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Alleviating Water Scarcity by Optimizing Crop Mixes

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Abstract

Irrigated agriculture dominates freshwater consumption globally, but crop production and farm revenues suffer when water supplies are insufficient to meet irrigation needs. In the United States

(US), the mismatch between irrigation demand and freshwater availability has been exacerbated in recent decades due to recurrent droughts, climate change, and overextraction that dries rivers and depletes aquifers. Yet there has been no spatially detailed assessment of the potential for shifting to new crop mixes to reduce crop water demands and alleviate water shortage risks. Here we combine modelled crop water requirements and detailed agricultural statistics within a national hydrological model to quantify sub-basin-level river depletion, revealing high to severe levels of irrigation scarcity in 30% of sub-basins in the western US, with cattle-feed crops – alfalfa and other hay – being the largest water consumers in 57% of the region’s sub-basins. We also assessed recent trends in irrigation water consumption, crop production, and revenue generation in six high-profile farming areas and find that in recent decades, water consumption has decreased in four of our study areas – a result of reduced irrigated area and shifts in the production of the most water-consumptive crops – even while farm revenues increased. To examine opportunities for crop shifting and fallowing to realize further reductions in water consumption, we performed optimizations on realistic scenarios for modifying crop mixes while sustaining or improving net farm profits, finding that additional water savings of 28-57% are possible across our study areas. These findings demonstrate strong opportunities for economic, food security, and environmental co-benefits in irrigated agriculture and provide both hope and direction to regions struggling with water scarcity around the world.

Introduction

Irrigated agriculture accounts for 88% of all fresh water consumed globally, meaning that seven times more water is consumed on irrigated farms than for all of humanity’s other water uses combined.¹ However, when water supplies become scarce – such as during droughts, or as a result of longer-term climate changes, or due to overextraction that depletes water stored in

aquifers² or reservoirs³ – both crop production and farmer livelihoods can suffer from water shortages.⁴

In many regions, irrigation water shortages result from purely physical reasons, i.e., the volume of water needed is simply not physically available or accessible. The water available to farmers can also be mediated by policy or regulatory actions, such as when a governmental entity imposes restrictions or curtailments on water use in efforts to balance water consumption with available supply and avert a ‘tragedy of the commons.’^{5,6} The vast majority of these governmental controls have been temporary in nature – meaning they are imposed only during drought periods and then removed when water availability increases post-drought – due to political concerns for minimizing economic impacts from water restrictions. In many regions with recurring shortages, there is great interest in implementing more permanent, non-regulatory strategies that can help avoid water-supply interruptions over the long term, such as by permanently reducing irrigation needs to a level more closely balanced with available water supply. This study explores ways to achieve this objective.

Farmers have repeatedly felt the brunt of periods in which water availability could not fully meet water needs. In 2018, more than 13,000 irrigated farms encompassing nearly 623,000 hectares in the US reported interruptions in irrigation supplies that impacted crop yields.⁷ Due to water shortages in 2021 and 2022, farmers in the Central Valley of California –one of the most productive agricultural regions in the world – had their water deliveries cut by 43%, resulting in fallowing of more than 304,000 hectares (10% of farmland), direct economic losses of US\$1.7 billion, and the loss of 12,000 farm jobs.⁸ Farm water deliveries within the Elephant Butte Irrigation District on the Rio Grande in southern New Mexico were reduced by 70% and then completely shut off in June 2021, months before the end of the growing season, when the

district's water-supply reservoir went nearly dry.^{9,10} In the Colorado River Basin, annual water consumption exceeded total river flows during 2000-2020 by 14% on average,¹¹ causing both Lake Mead and Lake Powell – the two largest reservoirs in the US – to drop to three-quarters empty at the end of 2022,¹² triggering regulatory curtailment of water deliveries to many farms in central Arizona.¹³

The overuse of water on farms relative to accessible, renewable water supplies has commonly been accommodated by depleting water stored in aquifers and surface reservoirs, thereby increasing future risks of water shortage. Globally, more than 20% of all crop irrigation is sourced from aquifers that are being unsustainably depleted⁴ due to water consumption exceeding replenishment. The North China Plain – which contributes 40% of China's grain production, including two-thirds of the country's wheat output – is illustrative of the risks associated with over-exploitation of groundwater sources for irrigation.¹⁴ Over the past 60 years, the region's groundwater levels have dropped at an average rate of 0.5–2 meters per year, causing widespread well drying, greatly increased pumping costs, and crop losses.

Heavy use of river supplies also has ecological consequences; recent work has shown that 52% of water consumed from rivers causes unsustainable reductions of environmental flows,¹⁵ thereby compromising ecosystem health. Some of the world's largest rivers – including the Yellow River and Tarim River of China, the Indus of Pakistan and India, and the Rio Grande and Colorado River in the US – have repeatedly dried up along some portion of their length due primarily to excessive irrigation extractions.⁶

Meeting the water needs of farms, cities, and ecosystems has become more challenging in the western US in recent decades due to climate change. Bass and others¹⁶ (2023) estimated that the average flow of the Colorado River decreased by ~10% due to climate warming that caused

increased evaporation of soil moisture and mountain snow cover. Other basins across the western US have been experiencing similar climate-change-induced declines in river flow and aquifer recharge, including the Rio Grande¹⁷ in New Mexico, the San Joaquin River¹⁸ in California, and the Missouri River¹⁹ in the northern Rocky Mountain region. The southwestern region of the country has been most intensely affected, where a 22-year ‘megadrought’ from 2000-2021 has been determined to be the driest in at least 1200 years.²⁰

In response to drying rivers and depleted water storage reservoirs and groundwater aquifers, water regulators are now planning or implementing mandates for reduced agricultural water use. In the headwaters of the Rio Grande, the Colorado state engineer has threatened to shut off 3,000 groundwater wells in the San Luis Valley unless farmers can find some way to recover depleted aquifer levels.^{21,22} In California, a Sustainable Groundwater Management Act²³ passed in 2014 calls for rebalancing of groundwater recharge and pumping by 2042, with potential implications of permanently fallowing nearly 20% of the San Joaquin Valley’s farmland.²⁴ Similar directives have been implemented in Canada,²⁵ the European Union,²⁶ and Australia.²⁷

There is growing acceptance that due to intensifying water scarcity under climate change, irrigated farming cannot continue in its present extent, and the mix of crops being grown in much of the western US must change. Nascent conversations in farming communities are exploring what a transformation of the agricultural landscape might look like.^{28,29,30} Yet a comprehensive and spatially detailed understanding of crop-specific water demands, their contribution to river and groundwater depletion, and opportunities for reducing water consumption by changing crop mixes remain unexplored to date.

In this paper we combine a process-based crop water model, a national hydrological model, and detailed agricultural statistics to identify the specific crops whose irrigation is contributing most strongly to annual water depletion across the western US and highlight the crops that appear most vulnerable to water shortages. We have selected six agriculturally important river basins in the western US that are experiencing irrigation scarcity, for which we document recent multi-decadal trends in water consumption, irrigated acreage, and farming revenues (detailed descriptions of each of our six study areas are provided in our Supplementary Information). We conclude with an assessment of optimized scenarios for minimizing irrigation water consumption in these study areas while sustaining or improving net farm profits, by shifting to less water-consumptive crop mixes including permanent fallowing.

Identifying Irrigation Hotspots

We build on the work of Richter et al.³ by extending our hydrologic simulation period from 1981 to 2019 and integrating new detailed monthly estimates of irrigation use for 30 individual crops (which account for 94% of total US irrigated area and 95% of irrigation water consumption; see Table SI-1). We estimated monthly hydrologic balances using the water supply stress index (WaSSI) ecosystem services model, which can simulate the hydrologic impact of extractions from surface water and groundwater sources separately as well as hydrologic interactions between river flow and groundwater.^{31,32} Richter et al.³ used static irrigation requirements based on annual average crop water requirements from 1996-2005. We have improved upon this approach by estimating crop water requirements at a monthly time step for each month from 1981-2019, which allows us to capture the seasonal and interannual variability of crop water use, facilitating our assessment of trends and changing crop mixes over time.

These estimates of crop water consumption are key input variables to our hydrologic model (see Methods).

We identified ‘irrigation scarcity hotspots’ based on the averaged degree of river flow depletion from all water uses during July-September for the recent period of 2000-2019 (Figure 1). Our sub-basin units are delineated using the eight-digit hydrologic unit code (HUC8) as defined by the US Geological Survey (see Methods).³³ We chose the July-September period to represent the season in which farmers in the US would be experiencing the greatest risk of water scarcity.

We use river depletion as a proxy for irrigation scarcity because nearly 60% of all farm irrigation in the western US depends upon river withdrawals³⁴ and an estimated two-thirds of all groundwater pumping in the region consists of captured river water;^{35,36,37} therefore, on a large majority of irrigated farms in the western US, irrigation is directly or indirectly dependent upon river water.

Our results depict heterogeneous patterns of irrigation scarcity ranging from negligible to severe (Figure 1). Given strong longitudinal gradients in precipitation and use of irrigation across the country, irrigation scarcity is (not surprisingly) far more common in the 17 conterminous western states than in eastern states.

Irrigation’s Influence on Water Scarcity

Irrigated farming is the leading driver of water depletion in the western 17 states within the conterminous US, as it is responsible for 86% of all consumptive water use²⁷ and is the most water-consumptive sector in 82% of all sub-basins in the region (Figure 2a). Cattle-feed crops (alfalfa and other grass hay) account for 21% of total irrigation water consumed in the region

(Table SI-2) and these two crops are the largest consumers of water in 57% of the region's sub-basins (Figure 2b).

Exposure of Food Production to Water Scarcity

Water is a critically important input to farming in the western US, and as such water scarcity can create substantial risk for farmers. We assessed the exposure of individual crops to water scarcity risk by accounting for the area of each crop within the western US that falls into the five depletion categories in Figure 1. We find that almonds, apples, rice, tomatoes, and walnuts are most exposed to 'severe' risk (>75% river depletion in July-September) in our categorization, with more than half of the production of these crops falling into the severe category (Figure 3). These results have strong implications for our San Joaquin River study area (see Figure 1 and Supplementary Information), where on average about 40% of almonds, 33% of tomatoes and 23% of walnuts produced in the US are grown. The contribution of the San Joaquin Valley to US almond production – a crop with high water intensity and exposure to water scarcity – has increased from about 37% in 2000 to about 45% in 2019.

Recent Trends in Crop Mixes, Water Use, and Farm Revenues

We investigated recent agricultural trends, including revenue generation, in six case study regions (Figure 1; see also Supplementary Information) to improve our understanding of changes in the western US farm landscape since 2000, when the current megadrought began to substantially worsen irrigation scarcity. We selected these six regions because water scarcity is stimulating active water policy dialogues and legislative action in each of these areas (as described in more detail in our Supplementary Information); we delineated the boundaries of our study areas to align with the focal geographies of these discussions.

While our study cannot establish water scarcity as the causation of the observed recent trends in water use, crop shifts, or revenue generation in these study regions, we can highlight changes in irrigated farming in recent decades that are beneficial or detrimental in the alleviation of water scarcity. We also note that multiple studies have documented the influence of climate and water scarcity on crop shifting in the United States; some of the climate variables used in these studies – such as the Palmer Drought Severity Index – serve as proxies for water availability.^{38,39,40,41}

One of the most important findings among our case study analyses is a decreasing trend in the total consumption of irrigation water in four of the six study areas during 2000-2019 (Figure 4, Table 1, and Table SI-4): -45% in the Rio Grande; -38% in the Platte River; -33% in the Snake River; and -18% in the Lower Colorado River. Modestly increased irrigation (+0.5%) occurred in both the Great Salt Lake and the San Joaquin River farming areas.

The greatly reduced water consumption (-45%) in the Rio Grande is predominantly explained by reduced irrigated area (-44%), but changes in irrigated area only partially explain water consumption changes in our other study areas (Table 1). The portion of water consumption changes not explained by changes in irrigated area can be attributed to changes in the average irrigation demand (total water consumption divided by irrigated area) for crops grown across the study area. Average irrigation demand is primarily influenced either by changes in the area's crop mix (because different crops have differing irrigation requirements) or changes in the way that water is being applied, e.g., a shift from flood to sprinkler irrigation.⁴² However, we find that changes in crop mixes have had a dominant influence on water consumption trends in our study areas (Figure 5).

In the Platte River area, a reduction in irrigation consumption of -39% was made possible primarily by an overall reduction of 20% in irrigated area and a shift away from corn production (-16%). In the Snake River area, a reduction in irrigation consumption of -33% was made possible by an overall reduction of 16% in irrigated area and a shift away from spring (-43%) and winter (-17%) wheat production. In the Lower Colorado River area, reduced irrigation consumption of -18% was made possible by an overall reduction in irrigated area of -3% and a shift away from durum wheat production (-70%).

In contrast, the Great Salt Lake area experienced a slight increase (+0.5%) in irrigation consumption even though 15% of the area went out of production. This is attributable to increased production of alfalfa (+11%) and other grass hay (+5%), both of which are relatively water-intensive crops. The San Joaquin River area also experienced a modest (+0.5%) increase in irrigation consumption despite a -9% reduction in irrigated area. This is largely explained by an increase in nut production, particularly for almonds (+29%) and walnuts (+57%).

Another important finding is that gross farm revenues increased substantially during 2000-2019 in the four study areas where total water consumption decreased (Figure 4 and Table SI-4): +24% revenue increase in the Rio Grande; +34% in the Lower Colorado River; +55% in the Platte River; and +41% in the Snake River. While net profit is a better measure of farmer prosperity than gross revenues (and we use net profit in our optimization scenarios described later), we were unable to document multi-year trends in net profit because the requisite data on revenues and costs are not available on an annual basis. That said, trends in gross revenues do provide useful indicators of growth or contraction of local and regional farm economies; changes in revenue are typically driven by both changing commodity prices as well as shifts in crop mixes that were quite pronounced in each of our study areas (Figure 5 and Figure SI-1). The

growth in gross revenues during 2000-2019 in four of our study areas occurred despite changes in the crop mix. This is important because farmers will be unlikely to shift to alternate crops if they cannot maintain or improve their net profits. Other studies have found that the ability of US farmers to maintain or improve their crop income was a significant factor in their decision of whether to shift to different crops.⁴³

Optimizing Crop Mixes to Alleviate Water Scarcity

While four of our six study areas have achieved notable reductions in water consumption during recent decades, we sought to explore the potential for further lowering water use by optimizing crop mixes in all study areas. We constructed optimization scenarios focused on the objective of minimizing consumptive water use and constrained our analyses with six HUC-specific conditions: (1) net farm profit within the HUC cannot decrease; (2) substitution crops must have occupied at least 10% of irrigated farm area during 2010-2019; (3) total irrigated area in the HUC cannot increase; (4) crops lacking cost data – i.e., where net profit could not be calculated – were held unchanged in irrigated area; (5) the allowable change in any one crop's irrigated area can range from 5-30%; and (6) allowable fallowing of cropland can range from 0-30%. In estimating net profits, we also considered the financial influence of fallowing payments in three of our six study areas – Rio Grande, San Joaquin River, and the Lower Colorado River – where publicly funded, voluntary fallowing programs presently exist.

We find that maximum water savings of 28-57% across our six study areas are possible when fallowing is integrated into the crop mix (Figure 6). Further, without fallowing, potential water savings from crop shifting can still reach 7-24% across the study areas. The volume of potential water savings at each of our six study areas increases as constraints on fallowing or the allowable reduction in any crop's irrigated area are relaxed (Figure 6 and Tables SI-5 through SI-

11). For example, the potential range of water savings in the Snake River Plain in Idaho increases from only 4% with no fallowing and allowable crop reduction of only 5% to water savings of 45% with 30% fallowing and 30% allowable crop reduction.

When fallowing payments are available to farmers, the potential water savings can increase further because this compensation may enable lower value but less water-consumptive crops to become substitute crops (Figure SI-2). For example, without fallowing payments the maximum potential water savings in the San Joaquin River is 45% (Figure 6) but with inclusion of fallowing payments it rises to 57% (Figure SI-2). However, the fallowing payments must be high enough to compete with the net profits gained from crop production. This explains why we find that potential water savings in the Lower Colorado River do not improve with fallowing payments (comparing Figures 6 and SI-2); in the Lower Colorado, current levels of fallowing payments are insufficient to compete with the net profit potential of the crops being grown there.

The specific conditions that limit the potential benefits (i.e., binding constraints) from optimized crop shifting vary under different scenarios and HUCs. In the more restricted scenarios (e.g., 0% fallowing, 5% change in irrigated area), total fallowing, irrigated area, and total net profit bind in most HUCs; however, as these constraints are relaxed, they bind in fewer HUCs (Tables SI-5 through SI-11). For example, the constraint of "irrigated area" in Great Salt Lake becomes binding in fewer HUCs as the allowable change in irrigated area increases. Compared to scenarios without fallowing payments (Table SI-5 through SI-8), total profit is much less binding in scenarios with fallowing payments (Table SI-9 through SI-11). These findings on binding constraints can help to tailor crop shifting strategies and incentives in specific locations to better ensure an alignment of co-benefits between farmer profit, crop production, and water savings.

The resultant mix of crops and fallowing understandably changes across the ranges of allowable crop-wise reductions and fallowing percentages, but some directional shifts are apparent in our optimization results (Figure 7 and Figures SI-3 through SI-8). Unsurprisingly, the optimizations targeted the most water-consumptive crops in each study area for the greatest reductions in area. Alfalfa was the primary crop selected for areal reductions in four study areas (Great Salt Lake, Lower Colorado River, Rio Grande, and Snake River), with corn and almonds targeted for greatest reductions in the Platte River and San Joaquin River, respectively.

However, during the past two decades the trends in four of our study areas went in the other direction by increasing the area of the most water-consumptive crops; only the Rio Grande and Platte River areas experienced reductions in their thirstiest crop. This is likely explained by the fact that commodity prices for both alfalfa and almonds rose sharply during 2000-2019, with increases of 233% and 372% respectively, enticing farmers to produce more of these crops.⁴⁴

Discussion and Conclusions

While only 16% of all global cropland is irrigated, it accounts for 44% of crop production;⁴⁵ clearly, irrigation is vital to global food and fiber security as well as farmer livelihoods. However, irrigated farming is being increasingly impacted by climate changes that reduce water availability. At the same time, many cities and industries share the same water sources as farmers, and heavy depletion of water sources by irrigation use places their water security at risk as well. As a result, there is great interest in finding ways to reduce farm water consumption while sustaining and growing both rural and urban economies.

Crop shifts beneficial to both alleviating water scarcity and improving net farm revenues have been occurring in many farming areas across the western US, as evidenced by six case studies evaluated here; we documented crop changes on 7-26% of these study areas during 2000-

2019. Total irrigation use decreased in four of our six study areas in recent decades, yet farmers in these areas continue to experience recurring water shortages because farm water use remains too high relative to available supplies when reduced by droughts, climate change, and depleted aquifers and reservoirs.

Our optimization efforts explored ways to reduce irrigation water consumption while sustaining or improving farm revenues in all six areas. The constraints placed on our optimization scenarios are intended to suggest plausibility by limiting alternative crop choices to those already being grown within each HUC, and to minimize supply chain disruptions by limiting the degree to which any individual crop could be replaced or fallowed within a HUC.

Our assessment of the water conservation potential associated with optimized crop shifting reveals that substantial water savings (28-57% across our study areas) can be attained if crop production can transition toward optimal mixes that include fallowing in each farming region. While the specific crop changes that are most important to water savings vary across our study regions, our optimizations targeted the most water-consumptive crops for greatest areal reduction in each study area. Alfalfa is the most prominent target for reduction in four of our six areas; this crop has become dominant across much of the western US (Figure 1b) due to its ability to tolerate variable climate conditions and fix nitrogen in soils, coupled with increasing demand and prices for this feed crop in the growing dairy industry of the region.⁴⁶

It is also important to note that some degree of farmland fallowing will be necessary in maximizing water savings (Figures 6 & 7), although we find that important savings (7-24%) can be realized without fallowing. While the proposition of fallowing some portion of existing farmland typically elicits concern or adverse reactions among both farmers and those concerned about food security and food prices, the reality is that a great deal of fallowing is already taking

place in water-stressed farming regions due to the lack of adequate water supplies. Our survey of six farming areas in the western US reveal that 3-44% of farmland in production in 2000 was not producing in 2019 (Table 1). We assert that planned, intentional fallowing of the least productive farmland, and land that is well suited for low-water demand alternative uses, should be the first to be retired in the future, but this will require active prioritization through land planning and farmland protection in local communities.^{47,48,49} Such prioritization should also carefully consider possible impacts on food prices associated with any reductions in crop production.

We also note that farming areas do not necessarily need to be retired permanently, or even for an entire growing season, to yield important water savings. An increasingly popular approach in the western US is referred to as “split season” fallowing, in which irrigation of certain crops such as alfalfa can be terminated after half of the irrigation season, or during the hottest part of the growing season. This enables the farmer to produce a partial-year crop, while receiving financial incentives for saving water during the remainder of the growing season.

Given serious concerns about windblown and rain-driven erosion as well as potential weed invasions on fallowed farmlands, it will be critically important that fallowed areas are properly revegetated to prevent erosion, ideally with native species that provide wildlife habitat. The federal Conservation Reserve Program pays farmers willing to retire environmentally sensitive agricultural land for 10-15 years, with requirements to revegetate fallowed lands.⁵⁰ Alternative uses of fallowed lands, such as repurposing them for solar or wind production, has been shown to be a lucrative option for farmers due to attractive lease rates paid by energy companies.⁵¹ Emerging programs, including California’s Multi-benefit Land Repurposing Program, offer incentive payments to growers for voluntarily transitioning formerly irrigated farmland to new uses that create environmental and community benefits that use less water.

Full realization of the water-saving potential of crop shifting will almost certainly depend upon being able to provide farmers with financial incentives, market assurances, and technical assistance to foster transitions to alternate crops. While greater profitability associated with some alternate crops may obviate the need for subsidizing farm transitions, most farmers will face formidable obstacles in making crop changes, ranging from lower commodity prices, existing contractual obligations, less certain market conditions for different crops, or needing to install new irrigation equipment or purchase new farm machinery. However, recent work has shown that an ability to modify cropping patterns can be an effective strategy for adapting to climate variability and other environmental shocks;⁵² this adaptability is becoming increasingly important as farmers strive to optimize profits while facing severe water constraints. To help overcome these hurdles and entice crop shifting, both financial incentives and expansion of market potential for substitution crops will be essential in transforming agricultural landscapes in water-stressed regions.

While both state and federal governments will need to think creatively and strategically in funding incentive programs to stimulate crop shifting, some existing programs can be leveraged. For instance, repurposing some portion of the Federal Crop Insurance Program (FCIP) should be given serious consideration. This long-criticized crop support program dissuades farmers from adaptations such as switching to different crops better suited for changing environmental conditions such as climate change and water scarcity.^{53,54} Indeed, numerous recent assessments argue that crop insurance reduces the risk of planting water-intensive crops and has thus contributed to expanded acreage of these crops.⁵⁵ From 1995-2020, the FCIP paid US farmers an average of US\$2.28 billion per year in drought-related indemnity payments or subsidies on crop insurance premiums.⁵⁶ The program's indemnity payouts across all categories

of crop damage have increased nearly six-fold over this time period, largely due to increasing frequency of climate-related disasters.⁴⁶ A modest reallocation of program funds away from disaster compensation toward disaster avoidance – i.e., making cropland less vulnerable to water scarcity through crop shifting – is a sensible national investment in a time of great water urgency.

Methods

The data sources and analytical approaches used in this study are summarized below.

National hydrology model. The WaSSI ecosystem services model was developed by the US Department of Agriculture Forest Service and has been extensively tested using observed streamflow measurements, with excellent predictive performance relative to other continental and basin scale models. WaSSI operates on a monthly time step at the eight-digit hydrologic unit code (HUC8) sub-basin scale.⁵⁷ There are 2,099 HUC8 sub-basins in the conterminous US, each with a mean area of 3,750 km². All WaSSI input data and assumptions used in this study are exactly as described in Richter *et al.* (2020) but we have included updated climate and land use data for an extended period of 1981-2019 as described below, and we use substantially improved estimates of crop water consumption (also described below). An important feature of our hydrologic model is the tracking of surface water flows from upstream to downstream sub-basins within each drainage network. Within each sub-basin, at each monthly time step during our model simulation period of 1981-2019, both water inputs and water consumed by each water-use sector are accounted for; any residual river water is then passed to the next downstream sub-basin. Water inputs to each sub-basin therefore include residual river water inflowing from upstream sub-basin(s) as well as precipitation falling into the sub-basin at each monthly time step. We then calculate a ‘river depletion index’ for each sub-basin for each month of our

hydrologic simulation, based on the relative proportion of total river water available that is consumptively used in each sub-basin. Using this approach, our river depletion index cannot be greater than 100% because at that point the river is completely dry, and the hydrologic model assumes that any water-use demands greater than the water available from the river are met by using other water sources, including deep groundwater or water imported from other basins. While the WaSSI model simulates interactions of surface water with shallow, highly interconnected groundwater, the model does not simulate deeper groundwater use and therefore Figure 1 likely misses some areas of deep aquifer depletion. Farmers with access to both sources will commonly pump groundwater more heavily when surface supplies are scarce.^{58,59} Additionally, due to hydrologic connections between surface water bodies and shallow groundwater,⁶⁰ groundwater depletion is commonly synchronous with surface water depletion. Recent research estimates that half of global groundwater pumping and nearly two-thirds of pumping in the western US is capturing river flows.⁶¹ Further details on model structure and other recent applications in national water accounting can be found in Marston et al.⁶² and Richter et al.³

Climate and land cover data. Monthly total precipitation and monthly mean air temperature data were obtained from the PRISM Climate Group⁶³ for the years 1981 to 2019. The land cover data were downloaded from the National Land Cover Database (NLCD),^{64,65} which provides 30-meter resolution land cover data in the United States. We calculated the percentage of each aggregated land cover type and the proportion of each land cover type that is impervious as input for the WaSSI model. A weighted area average of the portions of grid cells within each HUC8 was used to scale both the climate data and land cover data to the HUC8s.

Crop water consumption. Monthly crop water requirements during 1981-2019 for 13 individual crops, representing 68.8% of total irrigated area in the US in 2019, were estimated using the AquaCrop-OS model (Table SI-1).⁶⁶ For the remaining 17 crops representing about 25.4% of the total irrigated area, we used a simple crop growth model following Marston *et al.*⁶² as crop parameters needed to run AquaCrop-OS were not available. A list of the crops included in this study is shown in Table SI-1. The crop water requirements used in our previous study³ were based on a simplistic crop growth model, often using seasonal crop coefficients whereas we use AquaCrop-OS⁶⁷, a robust crop growth model, to produce more realistic crop growth and crop water estimates for major crops. AquaCrop-OS is an open-source version of the AquaCrop model,⁶⁸ a crop growth model capable of simulating herbaceous crops. Additionally, we leverage detailed local data unique to the US, including planting dates and subcounty irrigated crop areas, to produce estimates at a finer spatial resolution than the previous study. We obtained crop-specific planting dates from USDA⁶⁹ progress data at the state level. For crops that did not have USDA crop progress data, we used data from FAO⁷⁰ and CUP+ model⁷¹ for planting dates. We used climate data (precipitation, minimum and maximum air temperature, reference ET) from gridMET,⁷² soil texture data from ISRIC⁷³ database and crop parameters from AquaCrop-OS to run the model. The modeled crop water requirement was partitioned into blue and green components following the framework from Hoekstra *et al.* (2019),⁷⁴ assuming that blue and green water consumed on a given day is proportional to the amount of green and blue water soil moisture available on that day. When applying a simple crop growth model, daily gridded (2.5 arc minutes) crop-specific evapotranspiration (ET_c) was computed by taking the product of reference evapotranspiration (ET_o) and crop coefficient (K_c), where ET_o was obtained from gridMET. Crop coefficients were calculated using planting dates and crop coefficient curves

from FAO and CUP+ model. Kc was set to zero outside of the growing season. We partitioned the daily ETc into blue and green components by following the methods from Marston et al. (2020)⁷⁵. It is assumed that the crop water demands are met by irrigation whenever it exceeds effective precipitation (the latter calculated using the USDA Soil Conservation Service method (USDA, 1968⁷⁶). We obtained county level harvested area from USDA⁶⁹ and disaggregated to sub-county level using Cropland Data Layer (CDL)⁷⁷ and Landsat-based National Irrigation Dataset (LANID)⁷⁸. The CDL is an annual raster layer that provides crop-specific land cover data, while the LANID provides irrigation status information. The CDL and LANID raster were multiplied and aggregated to 2.5 arc minutes to match the AquaCrop-OS output. We produced a gridded crop area map by using this resulting product as weights to disaggregate county level area. CDL is unavailable before 2008. Therefore, we used land use data from Sohl⁷⁹ in combination with average CDL map and county level harvested area to produce gridded crop harvested area. We computed volumetric water consumption by multiplying the crop water requirement depth by the corresponding crop harvested area. We then used consumption values to estimate water withdrawals by dividing the consumption values by irrigation efficiency for each area. The efficiency values were estimated using county-level data from the US Geological Survey.

Crop revenues and net profits. The revenue generated per hectare of harvested cropland was multiplied by the crop-specific harvested area to calculate the annual crop revenue for each of the six study areas between 1981-2019. The product of county-level, crop-specific yields (tonne/ha)^{80,81} and producer price received (USD/tonne) gave us crop-specific revenue per hectare for each county. For cross-year comparisons, producer prices for each year were converted to a common year (2020) using producer price index for each crop.⁶⁵ The crop revenue

generated per hectare for each HUC8 is the weighted average of the aforementioned county-level values, where each county value is weighted by the relative amount of the HUC8 subregion's irrigated cropland within that county. The net profit for each crop was calculated by subtracting production costs, operating expenses, and interest expenses from the crop revenue generated per hectare. Estimated crop-specific costs per acre are released at the regional or county level by offices of the Cooperative Extension System (CES). Due to the limitation in crop budget data available from New Mexico, information for some of the priority crops had to be supplemented with crop budget data available from other states. While assuming that crop budgets in other states are like those in New Mexico is a potential shortcoming of this study, the extension office in New Mexico provided county-level data for many of the priority crops, including green chile peppers, so the assembled database is as representative as possible. Thus, crop budget data was compiled for eight states: Arizona;^{82,83,84,85} California;⁸⁶ Colorado;^{87,88} Idaho;⁸⁹ Nebraska;⁹⁰ New Mexico;⁹¹ Utah;⁹² and Wyoming.⁹³ Since the number of reported crop budgets varies from state to state, additional crop-specific cost data was obtained at the regional level from the USDA's Economic Research Service.⁹⁴ Furthermore, the costs associated with sugarcane and pecans had to be estimated using data available from Louisiana⁹⁵ and Georgia,⁹⁶ respectively. When including fallowing payments as net profit for three of our study areas, we used publicized payment levels for the Lower Colorado River,⁹⁷ Rio Grande,⁹⁸ and San Joaquin River.⁹⁹

Trends and Significance. Trends (Sen's slope) and their significance (Mann Kendall test) were calculated for each of our study areas, for both total water consumption and net farm revenues over the period 2000-2019. The function `bbsmk()` from the R package `modifiedmk`¹⁰⁰ was used to perform the Nonparametric Block Bootstrapped Mann-Kendall Trend Test in order to account for the potential significant serial correlation present in the time series data.

Crop mix optimization. Optimizations were performed on six selected case study areas to determine the extent to which crop switching could reduce water consumption. Using HUC8s as the unit of analysis, we reallocated irrigated areas between crops in order to minimize blue water demand for each entire case study basin with the constraints that (1) the total net profit of each HUC could not decrease, (2) irrigated area within each HUC could not increase, and (3) only crops that have been planted in a HUC within the last ten years and occupied more than 10% of that HUC's irrigated area were considered as a substitute within each HUC. Allowable changes in any individual crop were limited to 5-30% and allowable fallowing ranged from 0-30%. Crops lacking cost data were held unchanged. Any costs associated with switching to other crops, such as necessary changes in farm planting and harvesting equipment or irrigation infrastructure, are not accounted for in the optimization analysis but are acknowledged under in the Discussion and Conclusions. The optimizations were performed using the "lpSolve" package in R. The specific conditions that limit the potential benefits (i.e., binding constraints) from optimized crop shifting vary under different scenarios and HUCs. In the more restricted scenarios (e.g., 0% fallowing, 5% change in irrigated area), total fallowing, irrigated area, and total net profit bind in most HUCs; however, as these constraints are relaxed, they bind in fewer HUCs (Tables SI-5 through SI-11). For example, the constraint of "irrigated area" in Great Salt Lake becomes binding in fewer HUCs as the allowable change in irrigated area increases. Compared to scenarios without fallowing payments (Table SI5-8), total profit is much less binding in scenarios with fallowing payments (Table SI-9-11). These findings on binding constraints can help to tailor crop shifting strategies and incentives in specific locations to better ensure an alignment of co-benefits between farmer profit, crop production, and water savings.

Data Availability

All data assembled or analyzed for this study are available from the corresponding author

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Author Contributions

BDR designed the study and served as lead author of the manuscript. YA, GL, DW, and MA provided data gathering, data analysis, and editing of the manuscript. LM and KFD helped design the study, supervised data analysis, and edited the manuscript.

Competing Interests Statement

The authors declare no competing interests.

Tables

Table 1. Summary of trends during 2000-2019. Average irrigation demand is calculated by dividing water consumption by irrigated area.

Case Study Area	Change in Irrigated Area	Change in Irrigation Consumption	Change in Average Irrigation Demand
Great Salt Lake	-15%	+0.5%	+18%
Lower Colorado River	-3%	-18%	-15%

Platte River	-20%	-39%	-23%
Rio Grande	-44%	-45%	-1%
San Joaquin River	-9%	+0.5%	+10%
Snake River	-16%	-33%	-19%

Figure Captions

Figure 1. Summer (July-September) river depletion across the US. River flow depletion, representing the proportion (%) of average river flow that is consumptively used, is ubiquitous in the western US due to lesser precipitation and greater use of irrigation in farming. Depletion percentages are based on July-September during 2000-2019. Six case study areas examined in this study are outlined in black. Detailed descriptions of each study area are provided in Supplementary Information. Sub-basin units depicted here are based on eight-digit hydrologic unit codes (HUC8s) as defined by the US Geological Survey.

Figure 2. Water demands for irrigation during 1981-2019. (a) The proportion of total consumptive water use attributable to crop irrigation in each sub-basin; and (b) the most water-consumptive crop in each sub-basin.

Figure 3. Exposure of individual crops to water scarcity risk in the western US. The crops most exposed to severe water scarcity (>75% summer depletion) include almonds, apples, rice, tomatoes, and walnuts.

Figure 4. Historical shifts in irrigation consumption and gross revenue. Changes in total consumptive use of irrigation water (bars) and gross farm revenues (lines) for 2000-2019 are shown for each of six case study areas. Water use is based on estimates of water consumption for all crops grown within the study area boundaries described in Table SI-3. Gross revenue is adjusted to 2020 dollars.

Figure 5. Historical shifts in crop-specific water consumption. Changes in irrigation consumption during 1981-2019 for each of the top five most water-consumptive crops is shown for each of six case study areas.

Figure 6. Water savings from optimized cropping mixes. Potential water savings from optimized crop shifting varies across the six case study areas examined. In each case, water savings increase as the allowable percentage of crop replacement increases (see x-axis) or the allowable area of fallowing increases (see graph titles). The objective of all optimizations is to minimize irrigation water consumption across each study area while maintaining or increasing net farmer profits in each HUC. (a) Water savings with no fallowing; (b) water savings with up to 10% fallowing; (c) water savings with up to 20% fallowing; and (d) water savings with up to 30% fallowing.

Figure 7. Optimized cropping mixes when fallowing of 30% is allowed. Histograms of crop mixes illustrate crop shifting among the most prominent crops in each case study area. Alfalfa is reduced in five of the six study areas (all but San Joaquin) due to its high volume of water consumption. All optimizations maintain or increase net farm profit in each HUC. Percentages shown on x-axis represent the proportion to which any single crop can be reduced in each HUC.

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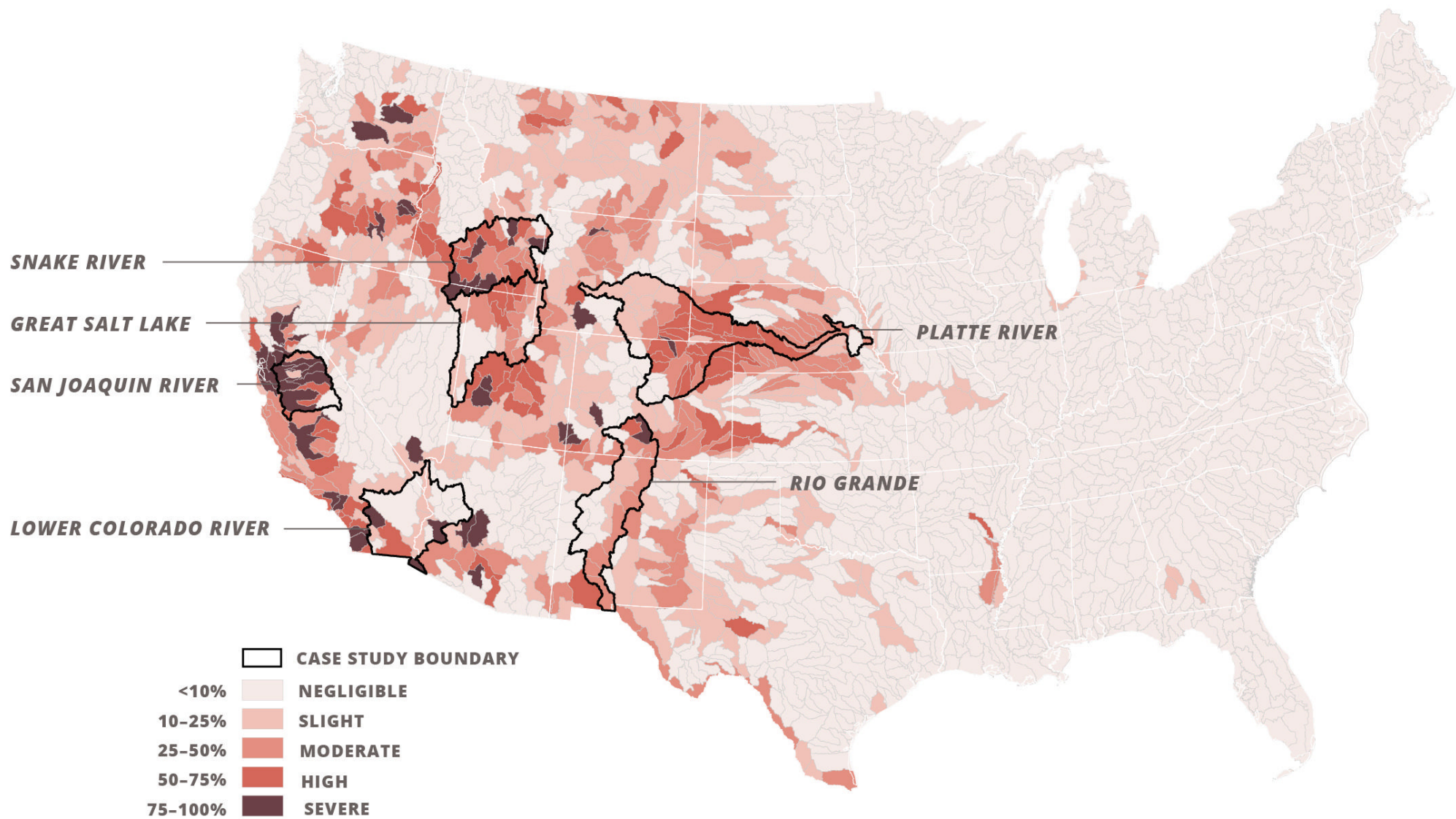
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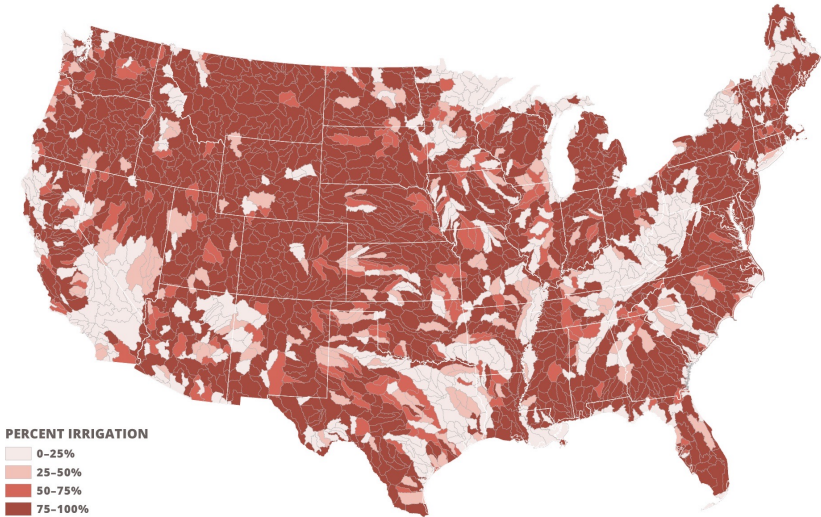
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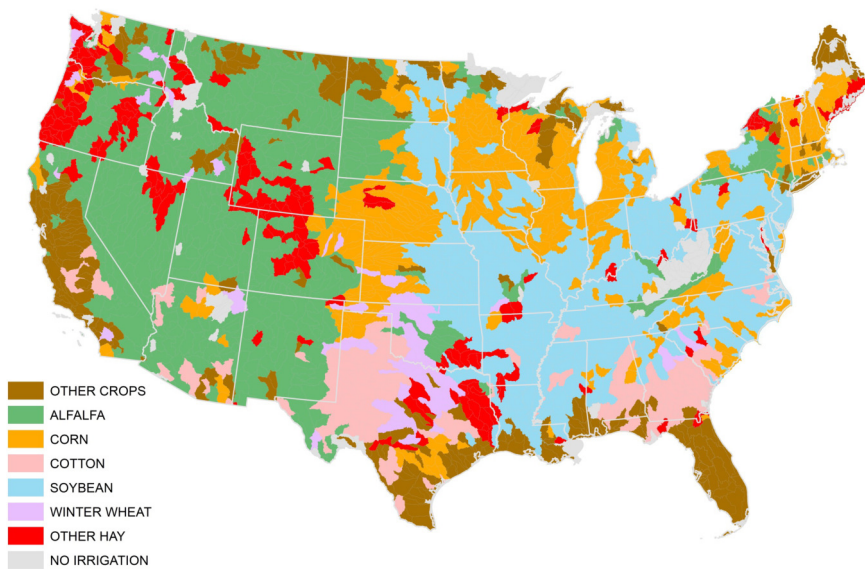
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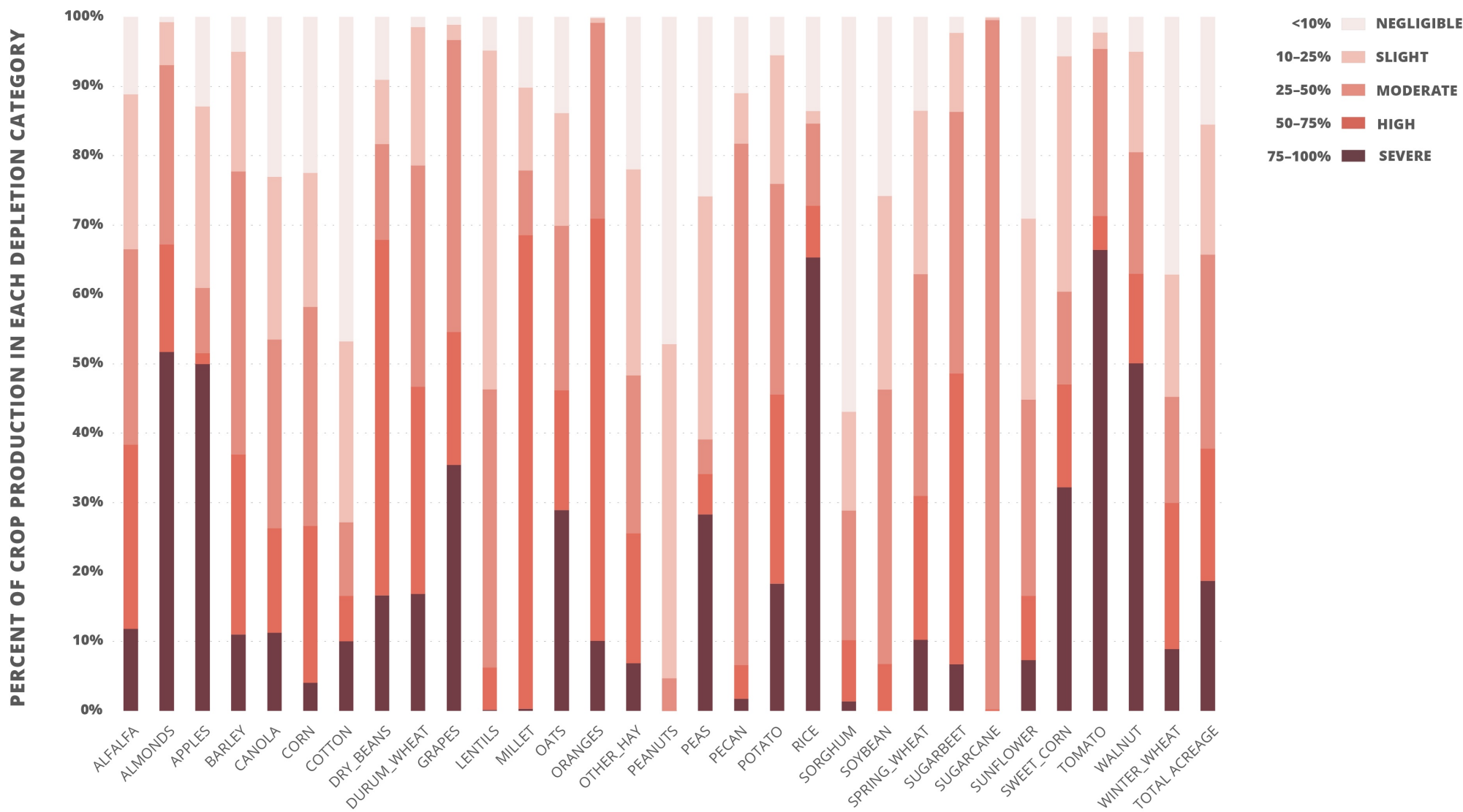




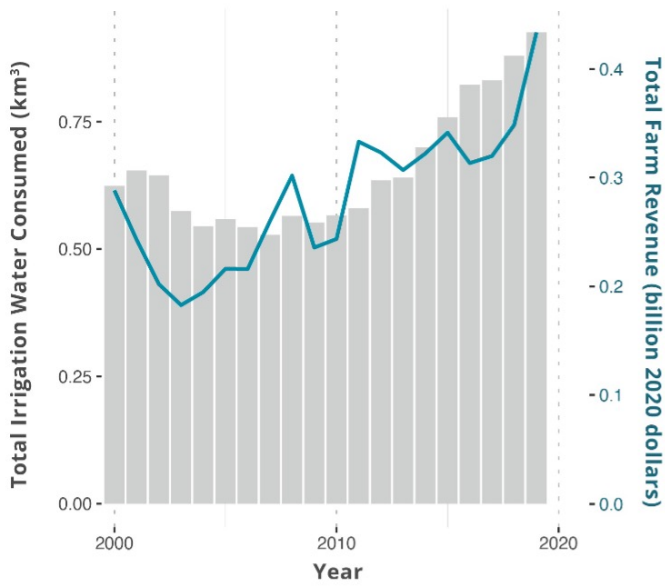
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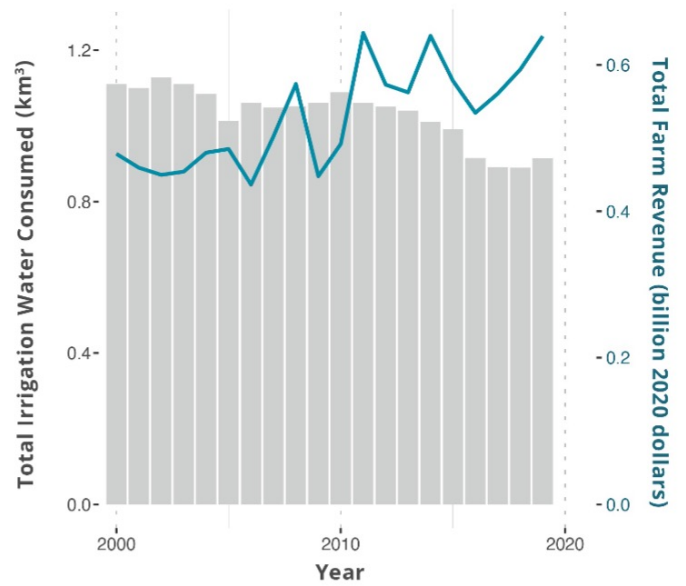
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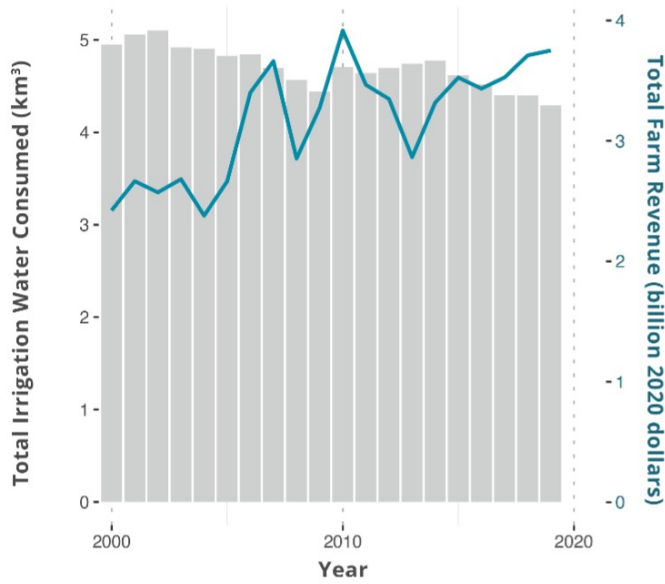
GREAT SALT LAKE



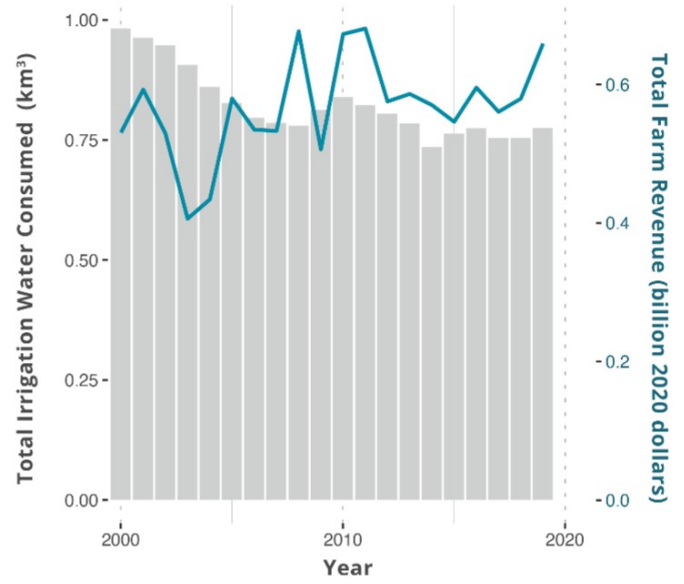
LOWER COLORADO RIVER



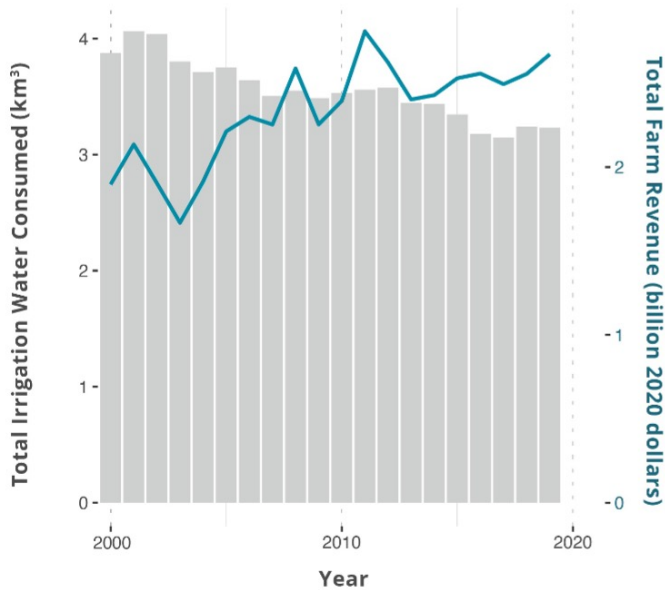
PLATTE RIVER



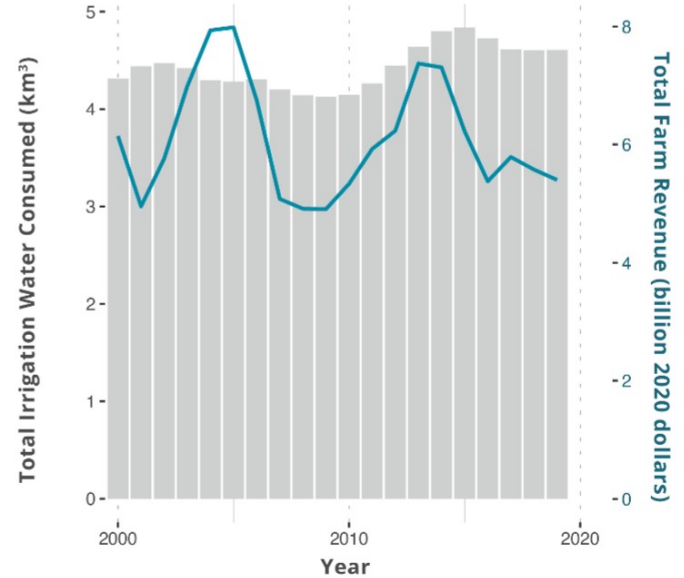
RIO GRANDE



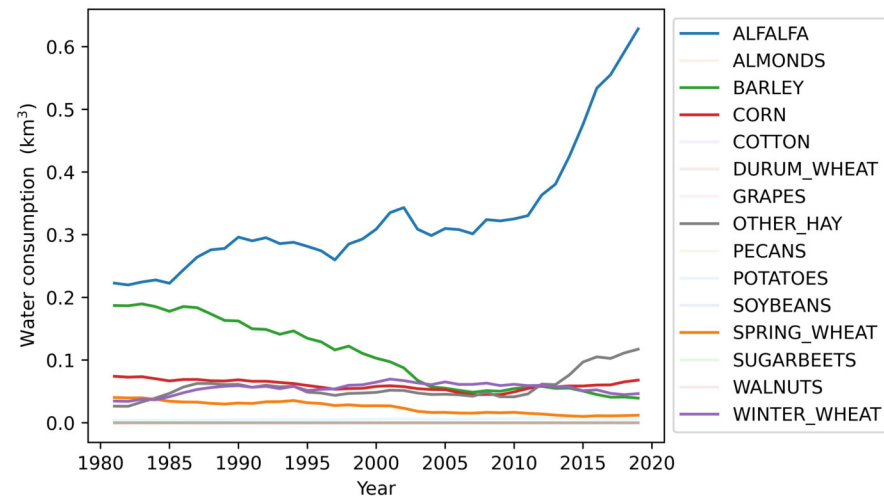
SNAKE RIVER



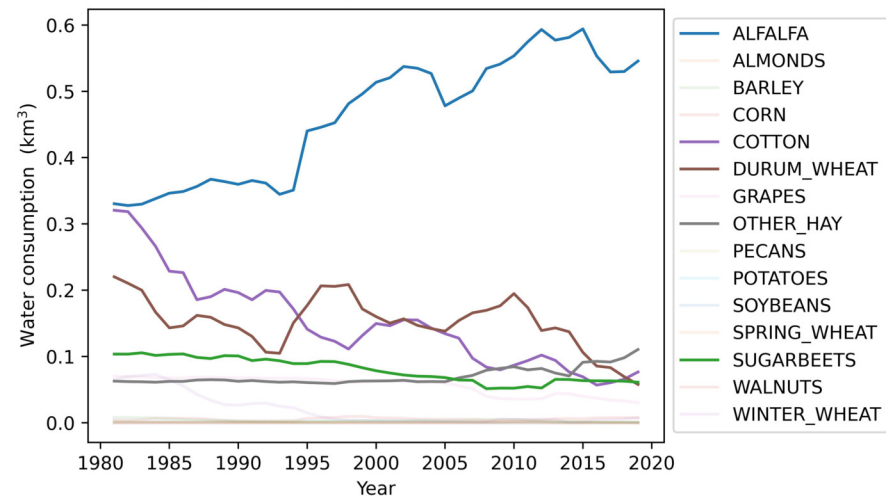
SAN JOAQUIN RIVER



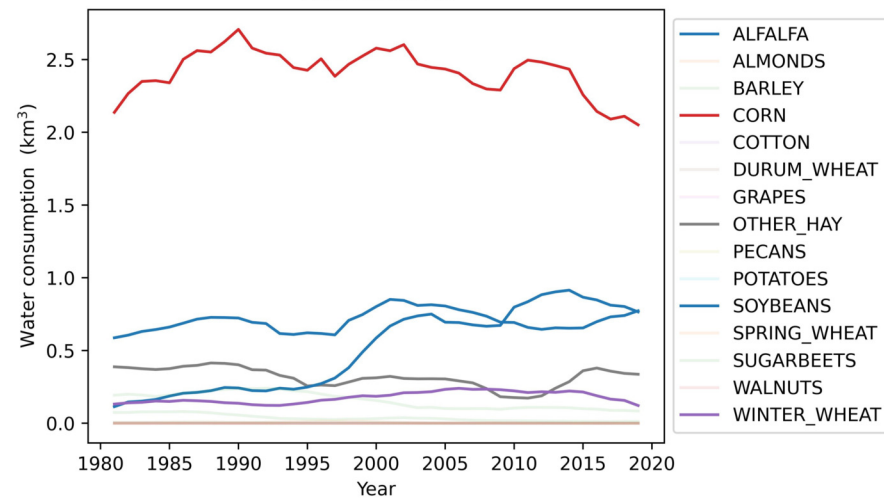
GREAT SALT LAKE



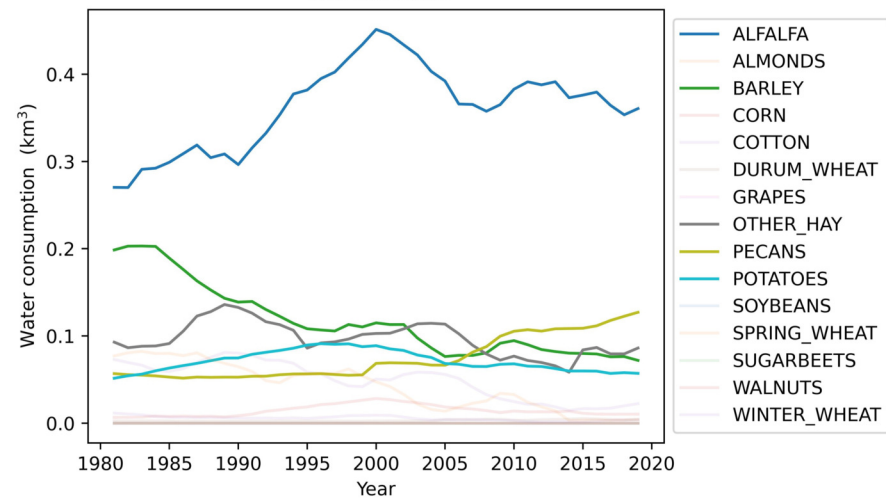
LOWER COLORADO-IMPERIAL VALLEY



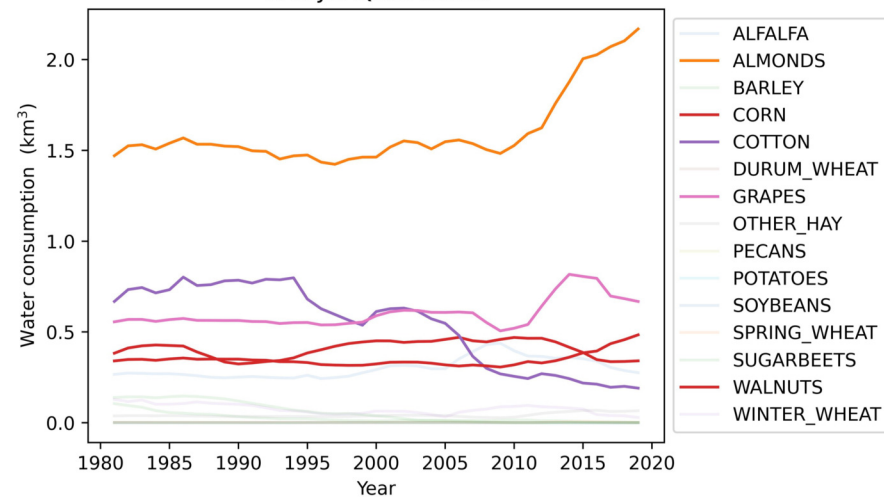
PLATTE RIVER



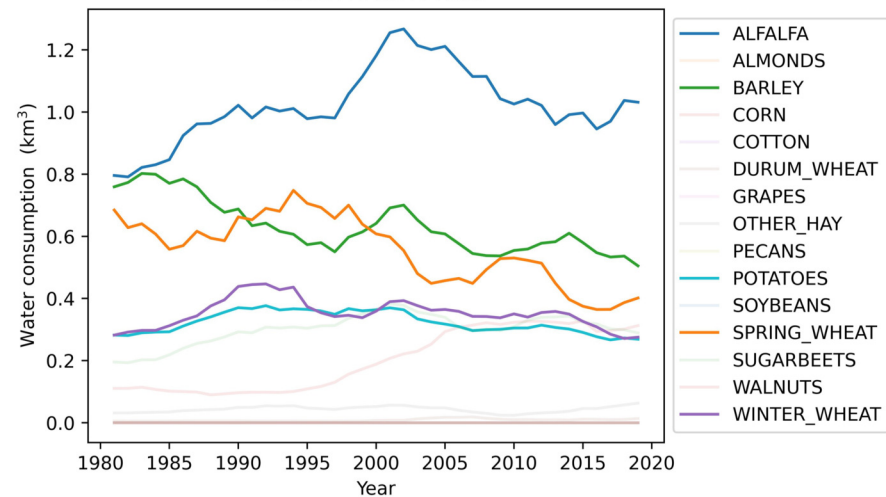
RIO GRANDE



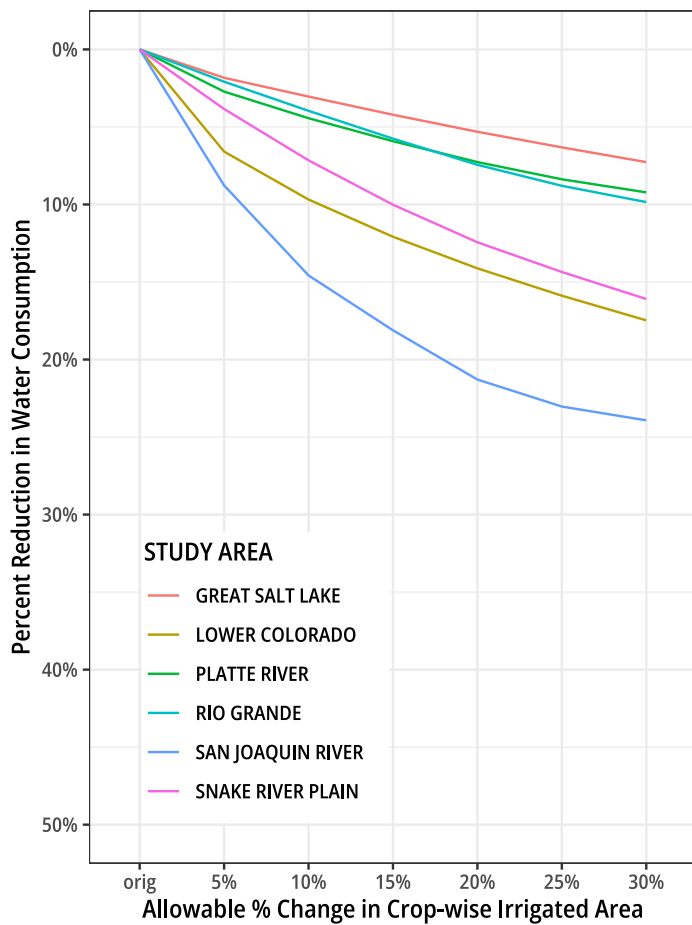
SAN JOAQUIN RIVER



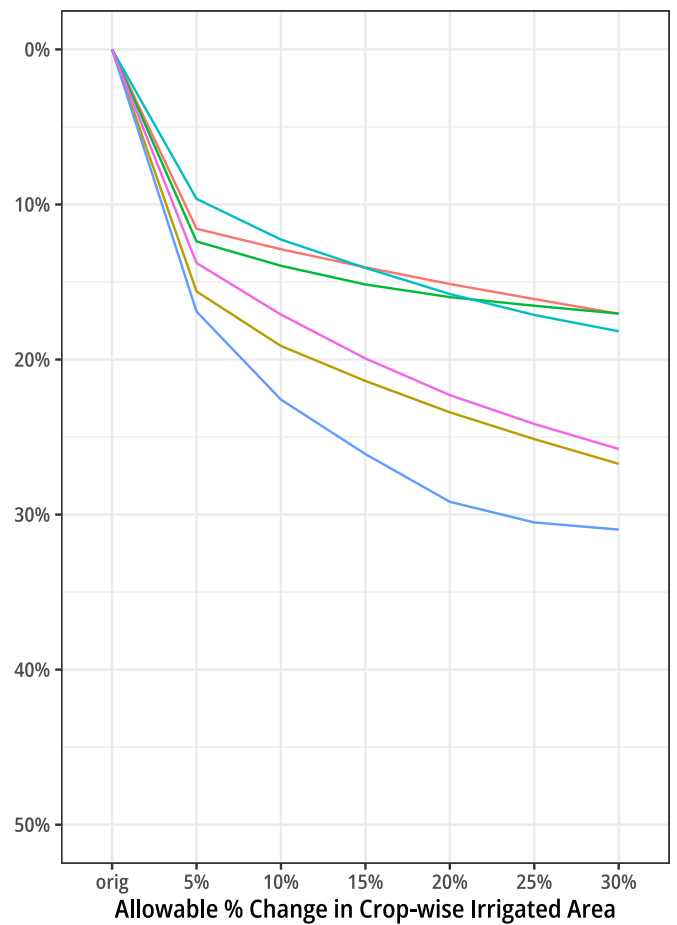
SNAKE RIVER PLAIN



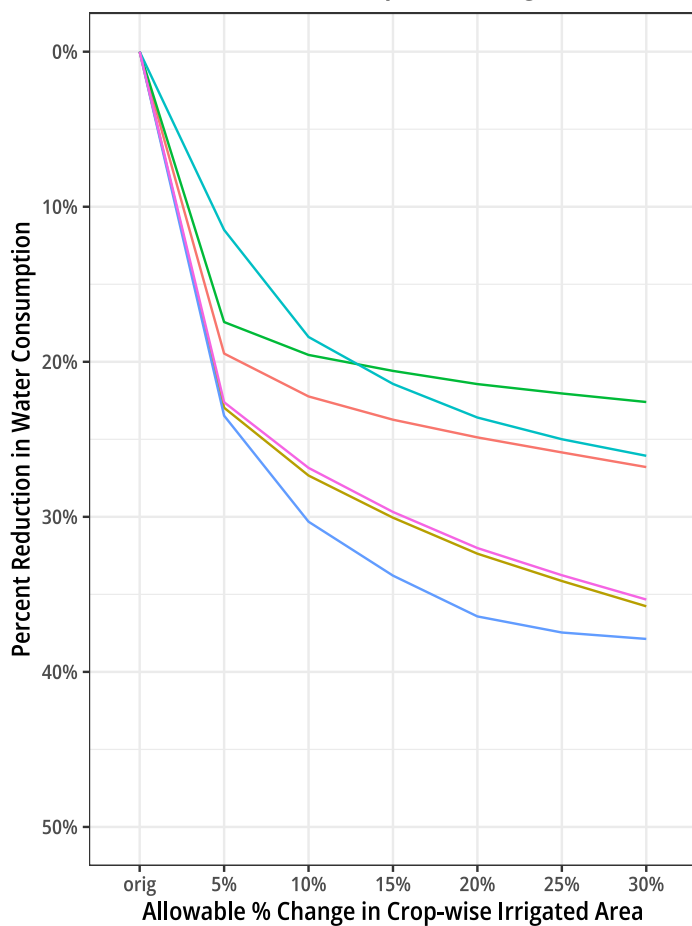
(a) Total Water Consumption Change, No Following



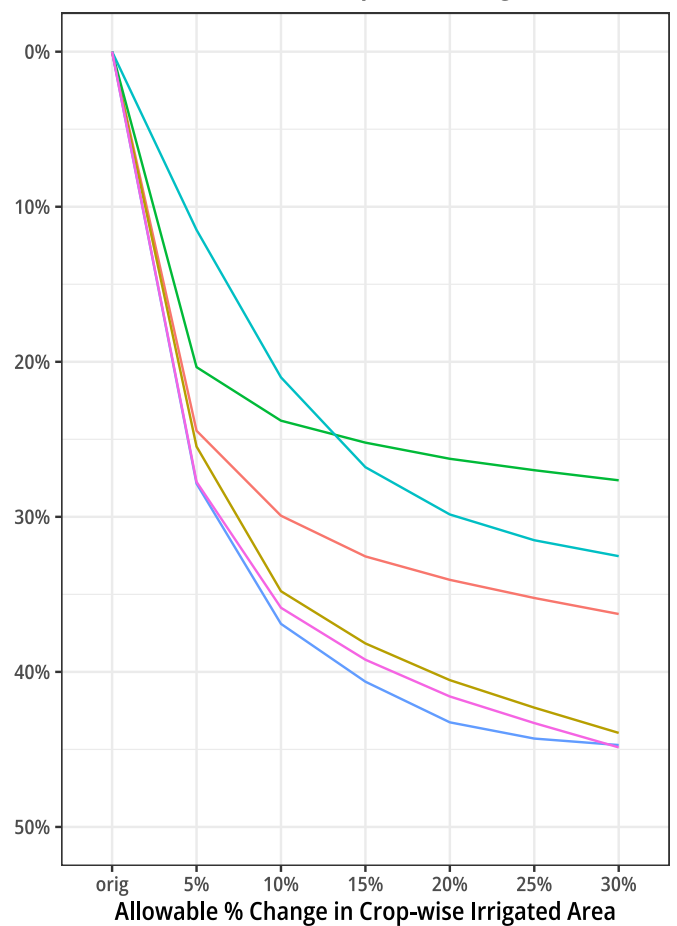
(b) Total Water Consumption Change, Fallow < 10%



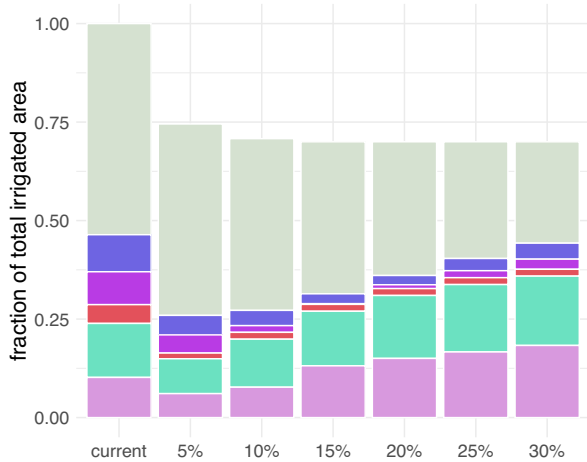
(c) Total Water Consumption Change, Fallow < 20%



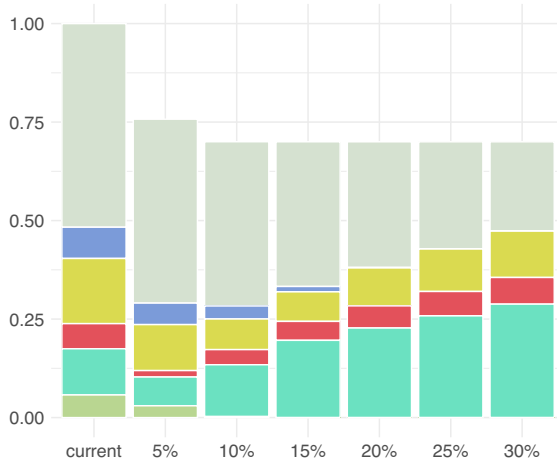
(d) Total Water Consumption Change, Fallow < 30%



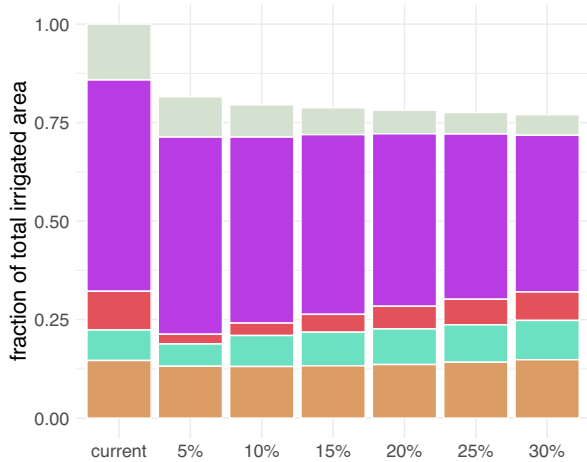
Great Salt Lake



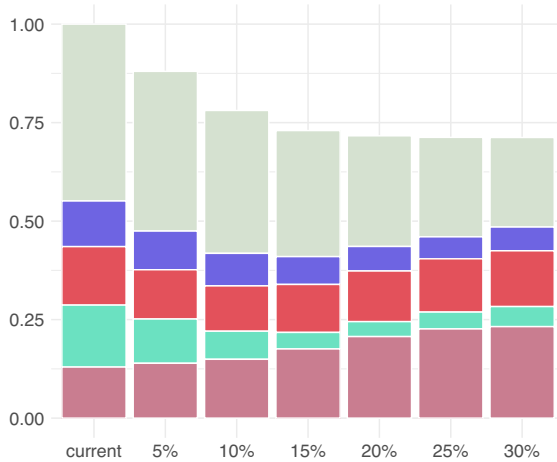
Lower Colorado River



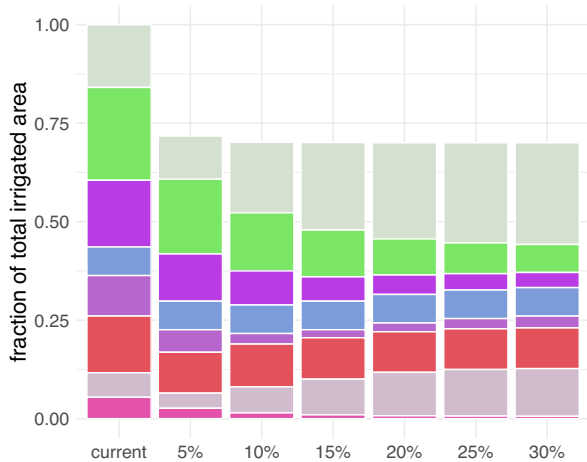
Platte River



Rio Grande



San Joaquin River



Snake River Plain

