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Abstract

WATER RISK HOTSPOTS FOR AGRICULTURE:
THE CASE OF THE SOUTHWEST UNITED STATES

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This report analyses trends in agriculture for the US Southwest region, one of the most water stressed and productive agricultural regions in the world expected to face further water shortages in the future due to climate change and continued growth. It examines projected water risks by mid-century without additional policy action, and discusses the expected implications for the agriculture sector, based on a review of existing data and available publications. The region will likely continue to be a major agricultural producer by mid-century but will be affected by more variable and uncertain water supplies and increased water demand. Irrigated area is likely to decline, with lower value, water-intensive field and forage crops experiencing the greatest losses. Livestock and dairy are also especially vulnerable to water shortages and climate change. Trade and employment may be affected, although projections remain uncertain. Policy options can help mitigate these projected water risks, such as agricultural and urban water efficiency improvements, refined groundwater management, investment in water banks and recycled wastewater systems, and well-defined water transfers.

Keywords: Agriculture and water risks, water competition, climate change, drought, California, Colorado River Basin, US Southwest

JEL: Q15, Q25, Q28, Q54

Acknowledgments

This paper was written by Heather Cooley, Michael Cohen, Rapichan Phurisamban, Pacific Institute, Oakland, California, and by Guillaume Gruère OECD, Paris. The authors acknowledge the valuable references and information provided by OECD delegations, especially the United States Department of Agriculture. The authors also wish to thank Kathleen Dominique, Franck Jésus, Rachel Bae, Carmel Cahill and Robert Akam for their comments on successive versions of the paper. They are grateful to Michèle Patterson for preparing this document for publication.

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EXECUTIVE SUMMARY

Despite being the United States' most arid region, the US Southwest – defined here as Arizona, California, Colorado, Nevada, New Mexico, and Utah – is one of the most productive agricultural regions in the world. Nearly 75% of total cropland in the region, and an even higher percentage of total agricultural productivity, depends on supplemental irrigation. The sector accounts for 70% of total freshwater withdrawals, which are supplied via a vast and largely integrated water infrastructure network.

Climate change and increased water demand are putting pressure on the Southwest's limited water supplies and raising concerns about the viability of agriculture in the region. The region is already prone to multi-year droughts, with wide ranging impacts, including on its agricultural sector. Across the Southwest, drought and its impacts have been exacerbated by growing water scarcity, whereby human demand for water has grown to exceed the volumes that can be extracted sustainably from surface waters and groundwater. Climate change will amplify the variability and uncertainty of water supplies and demand. At the same time, the region is expected to experience continued growth of its population, exerting pressure on land and water resources.

The report finds that while the region will likely continue to be a major agricultural producer for the next 50 years, it will be impacted by more variable and uncertain water supplies and increased water demand. This conclusion is reached by analysing trends in agriculture for the US Southwest region, examining projected future water risks by mid-century without additional policy action, and discussing the expected implications for the agriculture sector. This analysis is based on existing data and available publications.

Production will likely take place on a smaller land area due to limits on water supplies and urban encroachment. Total irrigated area is likely to decline, with lower value, water-intensive field and forage crops likely to experience the greatest reductions. Shifting to higher value crops, such as specialty crops, provides one mechanism to reduce the economic and employment impacts of reductions in irrigated area and keep agricultural land in production. However, some tree crops are especially vulnerable to climate change because of the resulting warmer temperatures and impacts on winter chill.

Different agricultural activities may need to be introduced, and some activities will be impacted more than others. Livestock and dairy, which are economically important to Southwest agriculture, are especially vulnerable to water shortages and climate change. Feed prices are likely to rise, thereby increasing costs for producers. Additionally, climate change is likely to alter the location and productivity of pasture and rangeland, the distribution of livestock parasites and pathogens, and the thermal environment of animals.

Trade and employment may also be affected, although projections remain uncertain. Given California's importance on the US and world markets, it is likely that shifts in production could have an impact outside of the region. On the other hand, it is uncertain whether employment will be affected. As has been seen in California during the current drought, shifting activities can minimize or even eliminate employment losses associated with reductions in cropland area. It is important to note, however, that these changes will likely not be uniform, and some areas will be more resilient than others.

These projected changes will be less disruptive if meaningful steps are taken to mitigate economic losses, protect ecosystems, and invest in productive strategies. Several options can

contribute to reduce water shortage risks for agriculture in the regions. Increasing urban water-use efficiency reduces pressure to take water from agriculture, while agricultural water-use efficiency can help maximize the productivity of limited water resources. Shifting from higher water-use to lower water-use crops, such as from forage crops to small grains or truck crops, can keep agricultural land in production with less total water demand. Groundwater can play a key role to increase agriculture's resiliency to future climatic changes; improving groundwater management and developing water banks can reduce vulnerability to more variable surface water supplies. As a complement, the use of recycled wastewater could be expanded, especially close to urban areas. Lastly, water transfers can also play a role, although they must be conducted within a clearly defined system, have explicit goals, and acknowledge and adequately mitigate possible adverse impacts.

Introduction

The Southwest United States – defined here as Arizona, California, Colorado, Nevada, New Mexico, and Utah – is a rapidly growing region that faces major water challenges. It has the fastest-growing population and one of the most economically productive regions of the United States. It is also the most arid region and is prone to long-term droughts. These dry conditions, combined with a water allocation system based on prior appropriation — whereby the "first in time" is the "first in line" to access water[1] — generate tension between stable or declining sectors of the economy that hold the majority of the rights to water and the fast-growing sectors of the economy that have more limited water rights. The Southwest provides a case study of the challenges posed by limited water availability and some of the successful methods used to bridge the gap between water supply and demand.

Agricultural production in the Southwest United States, which generates USD 72 billion per year in revenue or 17% of the US agricultural sales (BEA, 2015), relies heavily on irrigation. Most of the prime agricultural areas in the region receive supplemental irrigation to make the land viable for crop and livestock production. This irrigated land extends some 5.3 million hectares (ha) across the region; even if this represents only 29% of total agricultural land, it accounts for over 78% of total cropland (USDA-NASS, 2014a). While actual water use remains largely unknown due to a lack of consistent measurement and reporting, it is estimated that agriculture used 62 km^3 of water in 2010, which represents 70% of the Southwest's total freshwater withdrawals (Maupin et al., 2014).

Yet, even this large volume of water is insufficient to meet the total demand for irrigation in the region, as shown by various estimates of agricultural water shortages in Colorado and Utah (Figure 1). In Arizona, California, and Nevada, continued consumptive use of Colorado River water in excess of normal-year supply, exacerbated by a 16-year drought in the basin, has caused the elevation of Lake Mead to fall by more than 40 meters and system storage to decline by almost 50%, increasing the probability of shortage for Arizona, Nevada, and Mexico to more than 50% in 2018.

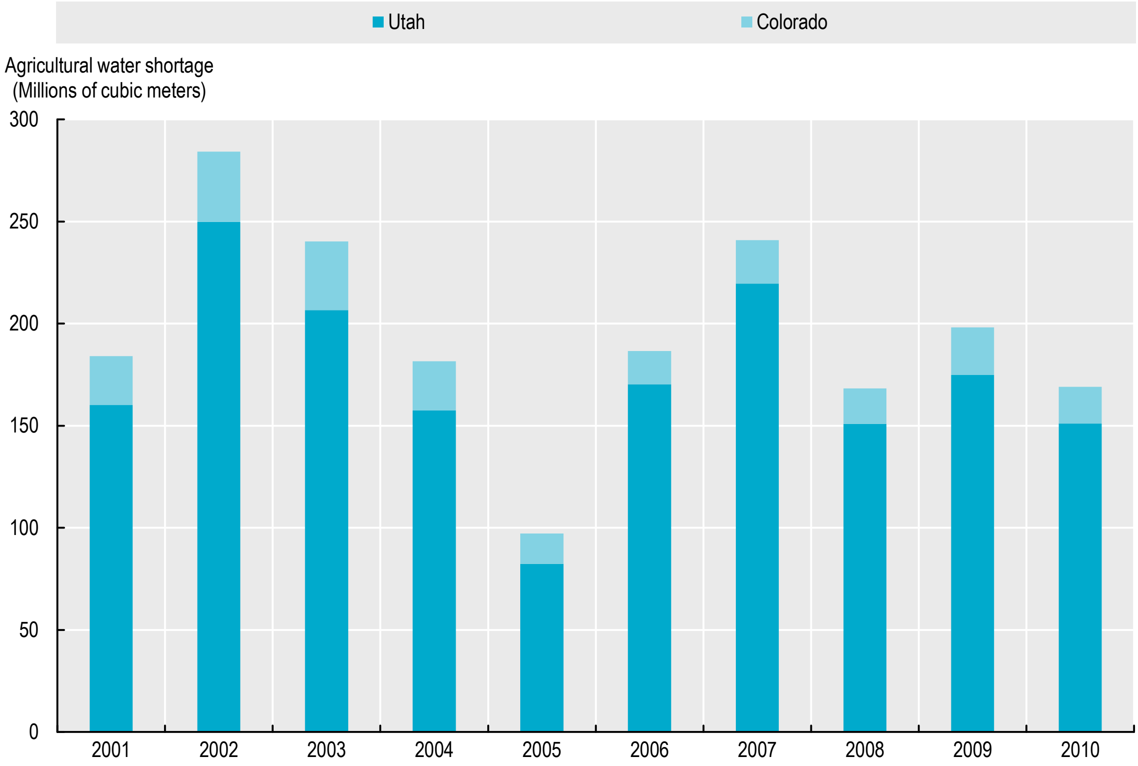
Evidence of the overuse of water resources[2] can be found across the Southwest. For example, the Colorado River – a vital water source for the region – has not flowed regularly into the Sea of Cortez for more than 50 years. In California, recent data show that the Sacramento and San Joaquin River basins collectively lost nearly 31 km^3 of groundwater between October 2003 and March 2010, or about 4.8 km^3 per year (Famiglietti, 2011), as irrigators ran their pumps to supplement insufficient surface water supplies. Such intensive use has not only resulted in dropping water tables but also generated multiple negative environmental externalities (Phillips et al., 2015).

Continued population growth puts additional pressure on the region's limited water resources. The Southwest has the fastest growing population in the United States. Between 2000 and 2010, the region added more than 6.8 million people, an increase of 14%; in comparison, the US population increased by 10% during this period (US Census, 2012). By 2030, the region is projected to add an additional 23 million people, bringing the regional population to 73 million, which is 48% higher than 2000 levels (US Census, 2005). However, cities throughout the Southwest have demonstrated a remarkable ability to decouple water demand from population growth: many cities and regions use less total water now than they did 20 and 30 years ago, despite adding millions of people overall (Cohen, 2011).

1. More specifically, prior appropriation can be defined as "a legal doctrine where the interests of the first person in time to take a quantity of water from a water source for a beneficial (agricultural, industrial and household) use has the right to continue to use that quantity of water for the same or similar purposes" (OECD, 2015c).

2. In this context, overuse can be defined as water demand exceeding the quantity available to provide, for example, regular environmental flows.

Figure 1. Total demand for irrigation water exceeds available supplies in Colorado and Utah



Note: Data for 2011-2013 are provisional.

Source: USBR (2015).

Limited water supplies and the growing demand for the resource are challenging historical water users' rights in the Southwest. Irrigators were among the first historically to divert and put water to beneficial use, securing legal rights to the use of that water under a system known as "prior appropriation." Under prior appropriation, the first person to divert and put a quantity of water to "beneficial use" is entitled to that quantity of water before any subsequent diverter can be satisfied, even if more junior rights-holders receive no water at all (Hundley, 1975 and 1986). Beneficial use was equated with economic development; water left instream was considered "wasted water" and subject to diversion by any entity that would put it to good use (Bates et al., 1993). The precedence of time over other possible criteria encouraged potential water users to stake a claim to as much water as they could divert, as quickly as possible, so that older users, such as agricultural irrigators, now have larger and more senior rights than users whose demands have grown more recently. With some of the oldest and largest water rights in the basin, irrigators face increasing pressure from urban interests to sell or relinquish some of these water rights.

Additionally, there is growing pressure to maintain and even increase instream flows to protect freshwater ecosystems and threatened and endangered species. In the Southwest, every state except New Mexico has recognized instream flow rights, or the ability to dedicate specific volumes of water to flow within a stream, to protect seasonal or minimum instream flow rates (Boyd, 2003). Several states have also recognized instream flow rights for recreational purposes, such as whitewater kayak courses. As climate change alters the volume and timing of spring runoff, the risk of extinction or extirpation rises for many aquatic and riparian species. Purchasing and dedicating water for instream flows can help mitigate these ecological risks, while increasing pressure on existing off-stream uses.

Climate change will make balancing water supply and demand even more challenging. Temperatures are projected to increase across the region (Cayan et al., 2013), increasing water demand for agriculture and urban outdoor uses, reducing snowpack, and altering the timing of runoff. Uncertainty is high for expected changes in precipitation, climate models suggest that precipitation will decline in the southern portions of the region and experience little change or a slight increase in the northern portions of the Southwest (Cayan et al., 2013). Additionally, floods and droughts are projected to become more frequent and intense (Gershunov et al., 2013). The Colorado River provides water, at least in part, to all Southwest states. Studies suggest that annual Colorado River runoff could decrease by an average of 9% (USBR, 2012a) to 19% or more (Ficklin et al., 2013) by mid-century, posing additional challenges to meeting demands in an already over-allocated system.

Applying a water hotspot analysis to assess implications of water overuse

The US Southwest region can be characterised as a future global water risk hotspot for agricultural production.[3] Hotspots are here defined as specific locations (regions) that are most likely to be subject to agricultural water risks in the future, because they are or will be significant agricultural producing regions and because they also are expected to be under water constraints. Practically speaking water shortage risks[4] occurs when shortages are likely in the future and that they can result in observable impacts. Hotspot regions like the US Southwest combine large likelihood of water shortages and potentially large impact on a globally significant agriculture sector.

This report reviews the evidence on regional agriculture water risks and further qualifies the risks for agriculture in the region under no additional policy action. It first reviews trends in agriculture for the US Southwest, examines water supply-demand gaps for agriculture in the region by mid-century and discusses the expected implications on agriculture, trade, and food security if no action is taken. The report concludes with a discussion of some of the key adaptation responses.

The information presented in this report was drawn from (1) available data on land and water use and farm income and (2) a review of the academic literature. However, much of the literature focuses on impacts on crop area and agricultural revenue, with only limited information about impacts on employment, trade, and food security. Furthermore, there is insufficient information about the likelihood of shortages to propose a full risk assessment; instead key trends are evaluated to propose elements to characterise the risks. An additional caveat is that the assessment focuses on water supply, rather than water quality, because the former currently poses a greater risk for agriculture in the Southwest United States.

3. Analysis conducted at the OECD, to be published in 2017, has identified the US Southwest as a water risk hotspot region for agriculture

4. In the context of water shortages, water risk can be defined as the "risks of insufficient water to meet demand" (OECD, 2013).

1. Trends in Southwest agriculture: Falling irrigated crop area and water use but rising farm income and foreign exports

This section reviews the main trends in Southwest agriculture in the recent past, with agriculture becoming less water intensive and value oriented in the presence of increasing water stresses. Persistent drought conditions have affected much of the Southwest since the early 2000s (Woodhouse et al., 2010; NOAA, 2004). At the same time agriculture reduced its irrigation area, while increasing its overall water use and revenues.

Irrigation central to cropland farming

Most of the prime agricultural areas in the Southwest receive supplemental water to make the land viable for crop production. In 2013, Southwest farms irrigated 4.8 million hectares of cropland, or 78% of the total cropland in the region (USDA-NASS, 2014a). Of all Southwestern states, California had the largest crop area under irrigation in 2013 (2.9 million hectares) and the largest proportion (94%) of cropland irrigated (Table 1). Colorado also had large expanses of irrigated cropland, although of all the states in the Southwest, it had the highest proportion of rain-fed cropland. The remaining Southwestern states had much less cropland, although, with the exception of New Mexico, they were heavily dependent on irrigation.

Table 1. Agriculture in the US Southwest is largely dependent on irrigation

State	Irrigated cropland (ha)	Percentage of cropland irrigated	Irrigated pastureland (ha)	Percentage of pastureland irrigated	Total irrigated land area (ha)
Arizona	330 706	88%	14 030	1.0%	344 736
California	2 880 595	94%	174 445	7.5%	3 055 040
Colorado	814 713	50%	119 927	4.1%	934 640
Nevada	203 514	83%	75 700	5.4%	279 214
New Mexico	245 026	54%	36 081	1.2%	281 108
Utah	357 029	85%	98 286	7.9%	455 315
Total	4 831 584	78%	518 469	4.2%	5 350 053

Source: USDA-NASS (2014a).

Pasture and grazing land in the Southwest accounted for another 12 million hectares in 2013, of which 4.2%, or 520 000 hectares, was irrigated.[5] California had the largest tract of irrigated pastureland, followed by Colorado and Utah. Pastureland in Utah and California was more heavily dependent on irrigation than other states in the region, whereas pastureland in Arizona and New Mexico was the least dependent on irrigation.

The Southwest's crop mix varies by climate, soil type, geographic features, and reliability of water supply (Table 2). Forage and field crops accounted for nearly two-thirds of the irrigated harvested cropland in 2013 (USDA-NASS, 2014a). In all Southwest states except California, field and forage crops were the dominant crop type. Fruits and nuts represented another 1.1 million hectares, or 22% of harvested irrigated cropland, followed by vegetables at 10%, and other crops at 2.9%. While Arizona and New Mexico are producers of primarily field and forage crops, agricultural production is more varied than their northern counterparts owing to a longer growing season and a milder climate. California's crop production is the most diverse and extensive; it is the top producer of vegetables, fruits, nuts, and nursery products in the United States (USDA-NASS, 2014b).

5. Pasture and grazing land includes permanent pasture and rangeland as well as other pasture and grazing land that could have been used for crops without additional improvements.

Table 1. Field and forage are the main irrigated crops, although there is more variety in California (2013)

	Field and forage		Vegetables, melons, and potatoes		Fruit and nuts		Other crops	
	ha	%	ha	%	ha	%	ha	%
Arizona	288 713	83%	41 671	12%	10 036	2.9%	8 653	2.5%
California	1 379 813	47%	411 985	14%	1 056 248	36%	100 994	3.4%
Colorado	755 781	92%	37 074	4.5%	925	0.1%	23 922	2.9%
Nevada	191 345	96%	3 493	1.8%	487	0.2%	3 270	1.6%
New Mexico	217 282	88%	9 513	3.8%	18 445	7.4%	2 786	1.1%
Utah	348 273	98%	1 556	0%	2 713	0.8%	2 389	0.7%
Total	3 181 207	65%	505 293	10%	1 088 855	22%	142 014	2.9%

Source: USDA-NASS (2014a).

Between 2003 and 2013, under recurrent dry conditions, total irrigated land in the Southwest declined by 6%; however, trends varied by state. Irrigated cropland increased slightly in Utah, Nevada, and Arizona; but these increases were offset by larger reductions in California, Colorado, and New Mexico. During the same period, irrigated pastureland declined by 11%, while rain-fed pastureland increased by 25% (USDA-NASS, 2004; USDA-NASS, 2014a). Irrigated pastureland increased in Arizona and Nevada but decreased in all other Southwestern states. While drought has likely contributed to this shift, some of these changes may also reflect long-term agricultural trends.

Agriculture water use is falling but the sector remains the largest user

Agriculture is the largest water user in the Southwest, accounting for about 70% of total freshwater withdrawals, or 63 km^3 in 2010 (Maupin et al. 2014).[6] The majority of freshwater withdrawals are in California, which accounted for 36% of regional withdrawals in 2010, followed by Colorado (15%), Arizona (7%), Utah (5%), New Mexico (4%), and Nevada (2%).

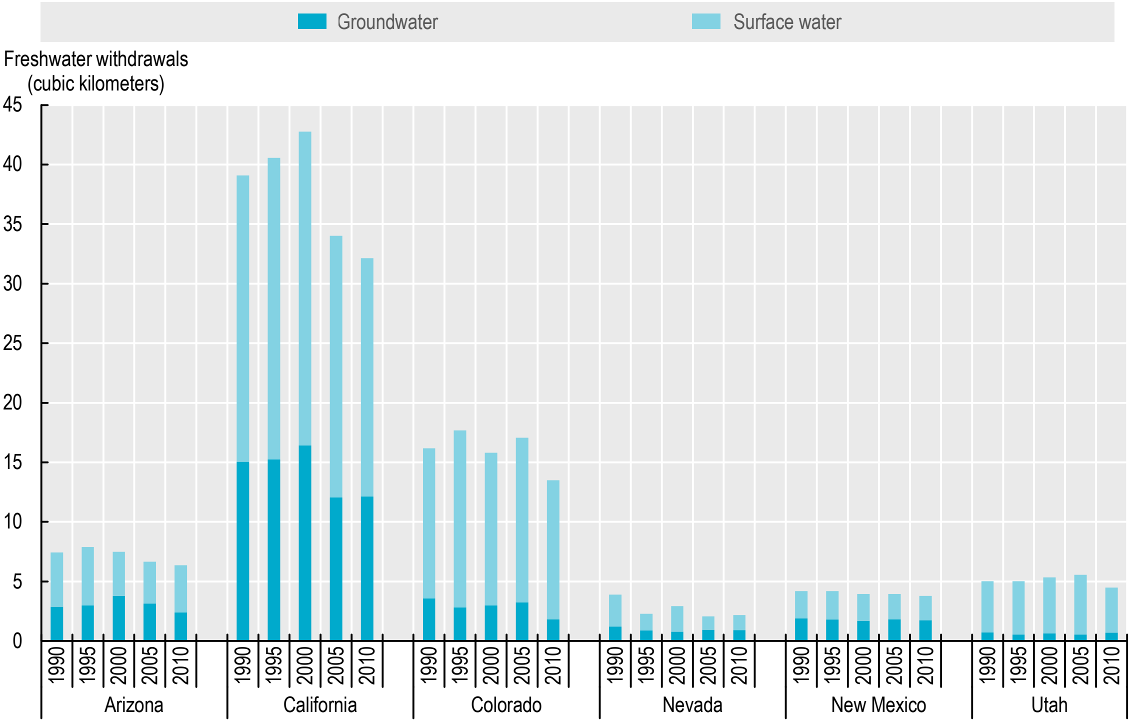
Much of the water for irrigation is from surface water, followed by groundwater and, to a much lesser extent, recycled water. In 2010, surface water and groundwater accounted for 68% and 32%, respectively, of water withdrawals for irrigation across the Southwest (Maupin et al., 2014). The balance between surface and groundwater usage varies from state to state and from year to year. In Colorado and Utah, for example, surface water usage is much higher, accounting for more than 80% of irrigation water. California and Nevada, by contrast, are more heavily dependent on groundwater, which accounts for 40% of irrigation water in 2010. Reliance on groundwater generally increases during dry years when surface water resources are more limited. During dry years in California, for example, groundwater dependence increases to 60% (CDWR, 2014a). Recycled municipal wastewater represents a modest source of water for irrigation in the region; however, data on its use are incomplete or unavailable.

From 1990 to 2010, agricultural freshwater withdrawals declined by 18% across the region, which is much higher than reductions in irrigated area (Figure 2). Reductions in both surface water and groundwater withdrawals were observed in all states, with the largest reductions in California, followed by Colorado and Nevada. Several factors help explain the decrease in agricultural freshwater withdrawals over this period, including a shift to less water-intensive crops and increasing irrigation

6. Agricultural water withdrawals include both irrigation (99%) and livestock (1%). A very small portion of irrigation water is also for golf courses.

efficiency, demonstrated by the shift from flood irrigation to sprinkler and micro-irrigation methods (Donnelly and Cooley, 2015).

Figure 2. Freshwater withdrawals for agriculture fell over the last 20 years



Note: Recycled water was not included because data are not available for all years or all states.

Source: Solley et al. (1993); Solley et al. (1998); Hutson et al. (2005); Kenny et al. (2009); Maupin et al. (2014).

Rising farm income and foreign exports due to a surge in agricultural sales in California

Agriculture income in the Southwest is dominated by agricultural sales, especially from California, and largely independent of government payments. In 2014, total farm income in the Southwest amounted to USD 77 billion (BEA, 2015).[7] Of this total, agricultural sales were valued at USD 72 billion — which represented 17% of the US total — and government payments and other miscellaneous income accounted for USD 4.7 billion (only 6.5% of the total income).[8] Most importantly, California's agricultural sales valued at USD 53 billion in 2014, representing over 68% of total regional farm income. With this amount, California is the leading US state in cash farm receipts and accounts for nearly three-quarters of agricultural sales in the entire Southwest.[9]

7. Values expressed in 2015 dollars unless otherwise stated.

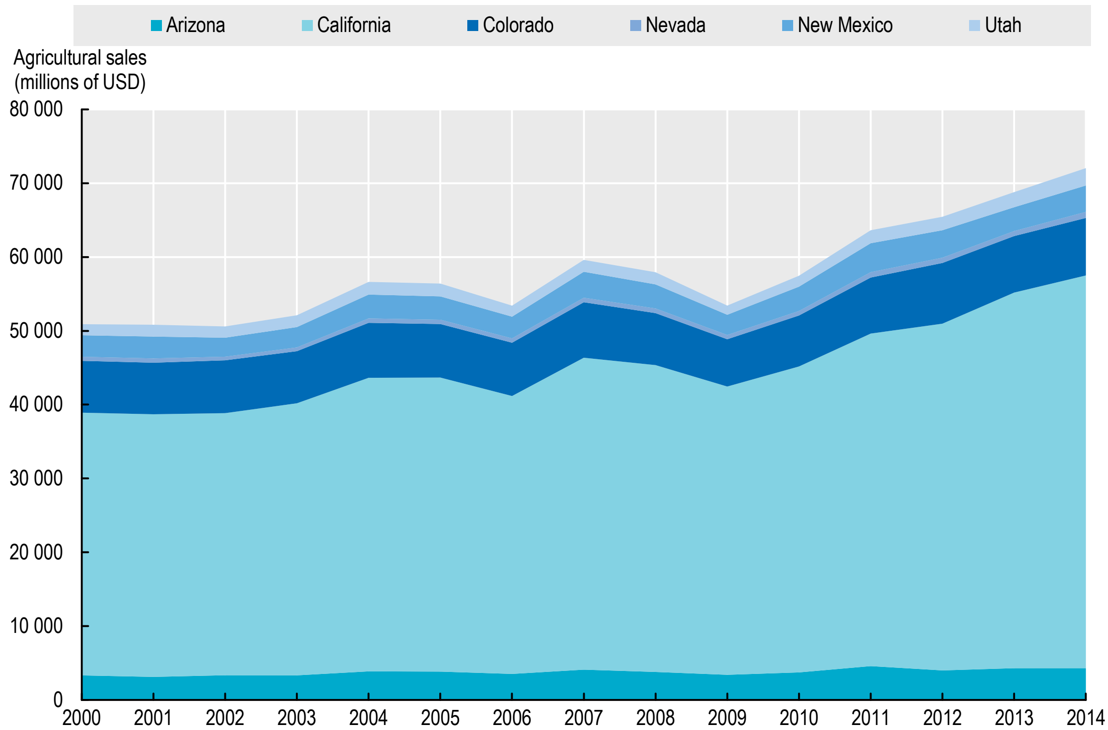
8. Agricultural sales are defined as gross revenue from cash receipts from crop commodities and livestock and their products during a given calendar year. The value of defaulted loans made by Commodity Credit Corporation (CCC) and secured by crops make up a very small portion of these agricultural sales.

9. Colorado's agricultural sales were valued at USD 7.8 billion in 2014, making it the second highest in the Southwest, followed by Arizona (USD 4.3 billion), New Mexico (USD 3.6 billion), Utah (USD 2.4 billion), and Nevada (USD 0.8 billion).

Further, livestock and products accounted for 41% of agricultural sales in 2014 (Figure 3) (BEA, 2015). Crops accounted for the other 59%. Of the crops produced, fruits and nuts provided the greatest sales, followed by vegetables, field and forage crops, and other crops. In most Southwest states, including Colorado, Nevada, New Mexico, and Utah, livestock and products represented more than 70% of agricultural sales. Agricultural sales in California and Arizona were much more diverse. Although the majority of agricultural sales (56%) in Arizona were from livestock and products, the state was also a major producer of vegetables. Unlike other south-western states, California earns most of its revenue from fruits and nuts (41%), followed by livestock and products (29%), vegetables (17%), field and forage crops (8%), and other crops (7%).

Despite reductions in irrigated land area and freshwater withdrawals, farm income has continued to rise. Sales in the region have increased by nearly 28% between 2005 and 2014 (Figure 3). California accounted for about 85% of this growth, with a large increase in revenue from crops (USD 8.7 billion) and a smaller increase from livestock and products (USD 4.7 billion). Crop sales in Arizona and New Mexico fell by about USD 0.2 billion; however increases in livestock sales more than compensated for this decline.

Figure 3. California drives agricultural sales increase



Note: All numbers have been adjusted for inflation and are shown in year 2015 dollars.

Source: BEA (2015).

In parallel, the Southwest's foreign exports of agricultural products totalled USD 28 billion in 2014, a doubling from 2005 levels (USDA-ERS, 2015). Much of that growth can be attributed to increased exports of meat and dairy products. The value of beef and veal exports, for example, increased nearly five-fold over the last decade, and the value of dairy exports has tripled. Since 2005, the export value of crop products also increased by about 86%. Growth in agricultural exports is largely driven by California, which accounted for 84% of total agricultural export value in the Southwest and 16% in the nation in 2014. The state also ranks first in the export of dairy products, processed vegetables, fresh fruits, processed fruits, and tree nuts.

2. Looking ahead: Water supplies uncertain in a context of climate change and growing demand

The risk of water shortage in the region is projected to increase due to a highly variable water supply under climate change in a context of growing water demand. As noted above, by 2030, the region is projected to add an additional 23 million people, bringing the regional population to 73 million, which will be 48% higher than 2000 levels (US Census, 2005).

The Southwest's water supplies vulnerable to the effects of climate change

The Southwest United States hosts a wide range of climatic conditions. The low-elevation Mojave and Sonoran Deserts of Southern California, Nevada, and Arizona are the hottest, driest regions of the United States, while the higher elevation mountains receive large amounts of snow during the winter months. Annual precipitation varies from less than 5 inches in parts of Arizona, California, and Nevada to more than 90 inches in parts of northern California, and is subject to significant inter-seasonal, inter-annual and inter-decadal variability (Steenburgh et al., 2013). At the same time, the Southwest is often associated with intense, prolonged droughts.

Because the water cycle and the climate cycle are inextricably linked, climate change has and will have major implications for the United States' water resources, particularly in the Southwest (e.g. Cook et al, 2015). In short, climate change will intensify the water cycle, altering water availability, timing, quality, and demand. All of the major international and national assessments of climate changes have concluded that freshwater systems are among the most vulnerable systems (Compagnucci et al., 2001; SEG, 2007; Kundzewicz et al., 2007; Bates et al., 2008; Jiménez Cisneros et al., 2014). These effects could be particularly important in parts of the region with low annual precipitation, for which a small set of climatic events often implies large changes in water supplies. Specific projections are reviewed for the key regions of the Colorado River Basin and central California.

Demand greater than supply in the Colorado River Basin and the gap is growing

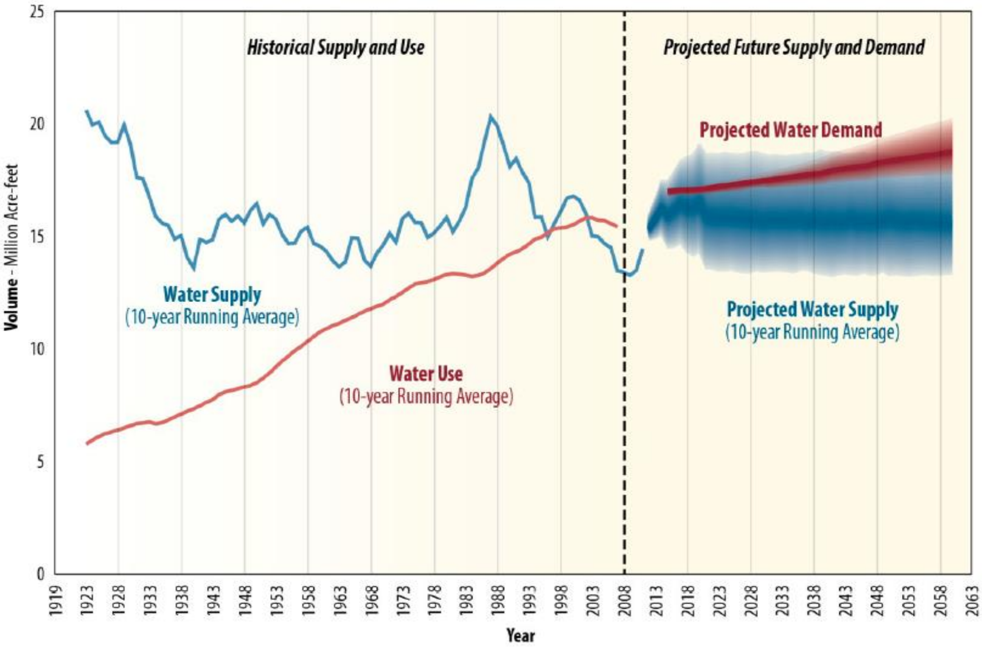
The Colorado River is an important water source for the Southwest, yet demand for water already exceeds supply (Figure 4). The Colorado River enabled the development of the US Southwest and parts of northwestern Mexico, supplying water for about 40 million people in both countries, and wholly or partially irrigating more than 2 million hectares inside and outside of the basin. A dense yet dynamic set of regulations, interstate compacts, agreements, contracts, judicial decisions, and an international treaty, known collectively as the "Law of the River," governs the allocation and use of Colorado River water within the United States and from the United States to Mexico. Massive dams on the river's mainstream and on many of its tributaries can store as much as four times the river's average annual flow but have devastated ecosystems and driven several native fish species to the brink of extinction (Rosenberg et al., 1991; Minckley and Deacon, 1991).[10] These institutional and structural controls severely constrain the river's natural variability with respect to the timing and volume of flows, sediment loads, and

10. See for example the Lower Colorado River Multi-Species Conservation Program at http://www.lcrmscp.gov/ and the Upper Colorado River Endangered Fish Recovery Program at http://www.coloradoriverrecovery.org/.

geomorphic processes, and significantly reduce the volume of water actually flowing to the border. In the past several decades, the river rarely has had enough water to reach the sea.

Water supplies in the Colorado Basin are projected to become more variable and uncertain due to climate change (Christensen and Lettenmaier, 2006; USBR, 2012a; Vano et al., 2014). The Colorado River Basin Study (USBR, 2012a) was finalized in 2012 and included four future water supply scenarios to help capture the range of potential futures and reflect the uncertainty of projecting water supply in a highly variable system. In the 100-year historic record, mean annual runoff at Lee's – the traditional measuring point for the Colorado River – has been about 18 km^3, with more than 80% of the runoff generated from about 15% of the Colorado River Basin at elevations exceeding 2 400 meters.[11] The climate change scenario projects a general drying trend in the basin, with the notable exception of increased precipitation in the higher elevation, productive headwaters regions. With climate change, total runoff was projected to decline by 9.1%, with even greater annual and monthly hydrologic variability, reducing predictability and reliability for water managers. The other water supply scenarios, based upon the 100-year historic record and the much longer tree-ring record, projected that runoff would decrease by less than this amount.

Figure 4. Historical and future Colorado River Basin supply and use



Note: Water use and demand include Mexico's allotment and losses, e.g. those due to reservoir evaporation, native vegetation, and operational inefficiencies.

Source: Figure C-9 in USBR (2012a).

11. The Basin Study notes the challenges associated with projecting climate change impacts on high elevation, snowmelt-driven headwaters, where the roughness and scale of climate models generate a high degree of uncertainty.

Reduced runoff in the south and shifts in the timing of runoff throughout California

Precipitation in California is subject to significant intra- and inter-annual variability, making the state dependent on natural and manmade storage and vulnerable to shocks. Indeed, studies show that California has the most variable climate in the United States, as measured by the coefficient of variation (standard deviation/mean) of water year (October – September) precipitation (Dettinger et al., 2011). A small number of winter storms typically account for the bulk of annual precipitation, so that small changes in the number or intensity of these storms can be the difference between a wet and a dry year.

Climate change is projected to shift the timing of runoff throughout the Central Valley and reduce runoff in the southern parts of the region. The US Bureau of Reclamation launched a study in California's Central Valley (USBR, 2014a), the state's main agricultural production region, to evaluate the impacts of climate change on water supplies and on the timing and volume of runoff under 18 socio-economic climate scenarios. Annual runoff in the northern part of the Central Valley was projected to show little or no change, while some drying was projected in the southern portions of the region. Warmer temperatures during the winter months, however, cause precipitation to fall as rain, rather than snow, increasing winter runoff and reducing spring runoff. Under current reservoir operating criteria, this seasonal shift reduces the ability to store water because "*With earlier runoff and more precipitation occurring as rainfall, reservoirs may fill earlier and excess runoff may have to be released downstream to ensure adequate capacity for flood control purposes*" (USBR, 2014a; p. 4).

3. Implications for agriculture: Less available water and reduced irrigation constraining multiple activities

Less water available for agriculture and reduction of irrigated crop land

The future is likely to see transfers of agricultural water to other sectors. There is a large and growing body of literature on the impact of water scarcity on Southwest agriculture (Booker et al., 2005; Harou et al., 2010; Coppock, 2011; Frisvold and Konyar, 2012; Frisvold et al., 2013). These studies show that while agriculture is projected to remain the largest water user, urban encroachment and growing demand for water to accommodate continued population growth and restore degraded ecosystems are projected to reduce water availability for agriculture. Moreover, recent trends in the Southwest and elsewhere indicate that non-agricultural users will seek to purchase or otherwise obtain agricultural water rights to meet their own projected demand and to protect against potential supply losses or limitations arising from climate change or other factors. Although these transactions are typically voluntary, the net result will be a transfer of agricultural water to other sectors.

In particular, the Colorado River Basin is projected to face a significant future reduction in irrigated land due to increased water demand from other sectors (USBR, 2012a). The Colorado River Basin Study analysed six scenarios of future demands for Colorado River water through the year 2060. The scenarios were selected to reflect specific, plausible narratives about potential futures and were based on estimates of population growth, per capita water demand, and projected changes in the amount of irrigated land. The study finds that while water supplies become increasingly uncertain, consumptive water use increases from the current level of about 18 km^3 to 22.1 km^3 under a "slow growth" scenario and to 25 km^3 under a "rapid growth" scenario, by 2060.[12] Much of the projected increase in water use is to satisfy municipal and industrial demands and, to a lesser extent, energy, mining, and tribal demand. Warmer temperatures and higher evapotranspiration rates are projected to increase water application

12. For additional description and documentation of the different demand scenarios, please refer to Appendix 14 of Technical Report C of USBR (2012b).

rates for irrigated land by up to 3%.[13] Yet, agricultural water demand in the basin and adjacent areas relying on the Colorado River water is projected to decline by 0.86 km^3 to 3.3 km^3 by 2060, 7% to 25% below current levels, due to reductions in irrigated area. The scenarios project a range of potential futures, including estimates that the total amount of land irrigated, at least in part with Colorado River water, could decline from current levels by between 4% and 16% by 2060, primarily due to reductions in irrigated acreage and land conversion in Arizona. Nonetheless, the scenarios still project that irrigated agriculture will remain a major land use and source of water demand for the foreseeable future.

Similarly, California's irrigated area and agricultural water demand are projected to decline by mid-century (CDWR, 2013 and 2014b). There, the principal tool for water planning is the California Water Plan, which is prepared every five years through a collaborative, multi-stakeholder process administered by the California Department of Water Resources (DWR). The California Water Plan Update 2013, the latest iteration, evaluated changes in urban and agricultural water demand for each of the state's ten hydrologic regions under nine growth and development scenarios and 13 future climate scenarios (CDWR, 2013). Urban water demand is projected to increase in all regions under all scenarios, reaching 16% to 74% above the historical (1998 to 2005) average. The scenarios project that urban growth would take 40,000 to 360,000 hectares of land out of agricultural production by 2050, reducing irrigated area by 1% to 9% (CDWR, 2014b). Due to urbanisation and implementation of agricultural water conservation measures, agricultural water demand *decreases* under all future scenarios, reaching 10% to 14% below the historical average. These scenarios, however, do not include implementation of recent groundwater legislation, which could further reduce the irrigated area and/or volume in some parts of the state, but increase groundwater reliability in the long term (Box 1).

In California, agriculture in the southern portions of the Central Valley is the most vulnerable to future water supply constraints. The Water Plan Update 2013 (CDWR, 2013) included a detailed assessment of the percentage of years in which water demand would be sufficiently met by supply (i.e. the reliability). The supply of water to agriculture in the northern portion of the Central Valley would remain highly reliable across all scenarios evaluated. In the central portions of the Central Valley, the agricultural sector would experience significant shortages under some scenarios, e.g. modestly warmer and slightly drier climate scenarios. Agriculture in the southern portion of the Central Valley would experience the greatest shortages, with reliability consistently below 95% across scenarios, and below 50% in the hottest and driest climate scenarios. In all regions of the Central Valley, reliability for the urban sector remains much higher than for the agricultural sector.

Although not much discussed in the literature, climate change may also increase the prevalence of weeds, pests and diseases in the region, leading to more intensive pest control and water quality consequences. Research projects a higher concentration of CO2 could increase the prevalence of pest and weeds on crops in California (CCAN, 2011). Such phenomenon would lead to increased likelihood of resistance to pesticides and herbicides. The responses could lead to more aggressive use of diverse phytosanitary controls (including more potent chemical approaches) with possible degradations of water quality, and ultimately reduce access to usable water for agriculture[14] and other consumers and ecosystems.

13. At the same time, a growing body of literature projects potential declines of biomass and yields for field crops due to temperature stress, particularly after mid-century (e.g. see Schlenker and Roberts, 2009). This may offset the needs for additional irrigation.

14. For instance, groundwater containing phytosanitary chemicals may affect the safety and/or quality of groundwater-irrigated produces. Groundwater containing herbicides may also impact plant growth for some irrigated crops.

Box 1. Efforts to address groundwater overdraft in California

Groundwater depletion for agriculture irrigation is a major challenge in California. Groundwater is an important water source for California farmers, accounting for nearly 40% of irrigation withdrawals in average years (Maupin et al., 2014) and up to 60% in dry years. UCCHM (2014) estimates that over 60 km^3 of groundwater have been lost in the Central Valley over the last half century. There are strong indications that groundwater overdraft is worsening: recent data show that the Sacramento and San Joaquin River Basins collectively lost nearly 31 km^3 of groundwater between October 2003 and March 2010, or about 4.8 km^3 per year (Famiglietti et al., 2011). Overdraft is especially severe in the southern parts of the Central Valley, where groundwater levels have reached more than 33 meters below previous historic lows (CDWR, 2014). Overdraft has resulted in saltwater intrusion and other water quality impacts, significant land subsidence, lost water storage, and increased energy costs, among other adverse impacts.

Groundwater use has been unregulated in much of California. In response to worsening groundwater conditions, the state recently passed the Sustainable Groundwater Management Act of 2014 (SGMA). The act provides a framework for local authorities to manage groundwater supplies but allows for state intervention if necessary to protect groundwater resources. Specifically, it requires the formation of local agencies by mid-2017 and requires those agencies to adopt and implement local basin management plans by 2022. Additionally, it requires basins to achieve groundwater sustainability goals by 2040 in medium- and high-priority basins in critical overdraft and by 2042 in all other medium- and high-priority basins. While it remains to be seen the extent to which sustainability goals will actually be achieved, SGMA is an important step toward more rational and sustainable use of California's groundwater resources.

Most of the state's critically overdrafted groundwater basins are in agricultural areas, and implementation of SGMA will have major implications for California agriculture. Because groundwater provides an important stop-gap when surface water supplies are limited, impacts will be especially severe during droughts. Scanlon et al. (2012) find that groundwater depletion in the Central Valley occurs mostly in the southern Central Valley and primarily during droughts. They also find that artificial recharge of excess surface water in aquifers "shows promise for coping with droughts and improving sustainability of groundwater resources in the Central Valley." While boosting groundwater recharge would help reduce the shortfall, these areas will also have to reduce groundwater pumping through a variety of means, including using water more efficiently, shifting to less water-intensive crops, and taking land out of production in some areas.

In the long term, the intention of SGMA is that its implementation should increase the reliability of groundwater for agriculture and other users, leading in particular to a new long term –sustainable- equilibrium for irrigated agriculture.

Source : Maupin et al. (2014); UCCHM (2014) ; Famiglietti et al. (2011) ; CDWR (2014a) ; Scanlon et al. (2012).

Lower water availability will have significant impacts on crop and livestock production

Assessment of the agricultural effects of water reduction in the region without additional policy action shows that *irrigated field and forage crops* would be the most impacted.

- Frisvold and Konyar (2012) used a hydro-economic model to evaluate the agricultural impacts of a 25% reduction in water availability in the Southwest United States and find that field crops are projected to experience the greatest changes while specialty crops are projected to change very little. The study found that irrigated area would decline by 1.5% but that these reductions would largely be offset by increases in dryland acreage. Total crop area would increase in Utah and Colorado and contract in Arizona and New Mexico. Land fallowing would reduce net income by USD 65 million in the region. These losses could be reduced to USD 15 million if farmers changed cropping patterns, practiced deficit irrigation, and adjusted the use of other inputs.[15]
- Howitt et al. (2009) simulated the effects of a warmer, drier climate on California agriculture in 2050. The study projects that state-wide irrigated land and water use would decline by 20% and 21%, respectively, while revenue would decline by only 11% due to partial offset from higher crop prices and crop shifting. The largest reductions in crop area were for lower value, water-intensive crops, such as pasture, field crops, grains, and rice.

15. Deficit irrigation refers to the practice of limiting water use to levels below the full watering requirement for a particular crop. Deficit irrigation seeks to optimize crop productivity per unit of water rather than per unit of land area.

Marshall et al. (2015) supports these findings. In an analysis of the regional impacts of climate change and changes in water availability on field crop production in the United States, the authors find that *field crop* production declines with welfare implications. The study finds that, by mid-century, climate change (1) reduces crop yield for all field crops, except wheat and hay; (2) reduces irrigated crop area due, in part, to reductions in surface water availability across much of the arid West; and (3) reduces the production of all crops. While commodity prices are projected to rise, higher prices are insufficient to offset declining crop yields and returns, thereby reducing producer welfare.

S*pecialty crops*[16] present a unique set of opportunities and challenges, and more research is needed to understand their vulnerability to climate change and more variable water supplies. Frisvold et al. (2013) note that compared to field crops, demand for specialty crops is price inelastic, such that demand falls little if price increases; additionally, small changes in output could lead to relatively large increases in price, thereby allowing farmers to withstand changes in production. Yet, specialty crops may be especially vulnerable to climate change because many of these crops are perennial crops that may be in the ground for 20 years and will be exposed to climate impacts that manifest over a longer time horizon. Additionally, perennial crops cannot be fallowed, and may be more vulnerable to droughts and other water supply constraints. Luedeling et al. (2009) examined projected changes in winter chill in California and found that projected climate conditions by the middle to the end of the 21st century "will no longer support some of the main tree crops currently grown in California." They also find that conditions will be the least detrimental to almonds and pomegranates because these crops have low chilling requirements. Lobell and Field (2011) find that while no crop clearly benefits from warming by 2050, cherries are at the greatest risk; additionally, they find that almonds are harmed by winter warming, although this may be offset by beneficial warming in spring and summer. The authors note that this study likely represents an optimistic scenario because it assumes that crop water needs are fully met. Auffhammer (2014), however, argues that the available data are inadequate for evaluating how individual crops will respond to climate change and that most studies fail to adequately capture the adaptation potential.

Long-term droughts or climate-change induced water shortages will likely lead to reductions in *cattle and dairy* operations throughout the Southwest. The livestock and dairy sectors are especially vulnerable to projected water shortages, due to high water needs for feed and drinking combined with the projected impacts of higher temperatures.

- First, feed production and prices could be directly affected. Beef cattle rely on rain-fed pasture for their first year of growth, while dairy cattle rely on forage crops, such as alfalfa. A large proportion of irrigated land and water in the Southwest is used to produce feed crops (Cohen et al. 2013), so continuing drought and long-term shortage can diminish the production of these crops, especially as other irrigators and other sectors seek to buy or lease water rights from these growers. Increased competition for water will likely continue the current trends of shifting water from irrigated agriculture to urban areas, reducing the availability and raising the price of feed crops, such as alfalfa.
- Climate change could also affect cattle and dairy production by altering (1) the location and productivity of pasture and rangeland; (2) the distribution of livestock parasites and pathogens; and (3) the thermal environment of animals—thereby affecting animal health, reproduction, and the efficiency with which livestock convert feed into retained products, especially meat and milk (Key et al., 2014). Frisvold et al. (2013) find that warmer temperatures will likely lengthen the growing season and improve pasture productivity at higher elevations and in more northern portions of the region, offsetting the impacts of rising feed costs. In southern regions, however,

16. Specialty crops are defined as fruits and vegetables, tree nuts, dried fruits, horticulture, and nursery crops, they represent a significant proportion of farm returns in some parts of the Southwest, including in California and Arizona, and demand for these crops is growing.

such as much of Arizona and central and south-eastern California, higher temperatures will shorten the growing season and reduce yields (Brown et al., 2015).

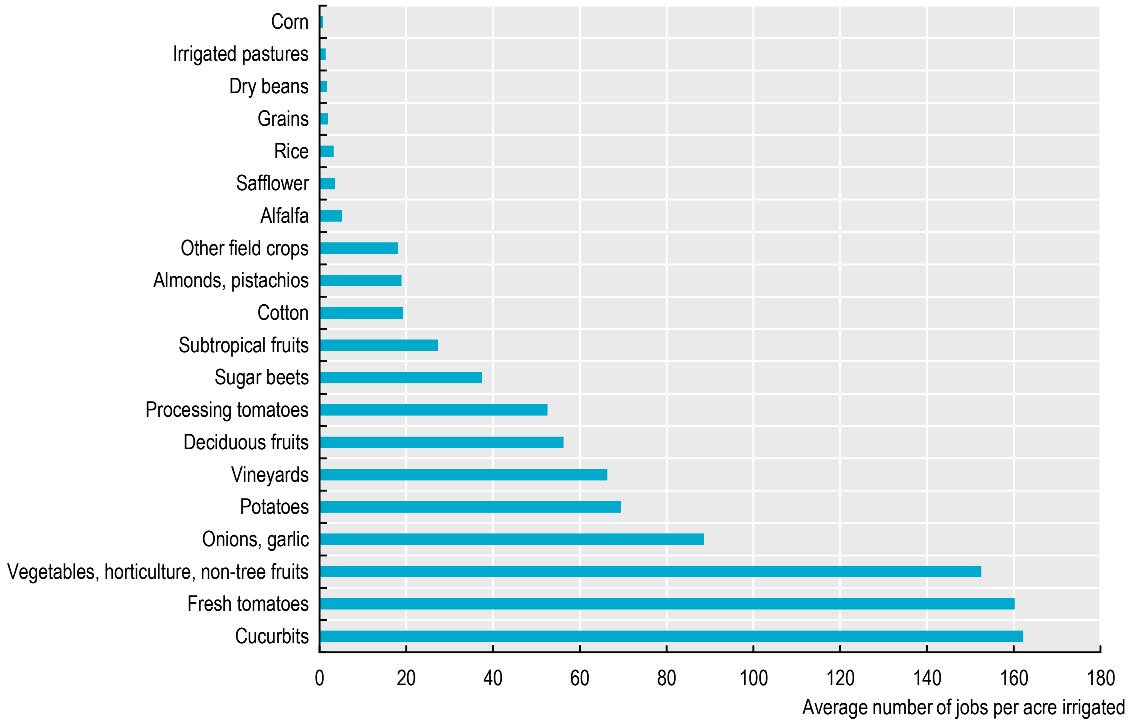
- Higher temperatures can also affect milk productivity. When paired with higher humidity, higher temperatures disproportionately affect dairy cows, diminishing their production due to their susceptibility to heat stress. Key et al. (2014) estimate that heat stress in 2010 cost the US dairy industry about USD 1.2 billion, or slightly more than 2% of total dairy revenue. Mauger et al. (2014) project that climate change will reduce US dairy productivity by 4.7% by mid-century (2050s) and 6.3% by late century (2080s), with large but varying impacts in the Southwest; for example, Maricopa County, Arizona, would experience a diminished dairy productivity of 18% by mid-century, compared to a loss of 4% in Tulare County, California, and 2% in Weld County, Colorado.

International trade impacts and reduced employment are possible but uncertain

These agricultural impacts may in turn affect *international agricultural trade*, especially in the case of California; more work is needed to fully assess such effects. In addition to California's leading role in agricultural productivity and consumption, agricultural exports from the state have exceeded USD 18 billion annually since 2012 (CDFA, 2015). Water shortages and reallocation will affect production and exports, magnifying local impacts across the global stage (MacDonald, 2010). Projected agricultural impacts reviewed above identified field crops, livestock and dairy products as significantly affected by increased water shortages. These activities represent a significant share of exports; in 2014, California's exports of dairy products, beef and related products, rice, cotton and hay amounted to USD 4.2 billion or 19.5% of total agricultural export value (CDFA, 2015). Still, given the large number of variables affecting future agricultural productivity, including irrigation efficiency, crop shifting, improvements in crop yields, variability in global markets, and demand generally, it remains difficult to project the possible economic impacts of long-term drought and water reallocations beyond the region.

In contrast, changes in the agricultural sector may mitigate the impacts of water reduction on total *employment*, although projections are subject to large uncertainties. Frisvold and Konyar (2012) estimated that a 25% reduction in water availability in the Southwest United States would reduce regional employment by only 3%, with the largest impacts in Arizona. Yet ex-ante projections remain difficult. For instance, Howitt et al. (2014) projected that the direct, indirect, and induced job losses from the 2014 California drought would total 17,100 seasonal and part-time jobs. Actual employment data, however, found that agricultural employment reached a record-high 417 000 people in 2014 (California Employment Development Department, 2015). While agricultural employment would likely have been even higher if there had been less land fallowing in 2014, these losses were offset by a shift away from field crops that employ relatively few people per hectare of land (Figure 5), toward tree crops and tomatoes that employ more people per hectare (Cooley et al., 2015a).

Figure 1. Average number of jobs produced per acre of irrigated land, by major crop type



Note: Crop categories are defined by DWR. Cucurbits refer to melons, squash, and cucumbers. Other field crops include flax, hops, grain sorghum, sudan, castor beans, miscellaneous fields, sunflowers, hybrid sorghum/sudan, millet, and sugar cane. Deciduous fruits include apples, apricots, cherries, peaches, nectarines, pears, plums, prunes, figs, walnuts, and miscellaneous deciduous. Subtropical fruits include grapefruit, lemons, oranges, dates, avocados, olives, kiwis, jojoba, eucalyptus, and miscellaneous subtropical fruit.

Source: Figure from Cooley et al. (2015a) and based on data on irrigated crop acreage for 2010 from CDWR (2015.), and employment estimates are from Medellin-Azuara et al. (2015).

4. Several options can help mitigate the projected adverse impacts

As noted in the previous section, increased competition for more variable and uncertain water supplies will undoubtedly affect the agricultural sector in the Southwest United States. These impacts can however be reduced by improving agriculture and water management policies and practices. This final section examines *some of the options* for mitigating adverse impacts on agriculture in the region, including reductions in water demand in agricultural and urban areas, improvements in groundwater management, and the transfer of water between users.[17]

Reducing agricultural and urban demand could mitigate the impact of water shortage

A variety of strategies are available to allow farmers to reduce water use, thereby reducing vulnerability to water shortages. For example, on-farm improvements, such as drip irrigation and irrigation scheduling with soil moisture monitoring and real-time evapotranspiration data, can help to maintain agricultural production with less water (Buchleiter et al., 1996; Dokter, 1996; Kranz et al.,

17. More general policy responses to water shortages can be found in OECD (2014 and 2016). Broader societal changes, such as shifting food consumption preferences from beef and dairy to less water-intensive agricultural products such as legumes and vegetables, could reduce water shortage risks but would require complex policy changes at multiple scales and therefore are not included here.

1992). Crop shifting could also be implemented to respond to projected water shortages and may also provide economic advantages to the region. Field crops, for example, can be more water-intensive and generate less value per unit water compared with other crop types, and thus, well-planned crop shifting could reduce water use while increasing revenue. Additionally, drought-, heat- or salt-tolerant crop varieties may also help to reduce vulnerability to greater climate variability.

Soil management strategies can reduce agricultural vulnerability to drought and water shortages. Conservation tillage, for example, leaves crop residue from the previous year on the soil, thereby reducing evaporation from the soil surface, boosting soil organic matter, and consequently improving soil moisture levels.[18] Finally, conveyance system improvements, such as lining canals and improving canal control, can help to conserve water.

One of the key challenges for agriculture in the Southwest is population growth and the resulting pressure to reallocate water from agriculture to urbanised areas. Improvements in municipal water conservation and efficiency have reduced that pressure. In major cities, such as San Francisco and Los Angeles, total water use has decreased since the late 1970s despite continued population and economic growth. At a larger scale, a recent United States federal study found that water conservation and efficiency efforts have reduced annual demand for water from the Colorado River basin by more than 2.1 km^3, a tremendous savings in an over-allocated basin (USBR, 2015).

Improving groundwater management could reduce vulnerability to greater water supply variability

Groundwater is an important water source for farmers in parts of the Southwest, especially in Arizona, California, Nevada, and New Mexico, and needs to be better managed for the future of agriculture. During drought years, when surface supplies are limited, groundwater becomes an increasingly important stop-gap measure for farmers (OECD, 2015a). Yet, the current use of groundwater is unsustainable in some areas, including in parts of California and throughout the Colorado Basin, threatening this precious water reserve for the future (Tillman et al., 2011; Castle et al., 2014; Famiglietti, 2014; UCCHM, 2014).

Managing the intensive groundwater use, as observed in California’s Central Valley, requires multiple conditions and can be facilitated by a combination of economic, regulatory and collective-action based instruments (OECD, 2015a, as shown in Box 2). The 2014 Sustainable Groundwater Management Act is moving in this direction by incentivizing collectives to take action and reduce groundwater use (Box 1; Gruère, 2015).

Aquifers also provide significant water storage opportunities and could help the Southwest region respond to climate change, particularly to reductions in snowpack due to warmer temperatures. With proper management, groundwater aquifers could help capture some of this water, reducing the risk of floods in the winter and drought in the summer. Additionally, excess surface water in wet years, treated wastewater, and storm water runoff could also be used to recharge groundwater.

18. In 2015, California launched the *Healthy Soils Initiative* to increase soil organic matter on agricultural lands as a means of improving water retention, soil stability, and nutrient use efficiency and capturing greenhouse gases. The Initiative seeks to improve soil management by expanding research, providing education and technical assistance, and creating incentives and market opportunities to promote healthy soils.

Box 2. What policy measures can help address intensive groundwater use in agriculture?

A comprehensive review of groundwater policies in OECD countries identified key conditions and approaches to address the effects of groundwater depletion and the associated negative externalities.

- Six general conditions are identified for successful management: 1) build and maintain sufficient knowledge of groundwater resource and use; 2) manage surface and groundwater conjunctively (together) where relevant; 3) favour instruments that directly target groundwater use over indirect measures (e.g. land use regulation), where possible; 4) prioritise demand–side approaches, that aim to reduce groundwater use, before moving to supply-side additions; 5) enhance the enforcement of regulatory measures (e.g. water entitlements) before moving to other approaches; and 6) avoid non-water related price distorting policy measures, such as subsidies towards water intensive crops and energy, that could affect groundwater use.
- To cope with intensive use, policies should be constructed as a "tripod", combining regulatory, economic and collective management instruments. Groundwater entitlement systems should remain the core of groundwater management. Collective action-based approaches are present in many of the successful cases to redress externalities. Economic instruments can support efficient solutions to groundwater scarcity and depletion problems.
- Measures that increase agricultural water productivity and support new recharge mechanisms, such as aquifer storage and recovery, provide complementary tools in cases of high water stress.

This three-part package should be adapted to locally-specific agriculture groundwater systems, which may call for the division of management into functional subunits.

Source: OECD (2015a).

Water banks provide additional flexibility to adapt to variable and uncertain water supplies

Water banks can increase storage capacity, either in surface reservoirs or in aquifers, providing additional flexibility and reducing vulnerability to future shortages. This can be done by coupling efficiency improvements with additional storage or preservation for other uses. A number of creative water banking approaches have been initiated in the Colorado River basin. These developments started in 1999, when the federal government adopted a new rule permitting interstate banking agreements within the basin (USBR, 1999). By the beginning of this year, Arizona and California had diverted and stored more than 1.14 km^3 of Colorado River for southern Nevada (USBR, 2016). In 2007, the seven basin states adopted a new set of rules managing the river that, among other key developments, permitted entitlement holders in Arizona, California, and Nevada to invest in various water efficiency projects within their own state and store a percentage of the conserved water in Lake Mead for later use (USBR, 2007). To date, more than 1.3 km^3 have been stored in Lake Mead under this new program; some 0.87 km^3 remained in storage at the end of 2015 (USBR, 2016). More recently, four large municipal water agencies in the basin, in cooperation with Reclamation, agreed to invest USD 11 million in fallowing and efficiency improvements and dedicate the conserved water to the Colorado River basin system as a whole, rather than claiming it for themselves (USBR, 2014b).

Recycled water can reduce the dependence on limited water supplies

Recycled municipal wastewater can be a safe, reliable water supply that reduces dependence on limited surface and groundwater supplies; reduces pollution in rivers and oceans from wastewater discharge; and even provides essential crop nutrients, thereby reducing fertilizer costs. It can be applied directly to the crop, blended with some other water source, or used to recharge groundwater that is subsequently withdrawn by farmers. In 1990, the last year for which regional data are available from the United States Geological Survey, recycled water supplied 3.4 percent of irrigation water in Arizona and one percent or less in other Southwestern US states. While it represents a modest source of water for irrigation in the Southwest, it could be expanded in those agricultural areas near urban centres.

Water transfers can reduce economic losses of water shortages if properly designed

Water transfers refer to the temporary or permanent transfer of the right to use water in exchange for some form of compensation. They are perhaps the best known and most widely used method of reallocating water between uses or users. Typically, temporary water transfers among farmers can allow for a response to drought or other short-term water supply constraint and help moderate the economic impacts of those constraints on the agricultural sector; e.g. by fallowing land and selling that water for use on higher value crops. Long-term and permanent transfers, by contrast, allow for changes in water usage and demand patterns, and in almost all cases, these transfers have shifted water away from agriculture to other uses.

While long-term transfers that shift water away from the agriculture sector may promote economic efficiency for society at a macro scale, the impacts on the agricultural sector depend on how water was made available for these transfers, i.e. whether it was from fallowing land, changing the type of crops grown (from more water-intensive to less water-intensive crops), or improving the efficiency by which these crops were grown. Moreover, economic benefit at the state or regional level can mask disparities between areas of origin and importing areas, and even within the areas of origin themselves (Cooley et al. 2015b).

While certain type of water transfers can be effective, such as those exchanging treated waste water in cities for groundwater conservation (as seen in particular in California, see OECD 2015b), or moving water to high value uses, other water transfers can result in significant, adverse socio-economic and environmental impacts. “Buy and dry” arrangements, where transfers curtail agricultural productivity, can be especially problematic, affecting areas well beyond just the source and destination of the water transfer, depressing tax bases, shuttering agricultural equipment suppliers, decreasing employment for farmworkers, and depopulating rural areas. Contingent water-market contractual arrangements that allow for pre-specified water transfers during peak drought conditions can help lessen the impacts on agricultural production and rural economies over time.

In practice, water transfers have generated mixed results. Active water transfers in several areas, such as Australia’s Murray-Darling Basin and the Mexicali Valley in north-western Mexico, have led to temporary or permanent reallocation of more than a third of total annual water use in these areas In the first case, this has helped maintain the economic value of agriculture under significant water reduction, greatly increased flexibility in water resource use under drought (OECD, 2014 and 2016). In other examples, such as irrigation districts in Colorado and California, the results have been less convincing.

These past experiences indicate that several common factors are important in creating successful water markets. These factors include water rights equivalency (as opposed to a prioritized system of water rights), low transaction costs, limited or otherwise mitigated impacts to third parties, and credible and timely information about the price and availability of water for trading. In Australia, for example, a USD 3 billion public subsidy in the form of federal purchases of water for environmental purposes effectively removed a significant constraint. In other areas, such as south-eastern California, the environmental impacts of a major agriculture-to-urban water transfer have yet to be addressed, threatening a valuable stop for birds migrating along the Pacific Flyway and threatening public health due to dust emissions generated by the shrinking of a lake fed by agriculture drainage (Cohen, 2014).

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