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Virtual Water and Agricultural Exports During Recent Drought in California

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Virtual Water and Agricultural Exports During Recent Drought in California

Abstract

In recent years, the western United States has been experiencing severe droughts. In this paper we focus on the state of California, which has a complex and vast water conveyance and irrigation system to support intensive agricultural production. We examine agricultural production and exports, in particular 'virtual water' exports, to better understand whether and how agricultural producers responded to recent drought conditions. We specifically focus on agricultural exports from 2010 to 2019 in order to better understand virtual water export during the recent drought. We show that despite occurrence of severe drought, California growers have largely continued their agricultural production and exports. The value of agricultural exports between 2010 and 2019 increased by 1.5 times. Water-intensive agricultural products, including dairy products and tree nuts, represent a high proportion of agricultural exports. This persistence of agricultural production and export is made possible due to a reliance on water management strategies that are unsustainable in the long term—primarily, in the case of California's Central Valley, overdraft of groundwater. We argue that despite recent policy advances such as attempts to control groundwater overuse, California's continued agricultural production and export system exacerbates an unsustainable situation, given persistence of drought conditions and the need to support many other human and ecological water uses.

Keywords

virtual water, drought, agriculture, water management, California

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1 INTRODUCTION

In recent years, the western United States has been experiencing severe droughts, which have resulted in a wide range of social and ecological impacts. Impacts include groundwater depletion, exacerbation of wildfires, degradation of aquatic and terrestrial ecosystems, and impacts on drinking water supplies and hydroelectric production (Cardil et al. 2021; Lund et al 2018; Chang and Bonnette 2016; Mann and Gleick 2015). Drought is not new to California by any means (e.g., Vaux 1992; U.S. Drought Monitor 2022), but recent droughts have set new records and have been linked to anthropogenic climate change (Diffenbaugh et al. 2015). Severe droughts have negative social impacts on vulnerable populations, which are differentially and inequitably experienced (Feinstein et al. 2017; Greene 2018).

In particular, drought has the potential to affect water-dependent industries – notably the agricultural sector (Howitt et al. 2014; Harou et al. 2010). Agriculture accounts for approximately 70-80 percent of the surface water supply in the western United States (Dieter et al, 2018). In this paper we focus on the state of California, which has a complex and vast surface water conveyance and irrigation system to support its intensive agricultural production system (Hanak et al. 2011). We examine agricultural production and exports, in particular 'virtual water' exports, to better understand whether and how agricultural producers respond to drought conditions. We show that in response to regular occurrences of drought and surface water limitations, California growers have largely continued their agricultural production and exports, but have intensified reliance on groundwater for agricultural needs, a move that has been characterized as maladaptation (Christian-Smith et al. 2015).

There is high demand for California-grown agricultural products both nationally and around the world. The global export of California's agricultural products, as well as the export of agricultural products to other regions of the United States, results in an indirect transfer of California's water, a concept known as 'virtual water' or 'water footprint' (Lovarelli et al. 2016; Konar et al. 2011; Oki and Kanae 2004). In this paper, we examine California's agricultural exports to better understand the export of virtual water in a water-stressed environment, focusing in particular on the relationships among virtual water exports, drought, and groundwater withdrawals.

Both the terms 'virtual water' and 'water footprint' refer to the water used to produce goods and items, but each has a slightly different emphasis. Virtual water typically focuses on exports from one country to another in order to trace the flows of water in the form of exported goods (Oki and Kanae 2004). The goal of measuring virtual water is to better understand global trade patterns and associated water flows. Meanwhile, the water footprint concept is oriented toward providing a detailed view of the environmental impact of an item or product. Water footprint is often divided into blue, green and grey water: blue water refers to the amount of surface water and groundwater required to produce an item; green means the amount of rainwater evaporated or used directly to produce an item; and grey refers to the amount of freshwater required to dilute the wastewater generated in manufacturing to maintain water quality (Mekonnen and Hoekstra 2011). While the concept of water footprint is geared toward allowing individuals to better understand the impacts of their consumption patterns, gain awareness of water sustainability, and to compare impacts

different items they consume, virtual water is better suited to understanding water use patterns in relation to exports. In this study, we use the concept of virtual water instead of water footprint for this reason.

Most previous studies have examined virtual water trade at a global (Wu et al. 2019; Zhang et al. 2016; Chen and Chen 2013; Konar et al. 2011; Hoekstra and Hung 2005) or a national level (e.g., Tian et al. 2018 for China and Lee et al. 2016 for Korea), with a few exceptions that examined bilateral trades (e.g., Jiang and Marggaraf 2015). For example, analysis by Zhang et al. (2016) showed that the structure of virtual water trade in China was highly concentrated on several trade partners, such as the United States and Brazil, noted that the net import volume of virtual water embedded in agricultural products increased 6.5 times during 2001-2013, and found that soybeans accounted for the largest quantity of virtual water embedded in agricultural products. Yet, in examining virtual water at the national scale, these studies are not typically able to connect their analysis of virtual water to dynamic, locally and regionally grounded ecological processes. For example, Brazilian soybean production threatens the environment through deforestation and development of massive transportation infrastructure in Brazil (Fearnside 2001); yet the aforementioned national-scale analysis of virtual water trade between China and Brazil does not capture these dynamic and grounded processes of socio-ecological degradation associated with the agricultural production. Further, existing analyses of virtual water trade typically do not examine changes in virtual water transfer in relation to climate variability and drought. As such, these studies offer limited insights on the policy implications for export-driven agriculture in relation to climate variability and water resource management at a regional and a local scale.

In our study, we address this gap in the literature by focusing on a specific region that has been heavily impacted by drought, and connecting a virtual water analysis to a broader examination of water use, drought, and sustainability. We specifically focus on agricultural exports during the 2010s in order to better understand virtual water export during the drought which includes the severe regional drought that peaked from 2014 to 2017 (Chang and Bonnette 2016). We examine how much water was exported in the form of agricultural products during the drought, and the destinations for agricultural exports during this time period. We also examine environmental impacts, in particular declining groundwater levels, which are related to imbalances between water use and water availability. We use this analysis to discuss the sustainability of export-oriented agriculture in California.

2 METHODS AND DATA

2.1 Study Region

Located in an arid-to-semiarid climate, California is the leading agricultural-producing state in the United States. In addition to supplying more than one-third of all vegetables in the U.S. and two-thirds of all fruits and nuts in the U.S. (CDFA 2021), California's agricultural exports have increased every year, rising to $21.7 billion in agricultural exports in 2019. California's role as a global leader in agricultural production is directly

attributable to its extensive irrigation system.

There are two main irrigated agricultural regions in California: the Central Valley and the Riverside/Imperial area of Southern California (Figure 1). The Central Valley region consists of productive farmland and is mainly an irrigated agricultural system. Water supplies in the Central Valley rely on a combination of local and imported surface water, which comes from Northern California via major irrigation conveyance infrastructure (the State Water Project and the Central Valley Project), and groundwater pumping (Jeanne et al. 2019). Groundwater has been largely unregulated historically, and as such has been overdrawn in the Central Valley in particular; groundwater in California only begun to face regulation as of 2014 via California's Sustainable Groundwater Management Act (SGMA), which requires local agencies to manage groundwater and mitigate overdraft. The land in the Central Valley has low relief and is suitable for agriculture due to the accumulation of alluvial and fluvial deposition of sediments derived from the bordering mountains (Sneed et al. 2013; Farrar and Bertoldi 1988). Meanwhile, the Imperial Valley region of Southern California is extremely arid, and is only a productive agricultural region due to its extensive irrigation system. This area receives water from the Colorado River Basin via the All-American Canal, with senior water rights to valuable Colorado River water. Water management in California has long been recognized as highly political and controversial, driven by power and politics (Reisner 1986; Worster 1985).

Overall, agricultural irrigation accounts for about 80% of the water used for all business and domestic use in California (Mount and Hanak 2019). Over recent decades, agriculture in California has shifted toward higher-value crops such as nuts, grapes, and fruit, increasing the value of agricultural production and the economic return on irrigation water used for crop production. Despite growth of agricultural value, agricultural water use has remained fairly steady for the past fifty years. Although California has also experienced urban and population growth during this time, agriculture has remained the dominant water user in the state by far (Dieter et al. 2018).

In this analysis, we specifically focus on the period from 2010 to 2019. This period was chosen because California faced a severe drought in the middle of this decade, which peaked between 2014 and 2017 (Figure 2). This severe drought caused many impacts ranging from ecosystem damage to drying of residential wells (Lund et al. 2018; Chang and Bonnette 2016). Yet, despite the severity of California's droughts, research has shown that agricultural production did not decline in a straightforward or uniform way in response (Cantor et al. 2022; Tortajada et al. 2017). In this paper, we further examine the relationship between water availability and agricultural production.

2.2 Data and Analysis

Table 1 shows the data we used in this paper and their sources. Annual data on agricultural products and exports in California were obtained from the California Agricultural Statistics Review and California Agricultural Exports published in the California Department of Food and Agriculture (CDFA), and the United States Department of Agriculture (USDA).

Figure 1. Irrigated farmland in California. Map Created by Elizabeth Martin, Portland State University. Data sources: California Department of Conservation, Natural Earth, Princeton University Library, and US Census Bureau.

To calculate virtual water exports, we used California's average water footprint of crop or derived crop product dataset from Mekonnen and Hoekstra (2010a). The water footprint was calculated using each agricultural and animal product's total annual exported weight multiplied by California's average water footprint of that crop (as calculated by Mekonnen and Hoekstra 2010a). We used country-level data rather than state-level for animal products due to the lack of availability of regionally specific data for animal products in particular (Mekonnen and Hoekstra 2010b). We also examined export destinations by country using CDFA and USDA data, and calculated the embedded virtual water for each product and how they have changed between 2010 and 2019. The California Department of Water Resources SGMA Data Viewer was used to complement our virtual water analysis by examining groundwater level and land subsidence trends since 2009.

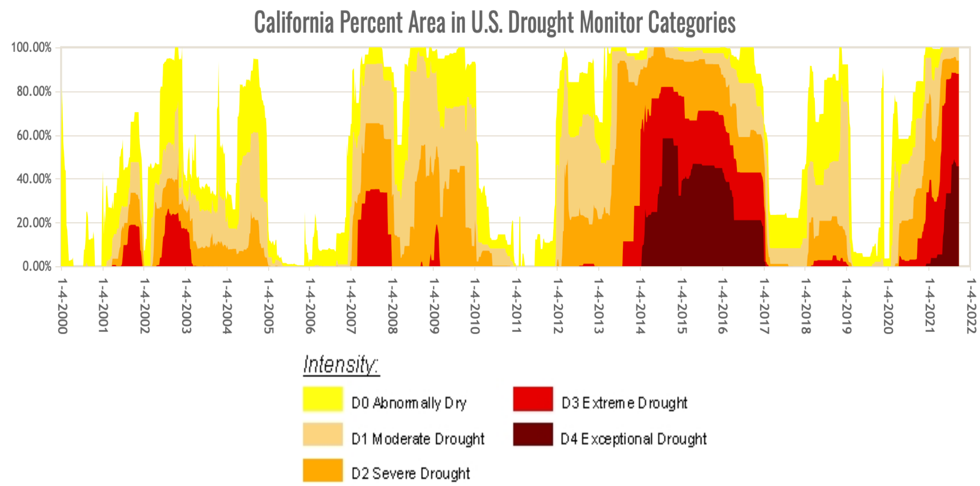

Figure 2. Percent area of California experiencing drought between 2000-2022, showing peak period of "exceptional drought" between 2014-2017. Source: U.S. Drought Monitor, National Drought Mitigation Center, Data Archive. "Exceptional drought" is defined by the U.S. Drought Monitor as "exceptional and widespread crop/pasture losses, and/or shortages of water in reservoirs, streams, and wells creating water emergencies."

Table 1. Data and sources.

Data	Source
Annual data on agricultural products and exports in California.	· California Agricultural Statistics Review (California Department of Food & Agriculture, CDFA, 2011-2020) · California Agricultural Exports (United States Department of Agriculture, USDA, 2011-2020)
California average water footprint of crop or derived crop product / The United States farm animals and animal products data.	·Mekonnen and Hoekstra (2010a, 2010b)
Groundwater level trends.	·The California Department of Water Resources SGMA Data Viewer. · National Water Information System (United States Geological Survey, 2010-2019)
Land subsidence.	· California Department of Water Resources SGMA Data Viewer.

3 RESULTS

3.1 California's Agricultural Exports from 2010 to 2019

From 2000 to 2019, the overall value of California's agricultural exports increased by 3.2 times, from $6.9 billion to $23.5 billion. California's severe drought began in 2014 and lasted for more than three years. During this period of drought, a slight dip in

agricultural export value is evident (Figure 3), but even during the drought, agricultural exports remained over $20 billion per year, far higher than pre-drought export values. Even at the height of the drought event, agricultural export values remained higher than any time in history before 2012, and after the drought, the value of agricultural exports reached an all-time high in 2019 (CDFA 2020).

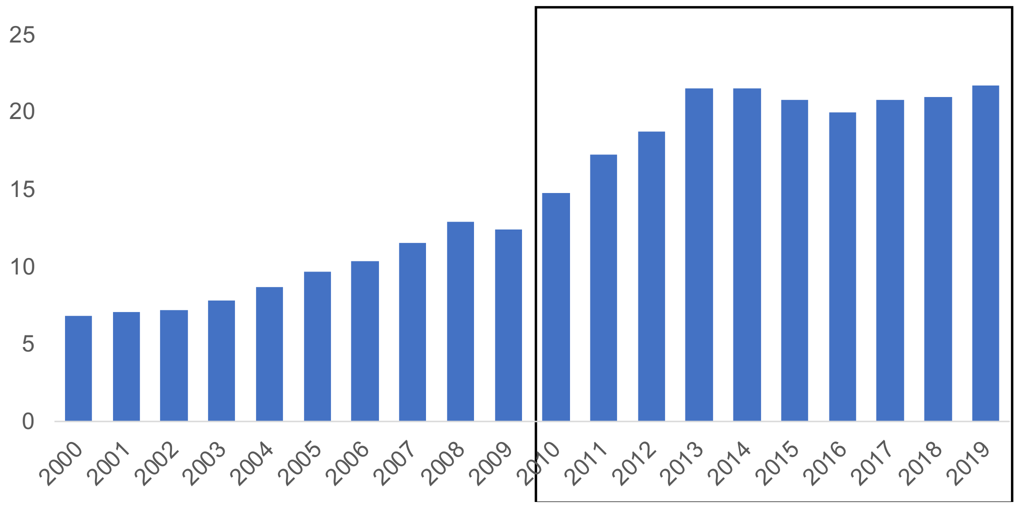

Figure 3. Total export value of California agricultural products, 2000-2019. The box around the time period from 2010-2019 indicates the time period that we examined for the virtual water analysis in the rest of the paper; the longer time frame is presented here for context. Data source: USDA.

Examining California's export agriculture at a crop level shows that tree nuts are a particularly high-value export commodity that is quickly growing (Figure 4). California's tree nut industry (which includes pistachios and almonds) showed a marked increase in production between 2000 and 2019, with the highest growth rates of any of the crops we examined (Figure 4(a)). Tree nuts exhibited a slight dip in 2016 export production values (Figure 4(a)), but once the drought conditions started to improve in 2017, total export value immediately bounced back.

Other agricultural exports (including fruits, vegetables, and dairy) also persisted throughout the drought and did not exhibit decline in export value (Figure 4(a)). These crops remained fairly steady compared to the large increase in tree nuts. Tree nuts are currently the highest value item for California's exported agricultural products, and their value is at an all-time high (Figure 4 (a)). Examining the overall volume of exports in terms of tons (rather than dollar value), dairy and dairy products stand out as a dominant and growing commodity (Figure 4 (b)). Compared to other top commodities, tomato exports decreased from 2010-2019, and exports of other products such as grapes, rice, and hay have stayed relatively steady, but dairy exports have continued to grow.

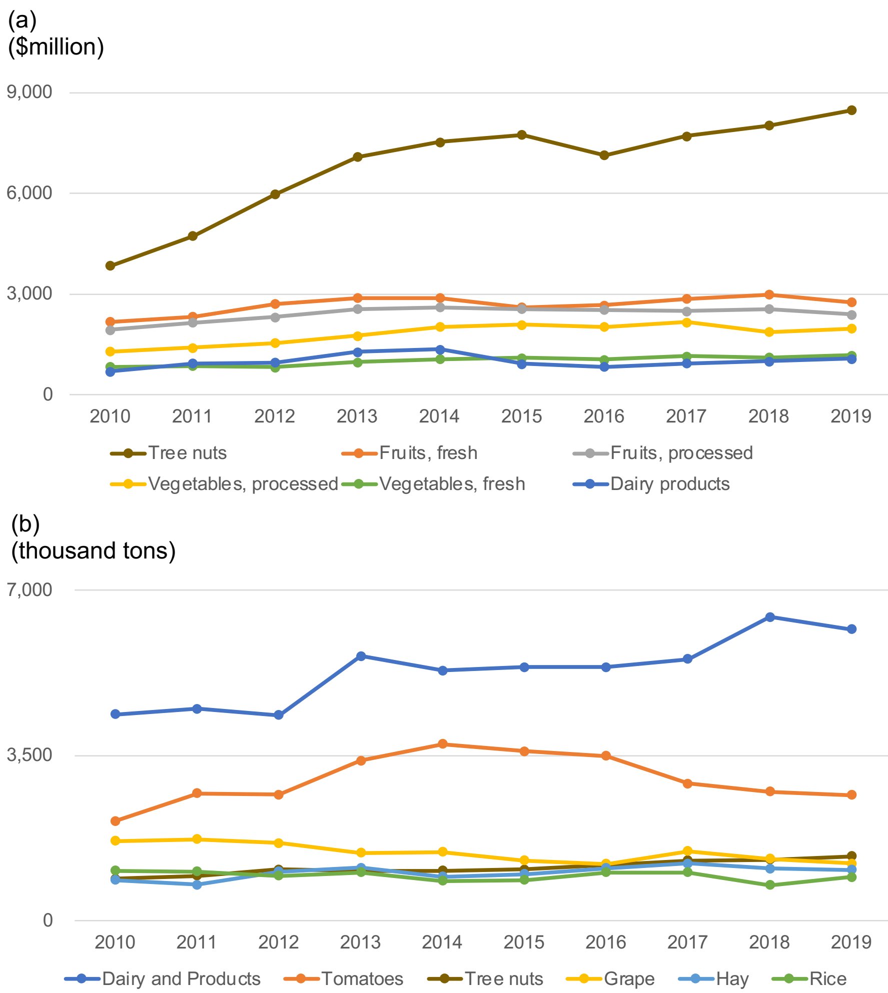

Figure 4. (a) Exported value of several top agricultural commodities in California, 2010-2019, Tree nuts are the highest export value item for California agricultural products. The value is at an all-time high. (b) Farm exported quantity of Top 6 commodities in California for 10 years. Dairy and dairy products stand out as a dominant and growing commodity. Data source: CDFA.

Figure 5 shows the ratio of agricultural exports as compared to the total quantity of agricultural production, focusing on the top commodities of tree nuts and dairy products. The ratio of California farm quantity exported to farm quantity produced was over 60 % in tree nuts, and over 30 % in dairy and products in 2019. The export rate of walnuts and dairy products increased by about 10 percent each during the period 2010-2019. By the end of the time period examined (2019), pistachios exhibited the highest export rate, about 77%, although over the previous decade the export rate of pistachios has fluctuated widely.

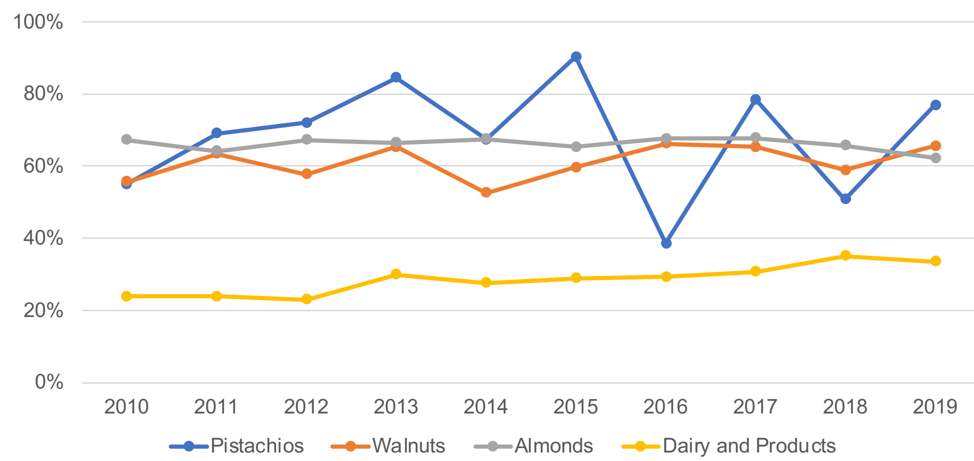

Figure 5. Ratio of California farm quantity exported to farm quantity produced, 2010-2019 (export volumes calculated on farm weight basis). Data source: CDFA.

3.2 Virtual Water Embedded in California's Agricultural Exports

The dominance of both tree nuts and dairy as exported agricultural products is notable because both nuts and dairy are extremely high water-intensive products. Alfalfa, an input for dairy and meat production, represents the largest net agricultural water user in California, followed by almonds and pistachios (Johnson and Cody 2015). Together, alfalfa (for dairy/meat), almonds, and pistachios account for approximately 1/3 of total net agricultural water use (Johnson and Cody 2015).

The virtual water embedded in exported agricultural products varies by product. The largest water volume is embedded in tree nuts, such as almonds, pistachios and almonds. Exported tree nuts embedded over 15 Gt of virtual water in 2019. As Figure 6 shows, tree nuts represent a significant increase in the export of virtual water. Over the study period, water footprint exports to tree nuts increased by about 50%, while dairy increased by 41%. Rice decreased by 13%, with a water footprint of 2.2 Gt. The next largest volume of virtual water is embedded in dairy and products. Virtual water value of dairy and products is calculated as milk, which is the minimum value.

We next examined export destinations for tree nuts (Figure 7) and dairy products (Figure 8) since these represented the largest categories of virtual water in exported crops. EU-28 was the largest export destination for tree nuts products, followed by China/Hong Kong, India, Canada, UAE, Japan, and South Korea in 2019 (Figure 7 top). In particular, the rate of increase in exports to India is notable. India had the highest increase in water footprint exports over the past decade with a 2.3-fold increase, followed by Canada with a 1.7-fold increase, and to the EU and Japan with a 1.6-fold increase. The export value of tree nuts, such as almonds and walnuts, has increased about tenfold between 2000 and 2019.

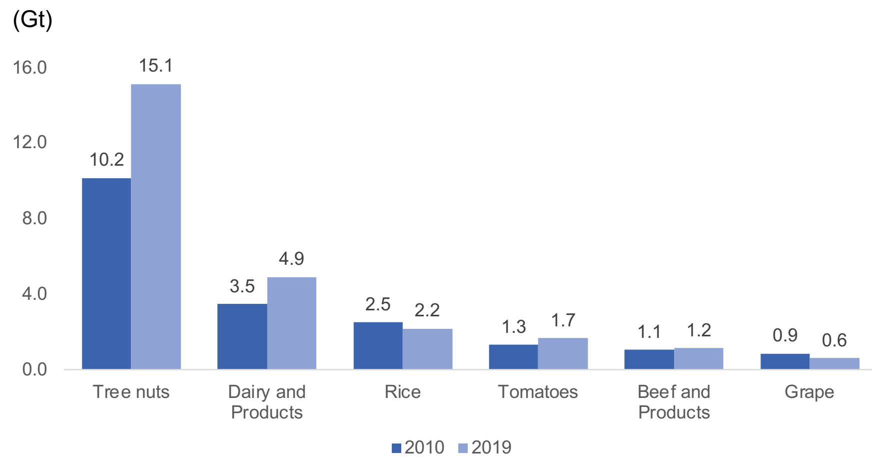

Figure 6. The virtual water embedded in exported agricultural products of California in 2010 and 2019. Large virtual water volumes are embedded in tree nuts (almonds, walnuts and pistachios) and dairy and products. Virtual water value of dairy and products is calculated as milk, which is the minimum value.

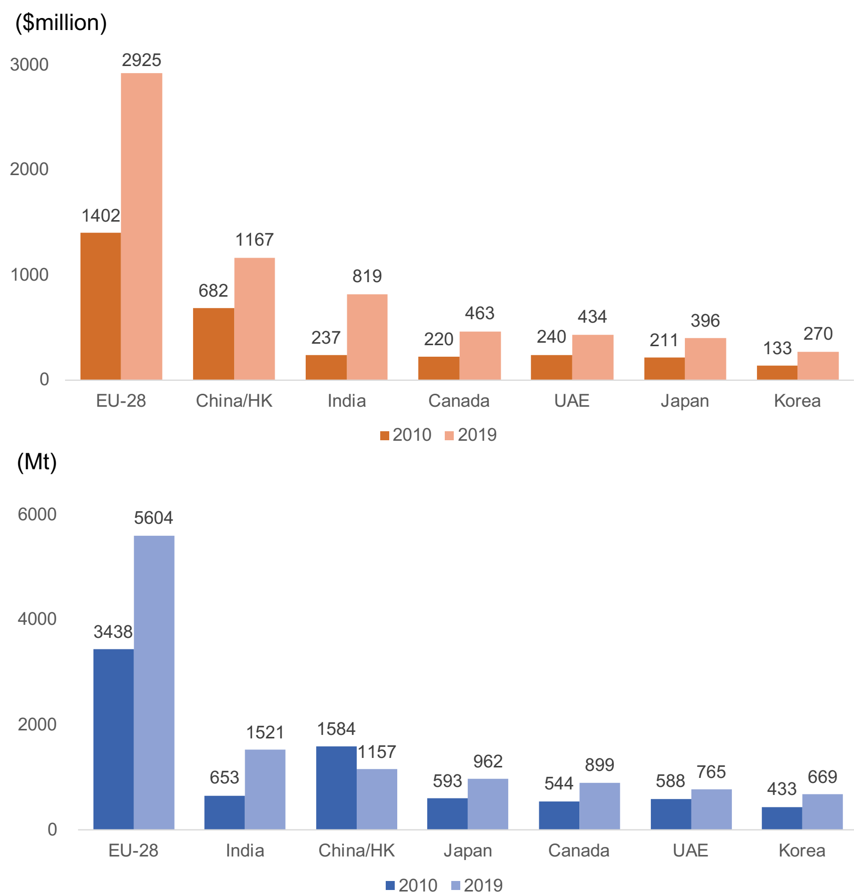

Figure 7. California's tree nuts (almonds, walnuts, pistachios) export value and destination in 2010 and 2019. The top graph shows US dollar value of tree nut exports to various destinations, while the bottom graph shows total exported water footprint of tree nuts in millions of tons of water.

Dairy products are the second largest share of California's virtual water outflow (Figure 6). Mexico was the largest export destination for dairy products, followed by the Philippines, China/Hong Kong, South Korea, and Canada in 2019 (Figure 8). In particular, the rate of increase in exports to Taiwan, Australia, and South Korea is very high. Export value of dairy and products to Taiwan has increased 7.1 times in the past 10 years. During the same period, the value of exports to Australia and South Korea increased 3.7 times and 3.5 times, respectively. Over the study period, the largest increase in exported water footprint has been in Taiwan (6.4 times), followed by Australia (3.4 times) and South Korea (3.3 times).

It is notable that some of California's largest and most rapidly growing agricultural exports—tree nuts and dairy products—are also some of the most water intensive. If export of water-intensive nuts and dairy products continues to increase, virtual water export will continue to increase as well, unless significant changes to agricultural production practices occur.

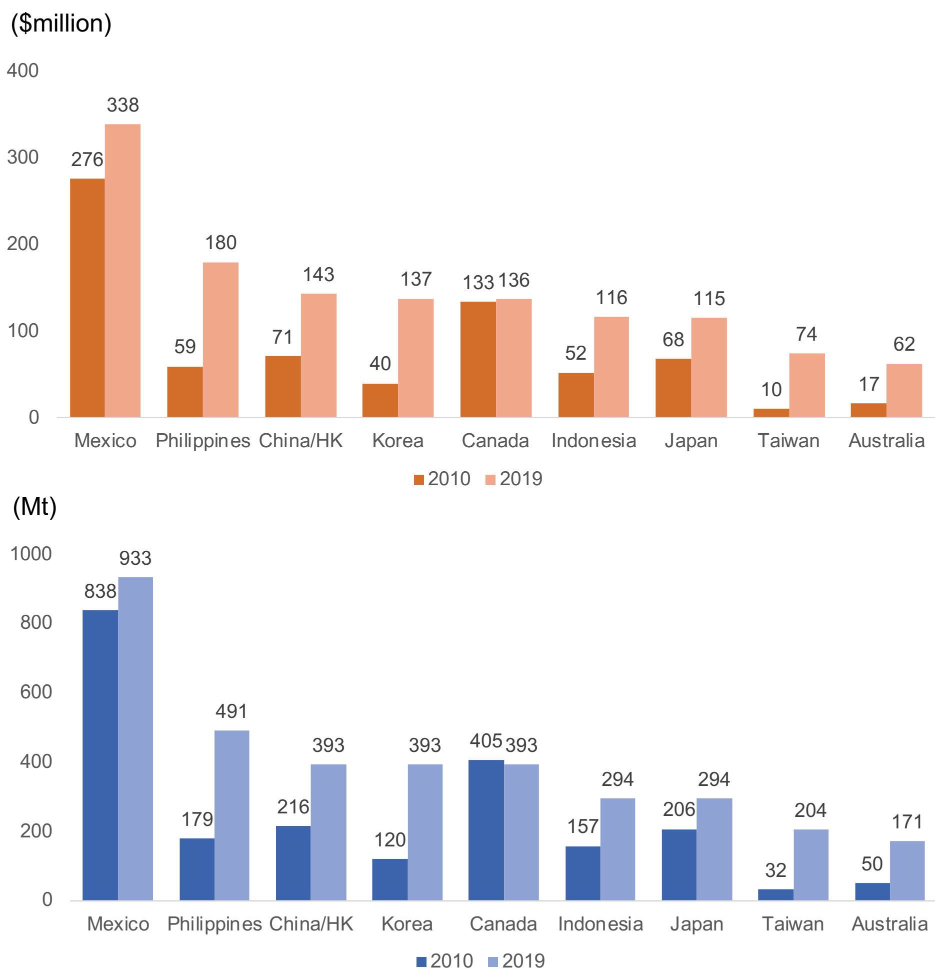

Figure 8. California's Dairy and dairy products export value and destination. The top graph shows US dollar value of dairy exports to various destinations, while the bottom graph shows total exported water footprint of dairy in millions of tons of water.

3.3 Understanding Groundwater Impacts of Export Agriculture During Drought

California's agriculture is centered in the Central Valley (see Figure 1). Within this region, the places with the highest value of agricultural products shipped include Fresno, Kern, Tulare, Monterey, and Stanislaus Counties (Figure 9). Fresno County had the highest agricultural production value in California in 2019; its main products are almonds, pistachios, livestock, and table grapes. The next highest producing county is Kern County, where the main products are almonds, table grapes, pistachios, and milk. The third most productive county is Tulare, County where the leading commodities are milk, oranges, grapes, cattle & calves. In all of these top three counties, dairy products and tree nuts, discussed above, are among the main commodities produced.

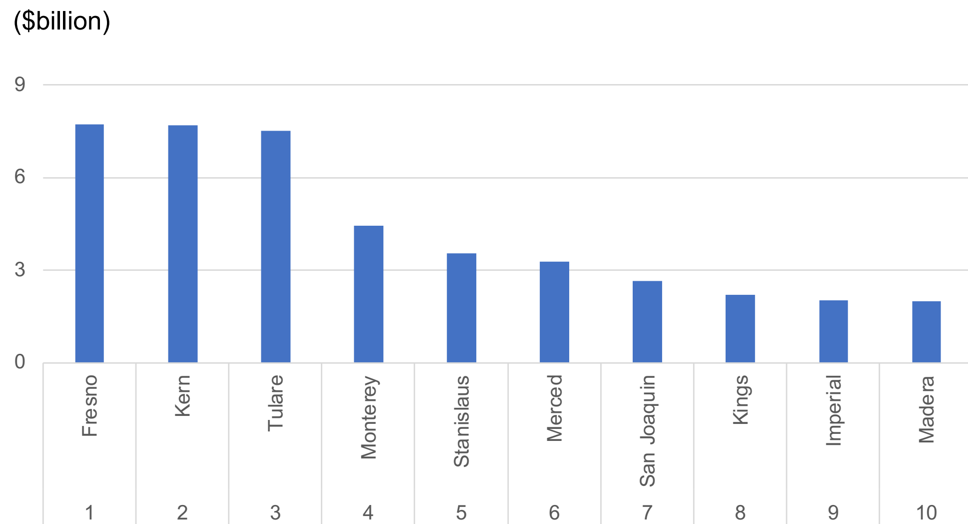

Figure 9. County rank, total value of agricultural production value in 2019. Data source: CDFA.

Fresno, Kern, and Tulare Counties all experienced a drop in production during the time of the severe drought in California, from 2014-2017, but recovered by 2017. Tulare County exhibited the largest amount of change: it was the top county by gross value of agricultural products in California from 2013 to 2015, but then declined and recovered from 2017 to become the third largest producer in California in 2019. Still, all three counties showed similar patterns of overall growth in agricultural production from 2010-2019 with only a small dip during the time of drought (Figure 10).

At the same time as the total value of agricultural production was increasing, surface water supplies were notably low. These regions received less than 400 mm of annual precipitation in 2010-2019, less than half the historical average, which represents a drought more severe than during the previous worst drought in California's history (1976-1977). In some agriculturally intensive areas, including Imperial County and Kern County, the total annual precipitation throughout the entire decade (2010-2019) was less than 1000 mm. However, the total value of agricultural products during the same period increased, as described above. In California’s Central Valley, this growth in agricultural production during a time of drought and low availability of surface water was made possible through reliance on groundwater

pumping. Groundwater levels dropped in the Central Valley during this time, despite the introduction of new groundwater management legislation through California's Sustainable Groundwater Management Act (SGMA) in 2014. For example, in Kern County, the second largest county by agricultural production, groundwater levels have dropped 9.4 feet (287 cm) in two years from 2018 to 2020. Figure 11 shows the change in groundwater level from 2009-2019; during this time period, groundwater levels dropped markedly in the irrigated Central Valley region, decreasing by more than 3 meters in many areas of the Central Valley.

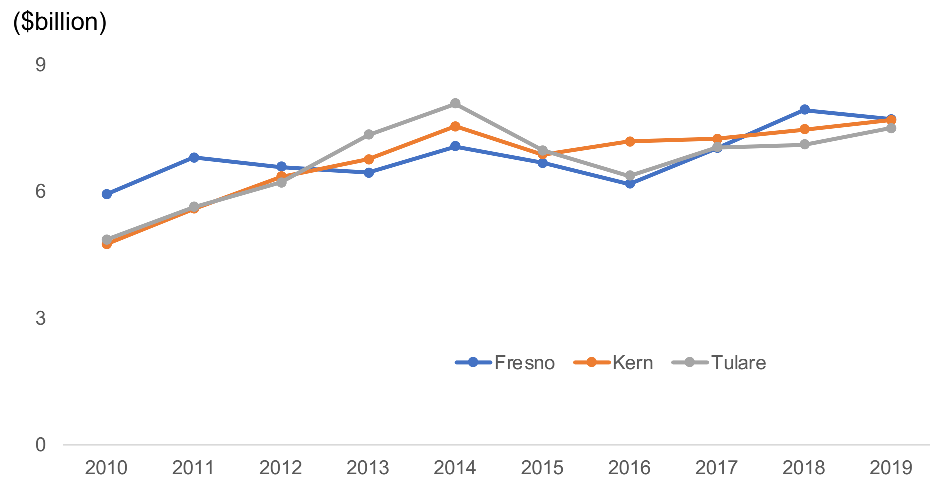

Figure 10. Total value of agricultural production of top three counties (Fresno, Tulare, Kern), 2010-2019. Data source: CDFA.

The passage of SGMA, after decades of inaction on groundwater depletion and related impacts, is important given the intensive groundwater overdraft in California's Central Valley. For example, as Figure 11 shows, land subsidence is a particularly significant consequence of groundwater depletion. Subsidence can occur when large amounts of groundwater are overdrawn, causing land to permanently sink. Land subsidence in the Central Valley is a significant problem that has been investigated and documented (Jeanne et al. 2019; Sneed et al. 2013; Bull 1975; 1964) and linked to groundwater pumping for agriculture. While SGMA was intended to halt overuse of groundwater and associated impacts including subsidence, the act faces implementation challenges and will take decades to fully implement (Leach et al. 2021; Lubell et al. 2020; Kiparsky et al. 2017).

4 DISCUSSION: DRIVERS AND CONSEQUENCES OF VIRTUAL WATER EXPORT

The practice of exporting virtual water in the form of agricultural products produced in drought-stricken California to other countries may seem paradoxical, but it is a trend that can also be seen in other countries. For example, within China, significant quantities of grain are produced in the arid northeast of China and sent to the south

where there is more population and water (Cai et al. 2019; Sun et al. 2016; Zhang et al. 2016; Zhao et al. 2015; Guan and Hubacek 2007). In both the cases of California and China, agricultural production is concentrated in areas with high-quality farmland and lower urban populations; however, these same areas may be prone to drought, creating long-term water sustainability issues when scarce water is used for agricultural exports (Escriva-Bou et al. 2020).

It is important to consider the political and economic contexts that drive export-oriented irrigated agricultural production even during times of drought. For example, Free Trade Agreements (FTAs), agreements between countries that seek to encourage international trade, have been shown to impact virtual water patterns (Falsetti et al. 2022; Dalin et al. 2012). The US has Free Trade Agreements in force with twenty nations, including Canada, Mexico, Australia, Korea, Japan, and more. Here we consider several of the countries that represent high growth as receiving destinations of agricultural exports from California, including Korea and Japan. Korea signed Free Trade Agreements with the United States in 2007 (United States Trade Representative, hereafter USTR 2007). On March 15, 2012, the United States-Korea Free Trade Agreement (KORUS FTA) went into effect. Significant growth in agricultural exports from California to Korea can be seen after the agreement went into effect: the export value of California agricultural products to Korea increased 1.8 times between 2010 and 2019, and Korea was the fifth largest agricultural product export market for California in 2019. In recent years, California agricultural products have become increasingly popular as the KORUS FTA has lowered tariffs and made prices more competitive. Japan has also exhibited growth as a destination of California's agricultural exports, a trend that is likely to continue. Japan was California's fourth-largest agricultural export market in 2019. In 2019, the US and Japan reached a free trade agreement to reduce or eliminate tariffs on certain agricultural products produced in the U.S., and for Japan to provide preferential U.S.-specific quotas on other agricultural products (USTR 2019). More than 90% of U.S. food and agricultural items imported into Japan will be duty free or have preferential tariff access after the agreement is implemented. As a result, tariffs on many of the water-intensive products that we examined in this paper, including almonds, walnuts, and cheeses, will be eliminated immediately or are scheduled to be phased out. For example, under this agreement, Japan's 40 percent cheese tariffs will be eliminated in 15 years (USTR 2019). This provides a context in which export of Californian agricultural products to Japan can be expected to increase, which in turn would increase export of virtual water.

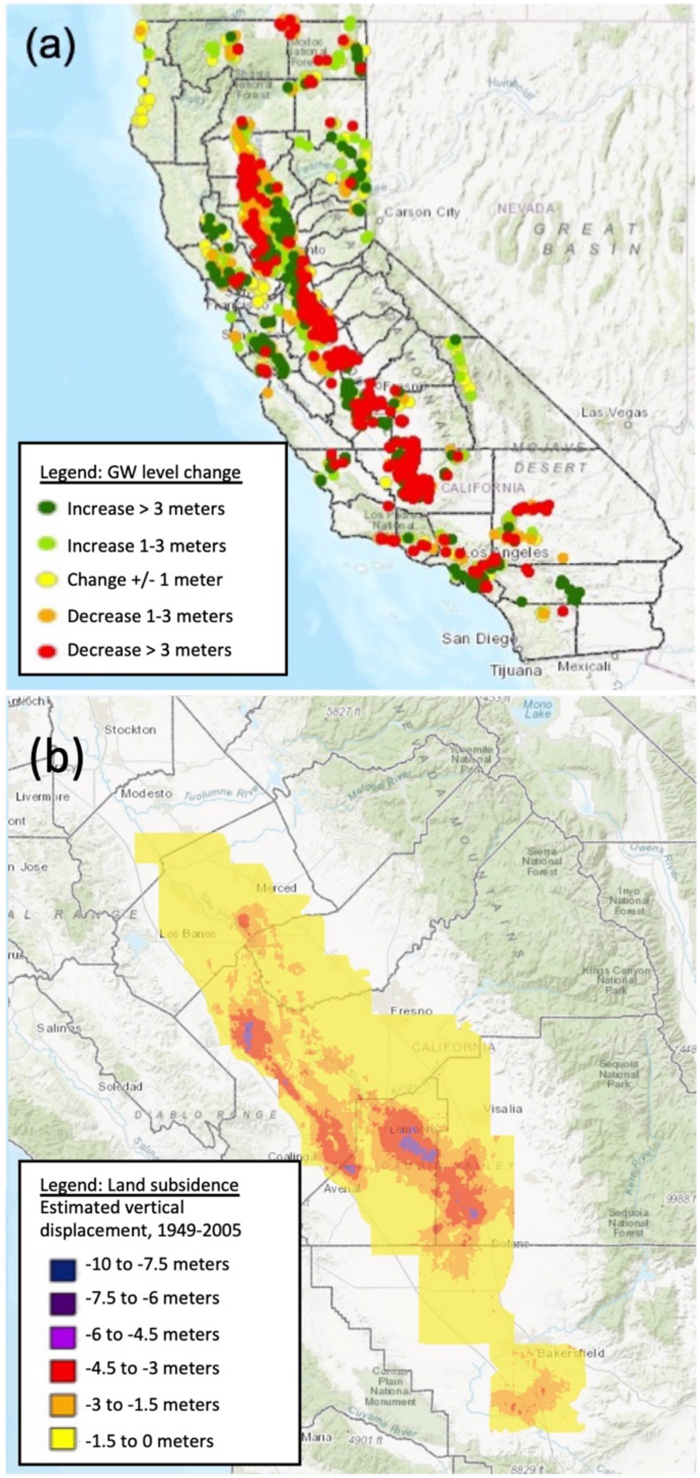

Figure 11. (a) Change in groundwater level from 2009-2019 (Note: Data were only available for 2009 rather than 2010, so this map's time scale is slightly different than the time scale used elsewhere in this paper.) (b) Land subsidence from 1949-2005, focus on California's Central Valley (Note: the time scale reflects data availability). Data source: Map created using California Department of Water Resources SGMA Data Viewer.

It would be reasonable to expect that droughts would have a significant negative impact on agricultural production, and that when droughts are severe, agricultural productivity would decline in response (Pathak et al. 2018; Rosenzweig et al. 2001). Relatedly, it could be reasonably expected that agricultural exports would decrease along with agricultural production during drought (Berardy and Chester 2017): if water resources are scarce, presumably local water managers would want to avoid exporting water in the form of agricultural goods. However, we observed that agricultural exports persisted during drought in California. Agricultural export values barely dipped during the severe drought beginning in 2014 (see Figure 3) and throughout the drought, remained higher than a few years previously. In particular, production and export of tree nuts and dairy products, which are both notably high-water users, persisted throughout the drought (see Figure 4). This finding echoes other research, which has also shown that agricultural production persisted during drought in California (Cantor et al. 2022; Marston and Konar 2017; Tortajada et al. 2017).

Despite the obvious presence of meteorological drought in California, agricultural systems were not impacted as severely as expected. Agricultural drought can be mitigated through strategies such as increased extraction of groundwater resources and importing water via complex conveyance systems. Groundwater depletion is a particularly significant consequence of maintaining high agricultural production during times of surface water drought. By maintaining production of irrigated agriculture, groundwater resources become overdrawn to make up for surface water scarcity. The trend of over-reliance on finite groundwater resources is one that can be seen in many places. For example, in California, 40.0 km^3 of groundwater was lost from October 2012 to September 2016 (Xiao et al. 2017) despite implementation of a new groundwater management policy during this time. This trend can be seen in other places as well. For example, farmers in some areas of Kansas and Texas can no longer pump enough water to fulfil crop demand due to depletion of the Ogallala Aquifer as a result of unsustainable irrigation practices (Basso et al. 2013). Declining groundwater levels can have many negative consequences. ‘Mining’ of groundwater resources causes groundwater levels to drop faster than they are replenished, resulting in devastating consequences such as land subsidence, saltwater intrusion along the coast, and impacts to groundwater-dependent ecosystems (Taylor et al. 2013). Exporting groundwater in the form of agricultural products has come under increased scrutiny. For example, Marston et al. (2015) recently examined virtual groundwater transfer as a specific sub-type of virtual water export, examining the groundwater that is embodied in irrigated agriculture, and found that virtual water transfer in the form of agricultural products involves significant quantities of groundwater and is a substantial contributor of the depletion of groundwater in the Central Valley of California.

The strategy of importing water from nearby regions via canals and aqueducts is limited as well, since drought at the regional level can impact the source regions where the water is drawn from. For example, Southern California’s Imperial Valley receives significant quantities of irrigation water from the Colorado River Basin, but the Colorado Basin itself is an over-allocated system that frequently experiences drought stress (Cantor 2021). Thus, the adaptations that enable export agriculture to persist during drought cause unsustainable impacts that are frequently not included in the cost

of production, but are borne by ecosystems and surrounding communities throughout the broader region (MacDonald 2010). Short-term adaptive strategies may be unsustainable in the long term (Tortajada et al. 2017) or even maladaptive (Christian-Smith et al. 2015) as the occurrence of severe droughts and groundwater depletion are likely to continue. As pointed out by Van Loon (2016), definitions of drought must include water shortages caused and modified by humans, in addition to precipitation patterns.

5 CONCLUSIONS

In California, despite a very severe drought for several years starting in 2014, the value of agricultural exports between 2010 and 2019 increased by 1.5 times. The value of agricultural exports in 2019 reached an all-time high. This agricultural persistence is made possible due to a reliance on water management strategies that are unsustainable in the long term—primarily, in the case of California's Central Valley, overdraft of groundwater. The overuse of groundwater by agriculture in California has caused many issues including land subsidence, impact on domestic wells, and damage to groundwater-dependent ecosystems. Import of water from nearby regions such as the Colorado River Basin is another example of a water management strategy that may be unsustainable due to increasing drought and pressure from other water users. Agriculture that relies upon unsustainable water management strategies exacerbates ongoing drought problems in arid regions.

California's agricultural production is characterized by a growing volume of exports to foreign countries, resulting in significant virtual water transfers. Global demand for tree nuts and dairy products, which require large quantities of water to produce, continues to increase and is expected to increase further as global income levels rise and more free trade agreements are implemented. California shows no sign of slowing its production of these water-intensive commodities, even after experiencing severe drought. However, if California continues to rely upon use of surface and groundwater resources for agricultural production and export, the environmental impacts will continue, damaging ecosystems and leaving fewer resources for the generations to come. Perhaps, given the many competing water needs of humans and ecosystems, now is the time for California to rethink the sustainability of the current agricultural production system, including the export of virtual water in the form of agricultural products.

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