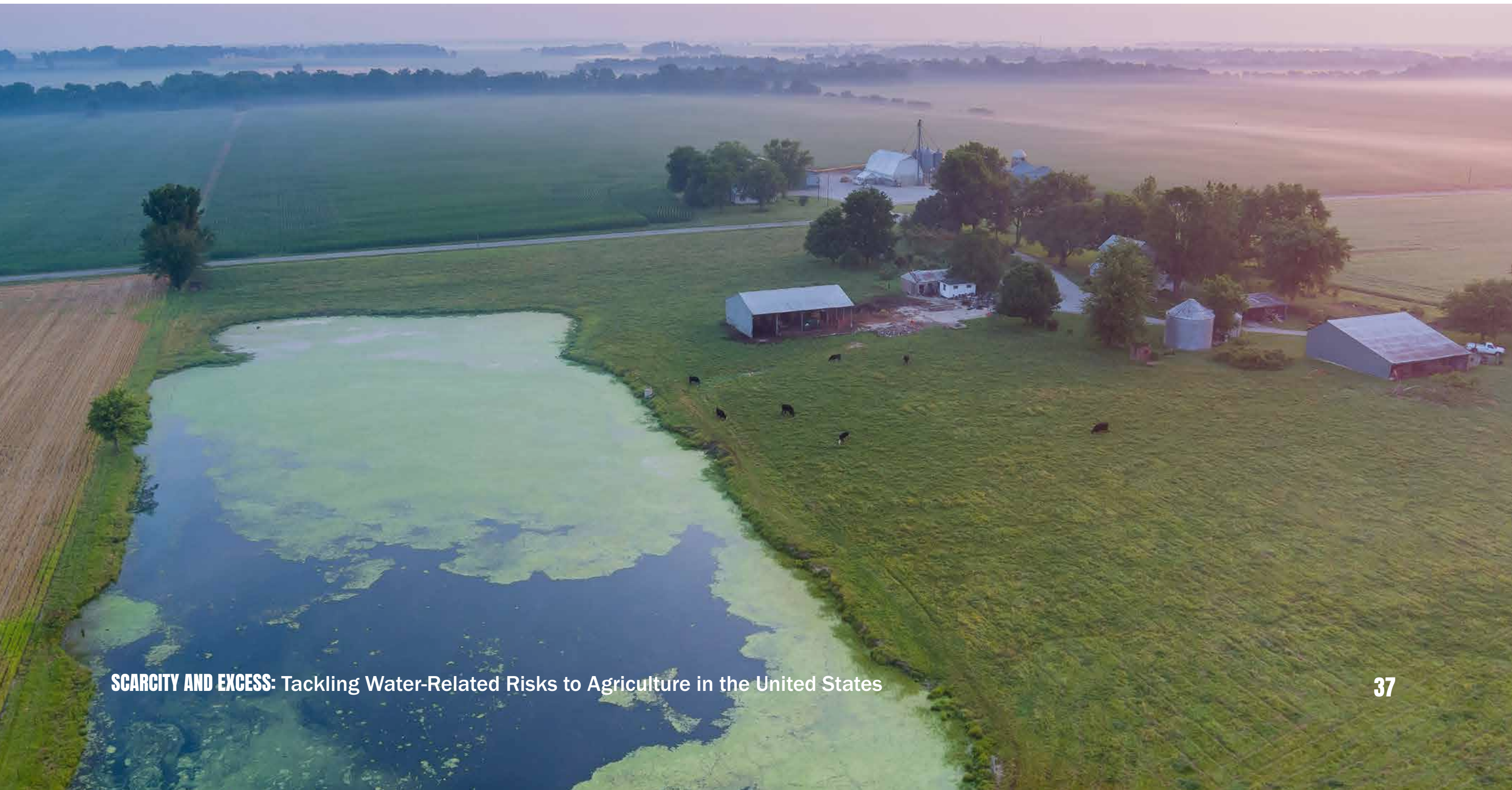
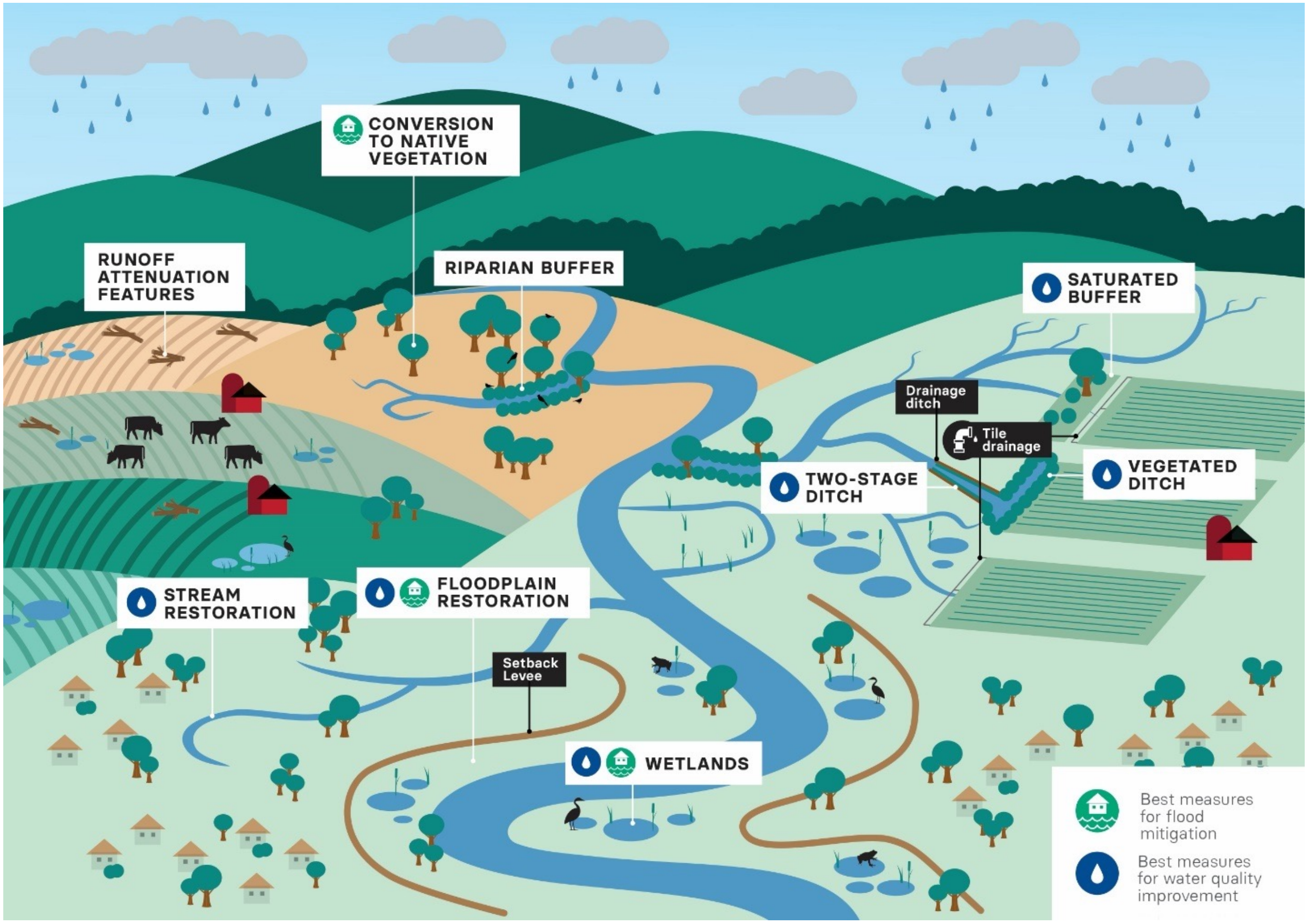


FIGURE 14.

Example of nine different natural infrastructure practices in different landscape positions throughout a watershed. Practices shown are both in-field and edge of field and located near tile drains, small streams, tributaries and rivers. This illustrates a suite of practices that could be used for flood mitigation.



Source: Suttles et al. 2021.[121]

Policy and funding mechanisms

Advancing smart groundwater governance

Several case studies above note that as surface water supplies grow scarcer and as precipitation patterns change, farmers and ranchers are increasingly relying on groundwater for irrigation. Many states' groundwater laws are not designed to promote long-term aquifer sustainability. As a result, water levels are declining or predicted to decline in response to growing groundwater demand. Declining groundwater tables can cause land subsidence, domestic and stock wells to go dry, lower flows in rivers and streams, and threatens the long-term viability of agricultural production.

Groundwater governance that aims to achieve long-term water security for people and nature should be 1) rooted in science, 2) inclusive of all stakeholder perspectives, 3) transparent in processes and decision-making, and 4) locally driven. EDF is working in states across the western U.S. to advance climate-resilient sustainable groundwater governance to ensure that water systems are balanced and can sustain communities, livelihoods and ecosystems.

In Texas, groundwater provides approximately 55% of the 16.1 million acre feet of water used in the state annually, with agricultural irrigation accounting for nearly 74% of groundwater use. Not only is groundwater itself an important water supply for agriculture, but discharges (through springs, seeps or otherwise) from aquifers help sustain surface water flows. Despite groundwater's importance to Texas, a recent study found that "groundwater conservation districts have made almost twice as much groundwater available for use in 2070 than can be produced sustainably,"[124] creating a risk to agricultural production reliant on groundwater.

EDF is working in partnership with water managers, community groups and other stakeholders to advance water governance through education, advocacy and policy reform. Several reports have been published to educate policymakers and local groundwater conservation districts on the need to proactively manage aquifers, such as **Beneath the Surface: Key Issues Underlying Groundwater Management in Texas**. To ensure decision-makers, managers, and communities are equipped with the best-available science, EDF and partners have advocated for increased investments in groundwater data and modeling. Additionally, the interactive story map, "**Water in the Texas Desert; the Story of the San Solomon Springs System**" demonstrates the value and importance of inclusive processes and locally driven water management efforts.

Financing solutions to support climate smart agriculture investments

Agricultural finance institutions are critical financial partners to farms and ranches across the country. In 2021, these lenders provided $474 billion in loans to farmers to finance their land acquisitions, their equipment and their operating expenses.[125]
But agricultural finance institutions have not proactively supported climate-smart agriculture investments with tailored financial solutions.

A 2022 survey conducted by EDF and Deloitte found that 87% of agricultural finance institutions expect climate change to pose a material risk to their business.[126] Eighty-eight percent of agricultural finance institutions responding to the survey expect the financing needs of their customers to change because of climate change. Agricultural finance institutions can play a critical role in advancing climate-smart agriculture investments by meeting the changing needs of their farmer and rancher borrowers.

Agricultural finance institutions can support more investments in climate-smart agriculture by providing financing solutions including sustainable supply chain finance, sustainable bonds and loans and agricultural lending incentives.[127] The Regenerative Agriculture Financing program launched by Farmers Business Network in 2022 is a leading example of a climate-smart agriculture financing solution. The program includes a 0.5% interest rebate to participating borrowers' farm operating loan if they achieve climate and water quality benchmarks set by EDF. The program provided $25 million in loans in 2022 and plans to provide $50 million in loans in 2023 to support farmers achieve climate and water quality goals.[128]

It is critical for climate-smart agriculture financing solutions, like the Regenerative Agriculture Financing program, to proliferate across the agricultural finance industry to ensure farmers have access to the financing required to adapt to the impacts of climate change. As these types of programs grow, it will also be important for them to incentivize adaptation to water-related risks.

CONCLUSION

Agriculture in the U.S. is susceptible to the dual water stressors of scarcity and excess. Both of these dynamics are worsening because of climate change. The viability of agriculture depends on adapting to mitigate the most significant impacts. The purpose of this report was to broadly characterize water scarcity and excess, identify potential impacts to agriculture and highlight emerging strategies on which EDF is working with partners to support efforts that will help agriculture adapt and become more resilient.

Several key takeaways emerge from this report:

- First, agriculture is foundational to the success of society. Agricultural production provides food security, creating a stable food supply to support the planet's population. In many areas, agriculture is an economic driver, providing employment opportunities and supporting the development of rural communities. Additionally, agriculture has a direct impact on human health through the availability of nutritious foods.
- Second, several natural and human-made conditions create or exacerbate water-related risks to agriculture. Climate change will affect precipitation patterns in myriad ways including more frequent and severe droughts, reduced snowpack and flashier precipitation events likely to cause flooding. Additionally, warming temperatures will increase evaporative demand of crops with more water required to achieve the same yield. Laws and policies in the western U.S. have led to the overallocation and overuse of available water resources, creating competition and conflict between different water users. Vast and complex infrastructure has been designed to adapt to conditions of scarcity and excess, enabling efficient and productive crop production, however not all infrastructure has been implemented in a way that avoids maladaptation.
- Thirdly, water-related risks pose a significant threat to agriculture. Water scarcity negatively affects crop yield, reduces the total acreage available for agricultural production and makes crops more susceptible to pest and disease. Water scarcity also increases the competition between different water users, further confounding and compounding the issue. Water excess also reduces crop yield, reducing the number of acres harvested and the ability of farmers to plant. Water excess can also cause downstream water quality issues through nutrient transport. Many of the risks and threats look similar across different regions—collaboration and shared learning should be pursued to learn adaptation techniques.
- Lastly, new information, technology and partnerships, as well as the spreading of effective traditional approaches, are building momentum towards increasing agriculture resiliency to water-related risks.

The report identifies four areas of opportunity:

- Changing land use and crop management practices to support a transition to an agriculture footprint that can be sustained by the available water supplies;
- Increasing farmer and water manager access to important data and innovative technological tools to support their efforts;
- Reimagining built infrastructure and better utilizing natural infrastructure so regions are better equipped to handle weather extremes;
- Developing policy and funding mechanisms to support mitigation and adaptation to water-related risks, avoid maladaptation and ensure food and water security.

Scarcity and excess are affecting farms and ranches across the Western and Midwestern United States today. From crop damage caused by flooding to curtailment of irrigation due to scarcity, and sometimes both impacts in short succession, there is urgency to expand the toolbox of responses and make them accessible on the ground. EDF is committed to working with producers and partners to do just that.

EDF IS WORKING WITH PARTNERS TO SUPPORT EFFORTS THAT WILL HELP AGRICULTURE ADAPT AND BECOME MORE RESILIENT.

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