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# The California drought: Coping responses and resilience building

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ABSTRACT

Building resilience to extreme events is very complex. It involves consideration of climatic and non-climatic factors, human and natural environments and their dynamics, and governance systems that include groups with wide-ranging authorities, influence and interests. In this article, we analyse the effects of the latest multi-year drought (2011–2016) in agricultural production in California; impacts on food security; and coping responses of several actors. We found that despite the drought and water shortages, California continued to be the leading state for fruit and tree nuts and that it did not affect food security. We also found that these results were strongly influenced by the numerous policy, regulatory, institutional, and management decisions taken at the local, state and federal levels, as well as to availability of groundwater, the primary drought reserve. The California case can be considered an example for the rest of the country, and the world, that extreme events require extraordinary preparedness and response measures just to cope with them, not to mention adapting to them, and that building resilience is a long-term process.

## 1. Introduction

Water management and climate change and variability, as well as their numerous interlinkages and the extent of related hydrologic, economic, social, environmental and political impacts over time and space, have become of increasing global concern. Uncertainties that prevent us from forecasting the likely future multidimensional and multi-sectoral impacts of climate change make policy alternatives, management, governance and development decisions, as well as investment choices on adaptation strategies, most challenging under the best of circumstances. As a consequence, non-climatic factors have become more relevant. Resource use and governance—that is, decision-making by multiple actors with numerous and dissimilar interests, and the formal and informal institutions they form—are some of the most important ones (Tortajada, 2016).

From the anthropocentric viewpoint, there is the concern that the extent and speed of the effects on global and local human and natural environments will be such that policies and institutions will not be enough to provide appropriate and timely responses. This, in turn, will result in economic, social, environmental and political vulnerabilities that will expose humankind to risks of irreversible change. (Carrao et al., 2016; Mastrandrea et al., 2015; Turner et al., 2013).

Resilience is often mentioned in the context of climate change as the ability of a social or ecological system to absorb disturbances while retaining the same basic structure or ways of functioning, the capacity for self-organization, or the capacity to adapt to stress and change (IPCC, 2007). However, system complexity is such that the prevailing language of 'resilience' may not necessarily reflect the practical realities (De Bruijn et al., 2017). In many situations, there may be mainly coping responses to address, manage, or simply overcome adverse conditions to achieve basic functioning in the short to medium terms (IPCC, 2012), as in the case of California. Therefore, rather than assuming that coupled systems can gain resilience, it should be acknowledged that the dynamic nature of human systems, characterized by constant change, may preclude them from becoming resilient. As Folke et al. (2010) have noted, this requires further understanding of the coupled systems as interdependent systems that adapt or not, and also transform or also can be made to transform.

This paper investigates decision-making and resource availability as essential elements to build resilience in a changing environment. It is part of a series of analyses of impacts of extreme events on coupled human–environmental systems and on their perceived resilience (e.g. Kastner, 2016; Tortajada, 2016; Tortajada et al., forthcoming).

The focus of our analysis is the effects of the 2011–2016 drought in agricultural production in California and the possible impacts on food security. We also discuss the importance of groundwater as the primary drought reserve, the coping responses and the decisions that were taken with the aim to build resilience. Finally, we present the policies that were taken at the state and federal levels to ameliorate the impacts of the drought. Our findings indicate that there were numerous

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management, operational and policy arrangements that helped the farmers to cope with the situation in the short- and medium-terms. Equally, that there were policy responses that aimed at building a more resilient system in the long-term. Overall, it was groundwater availability what helped to sustain agricultural production of the most valuable crops.

## 2. Addressing uncertainty through decision-making

The current global discourse emphasizes that the extent of change the coupled human–environment systems are facing and will continue to face, requires a new paradigm (Béné et al., 2014; Linkov et al., 2014). This paradigm should provide responses to the innumerable unknowns, and prepare humankind for the uncertain future. It is expected to encompass novelty while being based on long-term knowledge and experience; be flexible enough to provide alternatives to all types of conditions; and be sufficiently robust to lead policymaking and institutional responses with a certain hand into the uncertain future.

The lack of such paradigm and thus of a related policy framework, plus the number of interrelated constraints —economic, social, environmental, political and technological— present a serious global challenge. This has resulted in insufficient preparedness of formal and informal institutions on the types of responses that are and will be needed to address the many future possible but uncertain scenarios. These responses include understanding the driving forces that will shape future situations and how they will affect the coupled human and environmental systems; identification of policy, institutional and governance gaps and the ways to address them; robust financial instruments; data and information to provide evidence base for policy decisions; and, most important, decision-making in which long-term planning and not political gains are the priority.

Change affects society at large. Therefore, effective responses require collective actions determined by the modes of governance. To build resilience and foster adaptive capacity, polycentric systems are considered to be effective (Biggs et al., 2012; Underdal, 2010). They include more efficient responses to abrupt or incremental change because of the diversity of partners, more active participation processes and more open decision-making as well as inclusion of plurality of views, knowledge and experience as they provide an increased range of options (Jordan and Huitema, 2014). Polycentric systems, however, can also compromise resilience building when the scale of governance arrangements is too large, when there is lack of ability to respond cohesively to a certain situation, or when there is inconsistency between the scale of governance and the objectives. Therefore, one should not assume a linear response between polycentricity and improved decision-making. This depends on the specific situation.

Decision makers are challenged with the what, when, and how of their decisions. They are often strongly criticized for not considering adequately available information, including scientific information. Science is a very important element of decision-making, but not the only one. There are many other considerations with strong economic, social or political implications that many times take priority over science. To support decision makers to plan for more robust systems increasing their resilience, academia could make an effort to translate the concept into practice. This could include, for example, identification of policy tipping points when policies do not meet societal needs any more, and mapping alternative strategies (De Bruijn et al., 2017).

One example is that of water resources in climate change scenarios where an important question is whether and how climate change-related information can be used for water resources management decisions that are going to affect economic, social and environmental interests (Biermann et al., 2016; Biswas, 2016; Gober et al., 2010; Mastrandrea et al., 2015). What elements should be considered, and what would be the best way to include them? Traditionally, management of water resources has been based on stationarity or historical variability for estimating and managing risks (Wasson et al., 2013). Since these principles are no longer valid, water systems have to be optimized in different ways. The extent of alteration to the means and extremes of precipitation, evapotranspiration and rates of river discharges due to anthropogenic effects makes it essential to identify new nonstationary probabilistic models of relevant environmental variables (Milly et al., 2008; WMO, 2017). This is fundamental for preparedness, to aim at developing robust water systems that can respond to uncertainties about future water availability and their impacts (Gober et al., 2010), always keeping in mind the complex relationship between climate and hydrologic variability (Sheffield et al., 2012; Swain, 2015).

In the case of California, policy responses to the drought at the local, state and federal levels were very comprehensive. They were supported by robust studies from academic, research, think tank and governmental institutions. We used these extensively to strengthen the arguments of this paper.

## 3. Building resilience to extreme events: droughts and possible impacts on food security

Resilience is often discussed in the context of climate change as the ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organization, and the capacity to adapt to stress and change (IPCC, 2007). However, the related issues are much broader. Social and ecological systems have capacity to adapt to stress, and they have been essential to the progress of societies throughout the history of humankind. It has been the numerous local changes that have allowed systems to respond, cope and adapt.

In the case of climate variability and change, conceptual frameworks could be more useful for decision-making purposes if they referred more clearly to the non-climatic diversity of the local and regional contexts; if they considered the capacity of coupled human–environment systems to respond, cope and adapt to increasing stress; and if they studied the strengths and weaknesses of policy, institutional, governance, infrastructural and financial mechanisms that are necessary to fully function under different conditions. As discussed by Biermann et al. (2016) conceptual frameworks can be useful only when they consider broad cross-scalar perspectives and recognize the diversity of local and regional contexts and situations.

Some of the events related to climate and human change that expose the vulnerabilities of both human and natural environments are extreme events such as droughts and floods. They result in institutional responses (policies, management, governance or market mechanisms) that aim to re-establish a point of equilibrium for systems to respond and operate as soon as possible, initially in the short-term, and later on in the long-term. Their impacts depend on their severity and on the risks and vulnerabilities of the systems they affect, which in turn rely on policy and governance responses as well as economic, social, infrastructural and human and resource capacities (Mastrandrea et al., 2015).

Governance-wise, the most resilient States – normally the developed ones – will be those with functional, accountable and inclusive institutions that are able to overcome challenging situations and provide basic services efficiently and effectively (Rüttinger et al., 2015). States without such institutional capability are likely to be the most vulnerable.

Droughts are normal phenomena of all climates with characteristics that vary among regions. It is known that they are a reduction of precipitation from the long-term average and extend over a certain space scale for a specific period of time, resulting in impacts that vary in reach and intensity (FAO, 2015). Droughts produce complex webs of impacts that affect many sectors of society, both directly and indirectly, and result in numerous chain effects in all sectors, including the water sector (Fraser, 2013; Grigg, 2014; Mastrandrea et al., 2015; Swain, 2015).

There is the perception that droughts have become more widespread and prolonged in many parts of the world over the past decades and that they have resulted in more serious socio-economic and environmental impacts. However, Sheffield et al. (2012) have found little change in global droughts over the past 60 years. They note that the increase in global droughts has been overestimated and that greater availability of detailed meteorological data is necessary to make better estimates possible.

Among all the impacts droughts are having, and are expected to have in the future, one of global concern is the potential impacts on agricultural production locally and thus food security locally, regionally and even globally. This may result in possible increase in prices and market volatility at the local and global levels, seriously affecting food security and livelihoods of millions of people (FAO, 2009, 2015; Lesk et al., 2016; Schmidhuber and Tubiello, 2007; Wheeler and von Braun, 2013). While this has indeed happened in specific cases (FAO, 2015; FAO/IFAD/WFP, 2015) including in the central regions in the United States in 2011–2012 (Grigg, 2014), the relationships between the cause (drought) and the effects (e.g., food insecurity) are not linear. Interactions of food security and food systems are very complex and are influenced by a wide range of social, economic, environmental, political, technological, cultural and structural issues in the food system. Some examples include food production, processing, distribution, and markets; population increase, urbanization, demographic changes, improvement in quality of life, and change of diet (Brown et al., 2015). They also depend on decisions in numerous areas, such as demand for food but also non-food purposes (Headey and Fan, 2010); institutional weaknesses that lead to inefficient market systems; constraints on access to inputs, credit and technology; levels of investment in agriculture, including infrastructure; and speculation on commodity prices (FAO, 2009). On the positive side, because of its complexity, the food system has numerous potential points of intervention for improvement by decision makers (Brown et al., 2015).

In a global assessment of the influence of extreme weather events on global cereal crop production during the 1964–2007 period, Lesk et al. (2016) found that production losses caused by droughts were associated with a reduction in harvested area and yield and extreme heat were found to decrease only yields. No effects were identified from floods and extreme cold. A considerable damage to cereal production was found to have occurred on average: 19.9% in North America, Europe and Australasia, 12.1% in Asia, 9.2% in Africa and no significant effect in Latin America and the Caribbean. The study did not find significant lasting effects in the years after the disasters, but there is no mention on how many years were considered. Most important is the conclusion that the effects of droughts were only short-term. This is because agricultural output rebounds and continues a growth trend after the events.

The rest of this paper focuses on the impacts of the 2011–2016 drought in agricultural production in California and the use of groundwater that aimed at coping with it. It is a fact that the wealth of decisions taken at the different levels were essential to cope with the difficult situation and mitigate the impacts of the drought. However, it is also a fact that availability of groundwater resulted in less than expected effects on the agricultural production and on economic losses. In addition to decision-making, it was actually groundwater, when available, the key element that allowed the agricultural sector to cope with the drought.

## 4. Method

The paper analyses the impacts of the California drought on agricultural production and food security based on published data and information.

For the analysis on impacts on agricultural production and acreage, we collected and assessed annual utilized production, bearing acreages and yields of the crops (production per acre) that represented 90–100% of the crops in California's market share of the entire U.S. market in 2015, from 1990 to 2015 (13 crops). As bearing acreages vary from year to year, yield was calculated for each crop. We used Palmer Drought Severity Index (PDSI) values and compiled data-sets from the yearly citrus and non-citrus fruit and nut reports of the USDANASS. The monthly PDSI data for California were obtained from NOAA's Climate Divisional Database (nCLIMDIV). As agricultural production data are annual figures, the cumulative PDSI as an indicator of drought years was calculated by adding the monthly PDSI figures in a year.

Visual inspections of plots displaying cumulative PDSI and yield did not show a relation between drought (low cumulative PDSI values) and yields. To substantiate the visual observations, the relation between the PDSI and yields was investigated using the Wilcoxon signed-rank test, which is appropriate for data sets that are not normally distributed. The test was used to assess if population means differ significantly. In this case, the sample was split in years with low and high PDSIs and it was tested if the median yield differs. For all crops except one (nectarines) the hypotheses that the median yield in years with a high and a low PDSI significantly differs is rejected. Further inspection of the results for nectarines show that the relation is opposite of what is expected: in dry years yields are on average higher. This is possible as some crops grow better with dry weather.

## 5. California drought

The United States is one of the countries with the greatest contributions to global food security through trade, assistance programmes and technology transfer. The country is the third-largest importer of agricultural products and the largest food exporter, responsible for 16% of global agricultural exports. It influences the production choices and incomes of overseas producers and food systems, and its agricultural sector is responsive to the main drivers of global food demand, including population and income growth (Brown et al., 2015). It is estimated that droughts cost the country some $143 billion between 1980 and 2003, or 41% of the estimated $349 billion total cost of all weather-related events (Mishra and Singh, 2010). Table A1 in the Supplemental material is a summary of the impacts and the estimated costs of droughts in the U.S. from 1980 to 2105.

Within the U.S., California is one of the most important states, if not the most important, from the agricultural viewpoint. According to the California Department of Food and Agriculture (California Agricultural Production Statistics, https://www.cdfa.ca.gov/statistics/), the state produces more than 400 commodities, over a third of U.S. vegetables, and two-thirds of the fruits and nuts. Twelve of them are produced only in California. Agriculture is strongly supported by water markets that allow water allocations, extensive infrastructure development for irrigation, groundwater availability (the primary drought reserve), technological development, etc. Water management in the state will not be discussed in this article. It has been studied extensively elsewhere. For a recent analysis, see Hanak et al. (2011).

The state has suffered several droughts during the last century: 1929–1934, 1976–1977, 1987–1992, 2007–2009, and from 2011 to 2016. The 2014 water year (1 October–30 September) has been the third-driest on record in terms of precipitation at the state level. Both the 2007–2009 drought and the 2011–2016 resulted in statewide proclamations of emergency (California Department of Water Resources, 2015; Governor of the State of California, 2014).

According to the Public Policy Institute of California, the period between fall 2011 and fall 2015 was the driest since 1895 when records started. This drought may be the most severe in the last 1200 years (Griffin and Anchukaitis, 2014), because of variability in precipitation (Mao et al., 2015) and record-high temperatures (AghaKouchak et al., 2014; Diffenbaugh et al., 2015; Robeson, 2015; Shukla et al., 2015; Williams et al., 2015).

In 2013, many communities recorded their lowest-ever annual precipitation. The drought was declared an official state of emergency in 2014 when there were record-low water allocations for the Central Valley Project (CVP) and State Water Project (SWP) contractors. The water year 2015 was the state's warmest year on record. It also produced the lowest snowpack in the Sierra Nevada since records have been kept—by some estimates based on tree-ring analysis, the lowest in five centuries (Central Valley Project and State Water Project 2016 Drought Contingency Plan for Water Project Operations February–November 2016, n.d.). The period between June 2015 and May 2016 has been the third-warmest on record (California Water Science Centre, http://ca.water.usgs.gov/data/drought/).

In July 2015, almost half of the state was in 'exceptional' drought, over 70% in 'extreme' or 'exceptional' drought, and over 97% in one of the several drought categories as classified by the U.S. Drought Monitor. As discussed by Hao et al. (2017), the U.S. Drought Monitor has played a critical role in drought monitoring and to characterize drought severity. Their data and information have been important sources for decision-making purposes.

In California, the drought had impacts all over the state. It affected municipal, industrial, energy, agriculture and environmental sectors, with water shortages and cascade effects in all of them; degraded habitat for fish and wildlife; increased wildfires; threat of saltwater contamination; etc.

Most impacts were felt in rural areas (Richman and Leslie, 2015). In the agricultural sector, they included reduced cultivated acreage, fallowing of land with low value crops, historically low groundwater levels, purchase of water from other farmers, less traffic in ports, increased costs, loss of jobs in agriculture-related industries (Association of California Water Agencies, 2014a; Hanak et al., 2015; PPIC, 2016). In 2015 alone, Howitt et al. (2015) estimated losses of 21,000 agricultural jobs due to the drought and that the economic impact on agriculture would be on the order of $2.7 billion.

In 2016, precipitation was average in northern California. However, it was not enough to counteract the severe water deficit resulting from the drought (PPIC, http://www.ppic.org/main/publication_show.asp?i=1087).

Table 1 presents impacts on water availability and groundwater pumping and costs on the agricultural sector (Hanak et al., 2015). It shows that surface water deliveries were cut by 48% in 2015, year when groundwater extraction increased.

The numerous effects of the most recent droughts in the state, including the latest one, have been extensively documented; see for example California Department of Water Resources (2010a,b, 2015), Cooley et al. (2009, 2015), Dziegielewski et al. (1993), Ehlers (2016), Howitt et al. (2014, 2015), Christian-Smith et al. (2011, 2015), Folger et al. (2012), Cody et al. (2015), Mann and Gleick (2015), Mount et al. (2016), etc.

In the 2011–2016 drought, there were extensive research, policy, legislative, institutional, infrastructure and financial responses, which is why California was able to provide water to as many users as possible, and continue supporting the growth of the economy. These included further water use efficiency in urban and rural areas, use of water markets, extensive use of groundwater, increased water conservation, recycling, and stormwater capture practices, etc. (Hanak et al., 2012, 2015). These responses were similar to those taken by the several sectors during the Millennium Drought in Australia (Kirby et al., 2014).

The largest environmental impacts of the drought have been groundwater depletion, subsequent land subsidence and on aquatic ecosystems, both occurring at increasing rates during this event. The additional groundwater pumping, in conjunction with the previously decisions, resulted in less than expected food shortages, fallowing, and economic losses. The effect of extra groundwater pumping increased the depth of groundwater making it harder to extract or drying out wells altogether and resulting in serious land subsidence. The situation, as well as further decisions taken looking for a more efficient groundwater management, are discussed below.

## 6. Groundwater use

As it has been reported earlier, groundwater plays a fundamental role in agriculture in California, especially in the Central Valley (e.g., Miller et al., 2009). Its extraction has increased to unsustainable rates mainly during dry years (Association of California Water Agencies, 2014b). Pumping of extra groundwater during periods of drought has been historically documented in the state. Since the 1960s, groundwater has been depleted by almost 60 million acre-feet in the Central Valley. Some 20% of the groundwater demand at the national level is supplied through pumping from the Central Valley aquifer, making it the second-most-pumped aquifer system in the country (California Water Science Center, n.d.). Using 2010 as the baseline year before the drought began, in fall 2015, the groundwater level in 37.8% of all the wells counted had fallen more than 10 feet; in 30%, 2.5–10 feet; and in 26%, less than 2.5 feet. In contrast, only 3.2% and 2.7% had increased more than 10 feet and 2.5–10 feet, respectively (Fig. A1 in the Supplemental material).

According to California's Department of Water Resources, the maximum groundwater extraction between 2006 and 2010 was 8.4 million acre-feet. In 2015, the University of California, Davis, estimated that the 2015 drought had reduced surface water by 8.7 million acre-feet in the state and that this had been partially offset by an increase of 6 million acre-feet in groundwater pumping for an estimated net shortage of 2.7 million acre-feet (Howitt et al., 2015). There are records that show areas in the southern Central Valley where groundwater elevation has fallen by up to 50 feet (Fig. A2 in the Supplemental material), and more than 100 feet in the San Joaquin Valley (Faunt and Sneed, 2015).

NASA has determined subsidence for two time periods: a five-year period from 2006 to 2010; and a nine-month period from May 2014 to January 2015 (Melton et al., 2015). For both periods, two known subsidence bowls in the San Joaquin Valley were mapped: Corcoran (that affects the California aqueduct) and El Nido. For 2006–2010, South of El Nido, a maximum total subsidence was found to be 24 in. For May 2014–January 2015, maximum subsidence found in the same bowl was over 10 inches (Farr et al., 2015). Thus, the rate has increased in the recent past and coincides with the period that drought severity increased, underscoring the impact of groundwater extraction on land subsidence.

In the Central Valley, the San Joaquin and Tulare Lake basins especially experienced the most subsidence both recently and historically, and the risk of future subsidence is high for these areas. Also, recent land subsidence, coupled with future estimates, threaten the state's ability to mitigate the impacts of future droughts because

**Table 1**
Water availability and economic costs of California's drought on the agricultural sector.
Source: Hanak et al. (2015) What if California's drought continues? Technical Appendix, PPIC Water Policy Center, San Francisco.

| | 2014 | 2015 | 2016 (estimated) | 2017 (estimated) |
|---|---|---|---|---|
| Surface water delivery cuts (million acre feet, maf, % of baseline) | 6.6 maf (−37%) | 8.7 maf (−48%) | 8.8 maf (−49%) | 8.9 maf (−49%) |
| Additional groundwater pumping (maf, % of baseline) | 5.0 maf (+60%) | 6.0 maf (+72%) | 6.0 maf (+72%) | 6.0 maf (+72%) |
| Net water declines (maf, % of baseline) | 1.6 maf (−6%) | 2.7 maf (−10%) | 2.8 maf (−11%) | 2.9 maf (−11%) |
| Additional groundwater pumping cost ($) c/ | $454 million (+58%) | $587 million (+75%) | $650 million (+83%) | $698 million (+89%) |

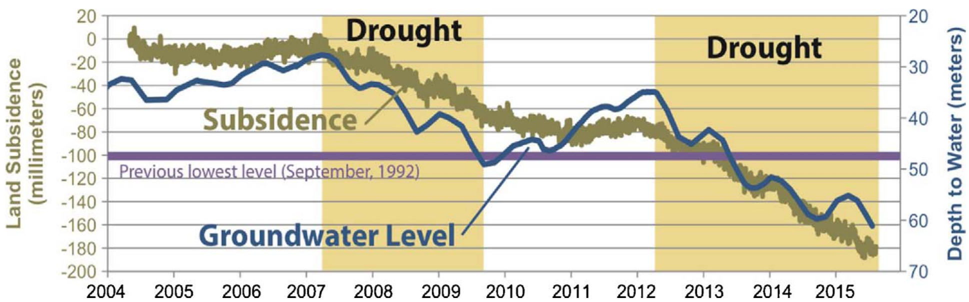


**Fig. 1.** Groundwater Depletion and Land Subsidence near El Nido, CA.
Source: Faunt and Sneed, 2015, Water availability and subsidence in California's Central Valley, *San Francisco Estuary and Watershed Science* 13(3), 1–8, 10.15447/sfews.v13iss3art4.

permanent land subsidence may reduce groundwater capacity and alter natural water flow patterns (Fig. A3 in the Supplemental material; see also Borchers et al., 2014; DWR, 2014; Kastner, 2016).

Fig. 1 shows the relationship between land subsidence groundwater depletion in the area around El Nido.

Based on an extensive study of land subsidence from groundwater use, the California Water Foundation (2014) notes that groundwater has been extracted throughout the years, as and when needed, without consideration of its long-term cumulative impacts, which have been calculated in the billions of dollars of damages. The Foundation also notes that there is no comprehensive land subsidence monitoring in the state. Harter and Lund (2012a,b) found that approximately 10% of all wells tested in California exceeded allowable nitrate concentrations, primarily in agricultural areas of the state, such as the Tulare Lake basin.

Groundwater is the most important insurance against drought, and the drought has made clear that it is necessary to understand and improve groundwater management practices. As discussed by Hanak et al. (2015) and Howitt et al. (2014, 2015), during a continued drought, groundwater substitution remains the main alternative to surface water shortages with resulting decrease in groundwater pumping capabilities and rising costs due to fast declining water levels. Although it is essential for the agricultural sector, its over-exploitation also increases the vulnerability of the sector.

As a response to groundwater depletion and land subsidence due to the prolonged drought, the governor of California signed into law the Sustainable Groundwater Management Act on 16 September 2014 (Government of California, 2015; Groundwater Information Center, 2015). Its implementation began on 1 January 2015. It prioritized basins in order to address the most threatened ones first. Deadlines and milestones will occur through 2042 (Water Education Foundation, 2015). A main problem of the SGMA is the lengthy timeline for its full implementation in 2042. By 2022, many basins will begin phasing in their groundwater sustainability plans that hold potential to slow depletion. However, this may be too little too late as groundwater depletion and subsequent land subsidence can permanently reduce groundwater storage capacity.

There is new research that indicates the existence of deep groundwater aquifers in California that may provide alternative sources of both fresh and groundwater (Kang and Jackson, 2016). These findings may affect the effective implementation of the Sustainable Groundwater Management Act, which has the potential to reduce overdraft and thus slow down land subsidence. A question is whether these resources may result in groundwater sustainability being overlooked.

In the following section, we discuss the effects in agricultural production and food security.

## 7. Agricultural production changes and impacts on food security

In California, fruit, tree nuts and vegetables play a dominant role in the agriculture. The state producers have a large share of the national production in these categories. Almost two-thirds of the agricultural crop value is from fruit and tree nut production ($20.3 billion average for 2012–2014) and approximately one quarter is from commercial vegetables ($7.1 billion, excluding potatoes, in the same years). These commodities represent some 70% of total U.S. fruit and tree nut farm value and 55% of vegetable farm value (Economic Research Service, n.d.). Therefore, a multiyear drought with high temperatures is of concern to the farmers, the state and also the country.

In 2012, 22% of all U.S. farms growing fruit (including berries), tree nuts and vegetables were in California, accounting for 43% of the total acreage for the sector, most of them under irrigation. In 2014, the state had the most agricultural cash receipts of any in the country, with $54 billion of output from 76,400 farms and ranches. Despite the ongoing drought and water shortages, California continued to be the leading state for fresh-market vegetables in 2014, accounting for 52% of production and 60% of farm value (CDFA, 2015a). For a number of fruit and tree nut crops, U.S. production volumes for 2014 were down from 2011 to 2013 average levels, largely because of lower production (California Agricultural Production Statistics, https://www.cdfa.ca.gov/statistics/). In 2015, sales generated decreased by 16.8% between the 2014 and 2015 crop years. As a result, farms and ranches received approximately $47.1 billion for their output, nearly 17% less than in 2014. This was largely due to price decreases rather than production decreases. This is also visible in Appendix B, where production increased or stayed the same, while value, especially for walnuts, pistachios and almonds dropped considerably. Even then, California remained the leading state in cash farm receipts in 2015 (CDFA, 2016).

In California, 75% of all irrigated land is in the Central Valley. With the drought, deliveries of surface water to the valley are said to have been 63% of average in 2014 and 52% in 2015. Over the years, farmers have improved irrigation efficiency and shifted to crops that generate more value, responding to incentives in commodity prices and profits per volume of water used (Hanak et al., 2012; Medellín-Azuara et al., 2012). When available, groundwater has been used extensively for irrigation. However, increased groundwater extraction has further accelerated depletion of groundwater reserves and associated land subsidence. Under normal conditions, almost 40% of urban and agricultural water needs are met by groundwater. However, this percentage increases in dry years (Association of California Water Agencies, 2014b).

Farmers received less water or none at all depending on priority water rights. They had to fallow land, purchase water from other farmers or pump additional groundwater to offset most of the missing surface water (PPIC, 2016; USDA, 2014).

In the assessment of land fallowing in 2015, USGS, USDA, California Department of Water Resources and NASA (Melton et al., 2015) found that more than 1.03 million acres in the California Central Valley remained fallow throughout the year—626,000 acres more than in 2011. The study also found that most of the fallow land was associated with annual crops such as cotton, rice and alfalfa and that impacts on perennial crops had been largely avoided. Table 2 shows NASA's estimates of the fallow land as presented by Melton et al.

Cooley et al. (2015) analysed harvested acreage and total market value of field crops, vegetables and melons and fruits and nuts for 2000–2014. Kastner (2016) compared 2011–2013 production levels to

**Table 2**
NASA estimates of fallow land in the California Central Valley (acres) (2011, 2015).

| Year | Winter | Summer[a] | Annual |
|---|---|---|---|
| 2015 | 1,778,174 | 1,917,058 | 1,032,508 |
| 2011 | 740,445 | 1,394,906 | 405,996 |
| Change from 2011 to 2015 | 1,037,729 | 522,152 | 626,512 |

[a] According to Melton et al. (2015) higher value crops in California are grown during summer production season.

2014 production levels of crops where California produces 30% or more of the domestic market share. In both cases, analyses were based on data from the USDA National Agricultural Statistics Survey. Scheer et al. (2015) analysed agricultural projections. Cooley et al. (2015) found that only fruit and nut acreage increased steadily, by 24% over the period studied. Other crops increased or decreased in different years. In terms of fruit and nut crops, the bearing acreage of some crops declined, but losses were offset by large increases in acreage of especially higher-value crops such as almonds, pistachios and wine grapes. Crop revenue increased from $21 billion in 2000 to $28 billion in 2011. It reached a record high of $34 billion in 2013, declining by 1.4% in 2014 compared to 2013. Pricing varied depending on the crops, but no relation to the drought was found.

According to Howitt et al. (2015) acreage of almond and walnut increased by more than 200,000 acres from 2010 in fields where cotton, irrigated pasture, grains, and hay had been grown earlier. The authors explain that this shift to perennial crops was driven by the markets.

Kastner (2016) also found that production of some crops increased but some others decreased, contradicting the hypothesis that the drought had affected agricultural production uniformly in the period studied. Regarding pricing, Kastner refers to the USDA's Economic Research Service (USDA ERS, n.d.). ERS estimated that the drought would have negligible effects on food prices at retail outlets not only in California but also in the U.S. during 2015. ERS mentioned that the strength of the U.S. dollar and lower oil prices could have a mitigating effect on fresh fruit and vegetable prices in 2015. ERS predicted that fresh fruit prices could fall as much as 2.25%, while fresh vegetable prices were forecast to rise as much as 1.75%, as of December 2015. In 2016, prices for fresh fruits were predicted to rise 2.5–3.5%, and prices for vegetables 2.0–3.0%. Data is not available on the prices yet.

One of the reasons for the drought's negligible impacts on food prices is that only a small percentage of the price of food is attributed to the price paid to the farmer. Transportation, energy, and wholesale and retail costs account for the majority of the price paid at a retail outlet. According to USDA ERS (2016) fresh fruit and vegetable markets are the most volatile sector of crops. It attributes only 40% of the price of fresh fruits to the cost at the farm; the other 60% is attributed to other factors, such a transportation and retail mark-up. Thus, food price changes are buffered significantly by other factors.

As noted by Howitt et al. (2015), Cooley et al. (2015) and Kastner (2016), water availability is an important consideration when deciding which crops to grow. However, as long as there are alternative water supplies (as groundwater in this case), other factors take priority in production choices such as prices of goods, changing consumer preferences, export market demand, and net income from each crop.

For our analysis, we assessed utilized production, bearing acreages and yields of the crops that represented 90–100% of the crops in California's market share of the entire U.S. market in 2015, from 1990 to 2015. We used Palmer Drought Severity Index (PDSI) values and compiled data-sets from the yearly citrus and non-citrus fruit and nut reports of the USDA-NASS. No clear impact of droughts on yield (production per acre) were apparent for any of the 13 crops we considered, with the exception of one of them, nectarines.

The median yield of years with a low PDSI was not significantly different from the yield of years with a high PDSI (see Appendix A and Appendix B for a more elaborate description of the method and results from Excel files with the peculiarity of the crops). Visual inspection of plots with PDSI and yield also did not indicate any clear relation, and hence other (climatic) factors should have a more significant impact than long-term droughts indicated by the PDSI. As shown by Lobell et al. (2008), temperature and precipitation in specific months can explain much of the variability in yields of specific crops, e.g. occurrence of frost during the flowering season or daytime temperatures prior to harvest.

The California Department of Food and Agriculture 2014–2015 (n.d.) mentions that despite the drought and water shortages, California continued to be the leading state for fruit and tree nuts in 2014, accounting for 51% of production and 71% of farm value. Production volumes for a number of fruit and tree nut crops that year exceeded the previous three-year-averages. The top agricultural county in 2014 and 2015 was Tulare (one of the basins where the most groundwater has been extracted), where commodities worth approximately $7.3 billion were produced in 2013, and $8 billion in 2014.

In 2015, the situation changed. Almonds had the lowest yields since 2009. Bearing acreage continued to increase, but kernel weight and size were smaller, partially due to the drought. Nuts per tree declined slightly each season since 2012 across all growing districts and all varieties. Regarding walnuts, another important commodity for California, nut sets per tree (and thus yields) declined in 2015 from the previous year. However, more bearing area and higher tree density per acre resulted in record production in the same year (California Department of Food and Agriculture 2014–2015, n.d.).

Groundwater availability was the primary reserve against the drought. Nevertheless, low precipitation and high temperatures exacerbated the effects of dry conditions from previous years, including low reservoir and groundwater levels. There were serious impacts on water availability and water quality through streamflow, surface water and groundwater. Numerous farmers had to receive financial support; field crop production was affected, although not uniformly; groundwater pumping increased, water levels declined, and land subsidence, seawater intrusion, and damage to ecosystems increased, and there was less hydropower generation, among other impacts (Congressional Digest, 2015). Food security was not threatened by the prolonged drought, mainly because the crops were still available and the prices were not affected. Had the drought lasted longer or had groundwater been insufficient, food security may have been a reality.

These events are not associated to a resilient system, but to one that is able to develop numerous coping responses to increasing stress. For the 2007–2009 California drought, Christian-Smith et al. (2015) discuss "maladaptation" to the drought, where responses in one sector had negative impacts on other sectors. The same can be said in the case of this drought. Planning, institutional, regulatory (state and federal levels), infrastructure development and financing responses indicate that the state is becoming increasingly more prepared to face droughts, but not through resilience.

## 8. Decision-making and policy responses

As mentioned earlier, decisions taken due to the drought were on improving water use efficiency in urban and rural areas, use of water markets, extensive use of groundwater, increased water conservation, recycling, stormwater capture practices, etc. (Hanak et al., 2012, 2015). These are explained below.

### 8.1. Policy responses from the California state government

The existing water governance structure in the state is presented by Hanak et al. (2011: 360). In addition to the Department of Water Resources (institution responsible for managing and protecting state water resources with four districts offices), other institutions are the State Water Resources Control Board (with regional water quality control boards), Fish and Game Commission (including the Department of Fish and Game policy), and the Department of Fish and Game (for policy implementation).

Response to the drought focused on four main areas: water supply, emergency response, water conservation and environmental protection. Coordination was under an Interagency Drought Task Force convened by the Governor and included a large number of institutions such as the State Water Resources Control Board (SWRCB), Department of Water Resources (DWR), Department of Social Services (DOS), California Department of Food and Agriculture (CDFA), etc. (For a detailed analysis of the state drought response appropriations throughout several years, see Ehlers, 2016).

At the state level, examples of policy changes include review of flow requirements of drought-related projects, adoption of water recycling requirements, habitat restoration projects, installation of Delta salinity barriers, suspension of certain provisions of the state Water Code, required 25% reduction in urban water use compared to 2013, expand authorised use of recycled water, increase penalty amounts for illegally diverting water during drought conditions, allow water right holders to deviate from the terms of their existing permits to provide relief from drought conditions, increase the Department of Fish and Wildlife authority to close waters to fishing based on drought conditions, enhance penalty authority for local public entities to enforce water conservation, among others (see Ehlers, 2016).

Governor Edmund G. Brown Jr. issued several Executive Orders, proclaimed a State of Emergency so that water was made available on urgent basis, mandated specific actions for water conservation, and signed emergency legislation Assembly Bills (AB) 91 and AB 92, to fast track over $1 billion for funding for drought relief and critical water infrastructure projects (Brown, 2015a). Executive orders issued by the State Government had the objective to streamline approvals for voluntary water transfers; expedite drought response activities and implement water conservation requirements; drinking water shortages, etc. Some examples are below.

The AB 91 is a budget appropriations bill. The primary provisions include: (i) provide $267 million of funding to safe drinking water and water recycling projects; (ii) provide $31 million in additional funding ($132 million total) to support emergency food and water aid in most severely drought stricken and disadvantaged communities; (iii) provide $660 million of funding for flood protection infrastructure in urban and rural areas to make the state more resilient to climate change and flood events; and iv) provide $30 million of funding to improve local and agricultural water use efficiency (Meindl, 2015), including $10 million for water efficiency projects specific to agriculture via the State Water Efficiency and Enhancement Program (SWEEP).

The AB 92 has the statutory changes necessary to implement AB 91 (Meindl, 2015). This includes: i) enhance the Department of Fish and Wildlife (DFW) authority to impose penalties on water diverters affecting salmon and steelhead fish passage; ii) creating an Office of Sustainable Water Solutions to help communities apply for state and Federal funds to help clean up drinking water and greater access to treatment technologies; iii) creating a revolving fund for water efficiency pilot projects to improve water efficiency in both public water systems and private property; and, iv) improving communities ability to access state disaster relief funds by loosening eligibility criteria.

Another Executive Order (B-29-15) followed on April 1, 2015 by Governor Brown (Brown, 2015b). Among its several objectives were requiring agricultural water suppliers providing water to more than 4047 ha to supply detailed drought management plans to DWR. In November 2015, in the Executive Order B-36-15 (Brown, 2015c), one of the main focus was that the State Water Board would prioritise temporary water rights permits, water quality certifications, waste discharge requirements, and conditional waivers of waste discharge requirements to accelerate approvals for projects to enhance the ability of a local or state agency to capture high precipitation events for local storage or recharge consistent with water rights priorities and protections for fish and wildlife.

In addition to these executive orders and legislative actions, California voters approved Proposition 1 on November 4, 2014, "The Water Quality, Supply, and Infrastructure Improvement Act of 2014". This measure authorised $7.545 billion in bonds to fund ecosystems and watershed protection and restoration, water supply infrastructure projects, including surface and groundwater storage, and drinking water protection (California Natural Resources Agency, 2015).

As a result of the executive orders and legislative bills, the California Department of Food and Agriculture (CDFA) provided $9.38 million of funding to 100 projects to improve water and energy use efficiency on farms with efficient irrigation technologies. In addition, five water reuse projects and two desalination projects received funding in 2015 to increase water supply (USBR, 2015).

### *8.2. Policy responses from the Federal government*

The Federal role in water resources and ecosystem management can be divided in interstate and international river management, water infrastructure, agricultural stewardship, forest and rangeland management, water information and forecasting, and emergency drought relief. As explained by Ehlers (2016), there have been more than two dozen federal agencies involved. In California, the Federal Government also assisted the state through funding projects.

In June 12, 2015, President Barack Obama announced that the Federal government would provide California with $110 million in funding to support workers, farmers and rural communities suffering from drought and to combat wildfires in California (White House, 2015). Most of that funding would be channelled through USDA. In this announcement, President Obama also stated that USDA's Risk Management Agency (RMA) was expanding a programme that would allow farmers to exclude bad production years (resulting from drought) from their calculation of crop insurance coverage. The amount of crop insurance coverage was based on recent production data and farmers that have fallowed land due to the drought could exclude those years of production data for their crop insurance assessments. This was expected to provide $30 million in additional relief in 2016 and $42 million in 2017 (White House, 2015).

On June 24, 2015 USDA's Natural Resources Conservation Service (NRCS) announced it was allocating $21 million to mitigate the short and long-term effects of drought via the Environmental Quality Incentives Program (EQIP). This programme shares with producers the costs of investing in technologies that improve environmental quality. Many farming practices are eligible for funds under EQIP ranging the gamut of farming practices, such as nutrient management, irrigation techniques, etc. Of the $21 million allocated specifically to water conservation across the U.S., 65% of that, $13.7 million, is prioritized just for California (USDA, 2015).

USDA's Farm Service Agency (FSA) also announced programmes to help California farmers cope with the drought (CDFA, 2015a). They included:

- Noninsured Crop Disaster Assistance Program (NAP) that provides financial insurance to producers of noninsurable crops due to natural disasters. Previously, the programme offered coverage for 50% of expected production at 55% of average market price. Now, producers can apply for coverage of up to 65% of expected production at 100% of average market price;
- The Emergency Farm Loans Program provides emergency loans to help producers restore and replace property, production costs during disaster years, and refinancing of debt and business/living expenses for producers in all counties of California, up to $500,000;
- The Disaster Set-Aside Program that provides producers who have existing loans with FSA can now delay scheduled payments up to one year from the originally schedule repayment of the loan; and
- The Tree Assistance Program provides financial assistance to

**Table 3**
State and Federal actions related to the California drought.
Sources: California state government responses, Governor's Drought Declaration http://www.water.ca.gov/waterconditions/declaration.cfm; Congressional Digest (2015) Legislative background on the California drought. Recent action by Congress on Western Water Bills; Agriculture Secretary Vilsack Announces $150 Million, New Partnership to Support Water Quality and Quantity in Drought-Stricken California. (Jun. 24, 2015). [Press release]. FACT SHEET: Supporting Workers, Farmers, and Communities Suffering from Drought. (Jun. 12, 2015). The White House [Press release].

| Date | Action |
|---|---|
| January 17, 2014 | Governor Edmund G. Brown Jr proclaimed a State of Emergency |
| February 5, 2014 | The Natural Resources Subcommittee on Water and Power of the House held a hearing on three proposals aimed at jumpstarting surface water storage development in the western United States. |
| March 19, 2014 | The Committee held a field hearing on the "California Water Crisis and Its Impacts" in Fresno, California. |
| May 22, 2014 | The Senate passed S.2198, the Emergency Drought Relief Act, introduced by Senator Dianne Feinstein (CA-D). The House did not act on the bill. |
| April 25, 2014 | Proclamation of a Continued State of Emergency |
| September 18, 2014 | Executive Order B-26-14. It provided temporary water supplies to households without water for drinking and/or sanitation purposes. |
| October 6, 2014 | Executive Order B-27-14. It directed State agencies to assist local governments in their response to wildfires during California's drought conditions. |
| December 9, 2014 | The House passed H.R. 5781, the California Emergency Drought Relief Act. The measure was never considered on the Senate floor. |
| December 22, 2014 | Executive Order B-28-14. It extended the suspension of Section 13247 of California's Environmental Quality Act and Water Code through May 31, 2016. |
| March 27, 2015 | Gov. Brown signed emergency legislation Assembly Bills (AB) 91 and AB 92 to fast track over $1 billion USD of funding for drought relief and critical water infrastructure projects. |
| April 1, 2015 | Executive Order B-29-15. It included, among others, restrictions to achieve a 25% reduction in potable urban water use through February 28, 2016. |
| June 2, 2015 | Announcement by President Barack Obama that the Federal government would provide California with $110 million in funding to support workers, farmers and rural communities suffering from drought and to combat wildfires in California. President Obama also stated that USDA's Risk Management Agency (RMA) is expanding a programme that allows farmers to exclude bad production years (resulting from drought) from their calculation of crop insurance coverage. |
| June 24, 2015 | USDA's Natural Resources Conservation Service (NRCS) announced it is allocating $21 million to mitigate the short and long term effects of drought via the Environmental Quality Incentives Program (EQIP). |
| June 25, 2015 | H.R. 2898, the Western Water and American Food Security Act was introduced. The White House issued a statement saying that the President would veto the bill should it come to his desk. |
| July 29, 2015 | A new drought relief proposal was introduced. It would funnel $1.3 billion over the next decade to storage, desalination, and other projects, but would not alter such laws as the Endangered Species Act and the Clean Water Act. |
| November 13, 2015 | Executive Order B-36-15. Among others, called for additional actions to continue responding to the drought. |
| May 9, 2016 | Executive Order B-37-16. The Governor's latest drought-related executive order established a new water use efficiency framework for California. It established longer-term water conservation measures that include permanent monthly water use reporting, new urban water use targets, reducing system leaks and eliminating clearly wasteful practices, strengthening urban drought contingency plans and improving agricultural water management and drought plans. |
| April 7, 2017 | Executive Order B-40-17. The executive order ended the drought state of emergency in all California counties except Fresno, Kings, Tulare, and Tuolumne, where emergency drinking water projects will continue to help address diminished groundwater supplies. It maintains water reporting requirements and prohibitions on wasteful practices. |

qualifying orchardists and tree growers to replant or rehabilitate eligible trees (fruit, nut, ornamental and Christmas trees), bushes and vines damaged by natural disasters.

In addition to these programs directly supporting farmers, funding was allocated to help communities to cope with drinking water quality degradation and quantity shortages, job losses, poverty, and economic damage caused by the drought on non-farm entities (CDFA, 2015a; White House, 2015).

Moreover, the Federal government, especially USDA, provided assistance to agricultural producers through a diverse range of programs to which producers could apply for to help them cope with losses from drought, for example crop insurance and technical assistance, among others. Considering that these were already in place prior to the drought, it would be inaccurate to state these existing programs and funding levels were mitigating the effects of the drought beyond the pre-drought status quo.

The Congressional Digest in July and September 2015 presents a series of analysis and actions of the Congress and the Senate that relate to the drought in California (Congressional Digest, 2015). The Congressional analysis acknowledges that the way the Congress responded to the drought was very important as it could set a precedent for possible similar responses across the country. These initiatives are summarized in the Congressional Research Service Report R40979 (Cody et al., 2015: p. 6):

> "The 113th Congress responded to the 2014 drought by reauthorizing several drought programmes, including the Reclamation States Emergency Drought Relief Act (RSEDR), the National Integrated Drought Information System (NIDIS), and agricultural assistance programmes (2014 farm bill; Agricultural Act of 2014 [P.L. 113-79]). Congress also included provisions to facilitate water banking, water transfers, and new storage projects in the FY2014 Consolidated Appropriations Act (P.L. 113-76). In addition, the 113th Congress debated California-specific legislation, including S. 2016, S. 2198 (which passed the Senate in May 2014), H.R. 3964 (which passed the House in February 2014), and H.R. 5781, a compromise bill that passed the House in December 2014; however, none were enacted.
>
> Several bills have been introduced in the 114th Congress. For example, H.R. 2898 passed the House on July 16, 2015. The bill is similar in several aspects to previously passed House bills (H.R. 3964 and 5781 from the 113th Congress). Several titles of H.R. 2898 focus on maximizing CVP and SWP water deliveries, while other titles address Bureau of Reclamation project authorization and financing throughout the West. With regard to California-specific provisions, a key challenge for legislators is whether to increase water supplies for CVP and SWP water users, particularly those in the San Joaquin Valley and Southern California areas (SOD), and how this could be accomplished without further threatening or endangering the survival of several fish species and degrading water quality for in-Delta water users. Other bills introduced in the 114th Congress would address drought management in California more broadly by focusing on increasing the provision of water supplies through conservation and recycling, among other activities (e.g., H.R. 291 and S. 176; H.R. 2983 and S. 1837; and H.R. 3045). The state also has been active in addressing the drought, including funding specific water projects and conservation activities and calling for mandatory statewide reductions in water use."

In 2016, President Obama issued a Memorandum and a Federal Action Plan on building national capabilities for long-term drought resilience (White House, 2016). For fiscal year 2016–2017, with existing resources and existing authorities, the main goals would be data collection and integration, communicating drought risk to critical infrastructure, drought planning and capacity building, coordination of federal drought activity, market-based approaches for infrastructure, and efficiency and innovate water use, efficiency and technology development.

Table 3 summarises the state and Federal actions presented before.

The array of measures were essential to respond to emergency conditions and will also be useful to respond to future droughts. Some of the measures are meant to build long-term resilience such as the Sustainable Groundwater Management Act and the Executive Orders that established longer-term water conservation measures.

Regarding the water system in California, the complexity of its management requires a longer-term framework. It has been generally recognized that the necessary trade-offs among the large number of users involved, and that disagreements over rights, the environment, and the role of agriculture have made it a non-sustainable system (Congressional Digest, 2015).

Hanak et al. (2011) and Null et al. (2012) discuss that water management is very decentralized resulting in advantages and disadvantages. Among the disadvantages are the fragmented and often uncoordinated decision-making from the hundreds of local and regional agencies in charge of water supply, wastewater treatment, flood control and land use. This, in turn, has resulted in numerous problems such as groundwater over-exploitation, pollution, and ineffective ecosystem management where strategies still do not consider ecological functions and human use of water and land resources coherently. Hanak et al. (2011) also argue that state and federal agencies have not achieved the necessary coordination and that this has affected seriously issues such as reservoir operation, ecosystem management, groundwater management and water markets, for example.

Extreme events expose concerns and vulnerabilities that under normal conditions can be addressed in more or less degree. That water management in the state is not resilient in spite of so many efforts, should be taken as an indication that stronger coordination is still necessary and that, as discussed extensively by Hanak et al. (2011) as well as many other authors, state and local institutions need to manage water in a more coherent manner.

## 9. Conclusions

The agricultural sector of California is an example of a system under extraordinary stress because of the multiyear drought. However, management and policy responses at the local, state and federal levels, and groundwater availability, significantly mitigated what could have been even more serious impacts on all spheres.

Many farmers suffered as a result of the drought. They had to fallow land, purchase water from other farmers or pump additional groundwater to offset most of the missing surface water. In 2015, more than 1 million acres in the California Central Valley remained fallow throughout the year, most of it associated with annual crops such as cotton, rice and alfalfa. It is considered that impacts on perennial crops were largely avoided. Farmers have moved to perennial crops not necessarily because of the drought, but driven by market opportunities.

Production of some crops increased and some others decreased, indicating that the drought did not affect agricultural production uniformly. Regarding high value crops, such as fruit and tree nuts, California continued to be the leading state in 2014, accounting for 51% of production and 71% of farm value. As discussed before, the top agricultural county in 2014 and 2015 was Tulare, within one of the basins where the most groundwater has been extracted. Commodities in this basin in 2013 were worth approximately $7.3 billion, and $8 billion in 2014.

Concerning pricing, it was found that the drought did not impact food prices at retail outlets not only in California but also in the U.S. during 2015. It has been discussed that the strength of the U.S. dollar and lower oil prices could have had a mitigating effect on fresh fruit and vegetable prices. It has also been mentioned that only a small percentage of the price of food is attributed to the price paid to the farmer. Transportation, energy, and wholesale and retail costs account for the majority of the price paid at a retail outlet. Food security was thus not threatened, mainly because crops were available and because prices were not impacted.

The extended drought exposed vulnerabilities from long-term cumulative effects on society and the environment. The effects could have been more severe if the drought had continued for longer time and if coping responses such as exploitation of the groundwater resources had continued. Governmental support at the state and federal levels were decisive in providing the required support. These, plus the availability of groundwater were essential for the systems to cope with the stress. With the drought over, coordinated plans as to how best to cope with extreme hydrological events in future, which will reduce the overall impacts on the society, could be routinely developed and implemented. As knowledge advances, more data becomes available and, if a more whole-stakeholder unified coordinated approach is taken, such plans would need to be updated periodically towards the aim of building resilience. The California case is an example from which to learn of the extent of responses that are necessary to cope with an extended extreme event. Risks and vulnerabilities would be much more severe in places and in situations where institutions and policy responses are not robust, the environment is more degraded, infrastructure is non-existent or not appropriate, and investments are not possible or have not been planned.

A very important element was decentralized decision-making, with numerous institutions being responsible for management of water resources. Within this system, decisions provided support to mitigate the multiple effects of the drought. However, given that many of them were not coordinated, they did not help towards the end goal of developing a more resilient system.

Risks and vulnerabilities will be much more severe in countries and in situations where governance mechanisms are weak, institutions are not robust, the environment is more degraded, infrastructure is non-existent or not appropriate, and investments are not possible or have not been considered.

Over the long-term, given the significant uncertainties associated with climate variability and change, especially when impacts are considered over a specific area, localities will have to develop robust plans on how best cope with hydrological extreme events like prolonged droughts and severe floods.

Coping, adapting and building resilience is a long-term effort that requires enormous engagement from all parties, one for which States and populations alike have to start planning. With accelerating human activities, magnitudes of extreme events are likely to increase damages in the future. Policy and institutional responses as well as a more comprehensive management of natural resources are essential to face challenging times and build a more resilient society.

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## Appendix A

Agricultural yields do not seem to be impacted uniformly during the period assessed. To support this statement, information on production and acreage was collected for 13 crops for which California produced 90% or more of the total volume in the U.S. in 2015 (Table A1). Annual utilized

**Table A1**
Crops in which California ranks No.1 in total volume of U.S. production in 2015.
Source: Compiled from reports: Citrus Fruits Summary, September 2016; Non-Citrus Fruits and Nuts Summary, July 2016. United States Department of Agriculture (USDA) – National Agricultural Statistics Service (NASS).

| No. | Crops | CA volume of utilized production in 2015 | U.S. volume of utilized production in 2015 | Percent volume of CA production in the total U.S. volume 2015 |
|---|---|---|---|---|
| | Citrus Fruits: Units: in 1000 boxes[a] | | | |
| 1 | Lemons | 20,500 | 22,250 | 92 |
| 2 | Tangerines | 21,700 | 23,115 | 94 |
| | Non-Citrus Fruits: Units: in short tons | | | |
| 3 | Dates | 43,600 | 43,600 | 100 |
| 4 | Figs | 30,200 | 30,200 | 100 |
| 5 | Kiwifruit | 23,100 | 23,100 | 100 |
| 6 | Nectarines | 155,000 | 164,600 | 94.16 |
| 7 | Olives | 179,000 | 179,000 | 100 |
| 8 | Plums | 105,000 | 105,000 | 100 |
| 9 | Prunes | 110,000 | 110,000 | 100 |
| | Berry: Units: in 1000 cwt | | | |
| 10 | Strawberries | 27,909 | 30,867 | 90.4 |
| | Tree nuts: Units (In-shell): in 1000 pounds | | | |
| 11 | Almonds, in shell | 1900,000 | 1900,000 | 100 |
| 12 | Pistachios in shell | 270,000 | 270,000 | 100 |
| 13 | Walnuts[b] | 603,000 | 603,000 | 100 |

[a] Net weight of Citrus Fruits (2015): One box is equivalent to 80 pounds.
[b] Units for Walnuts is in tons.

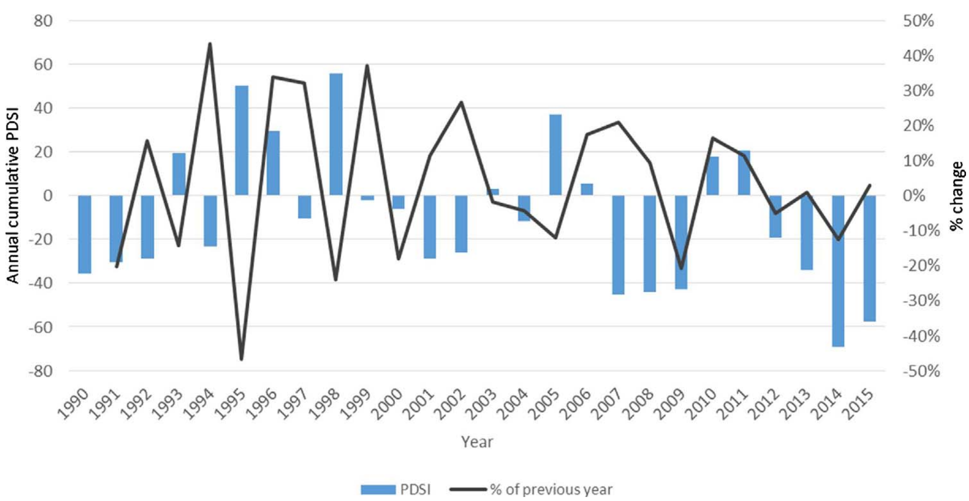


**Fig. A1.** Almond yield and PDSI.

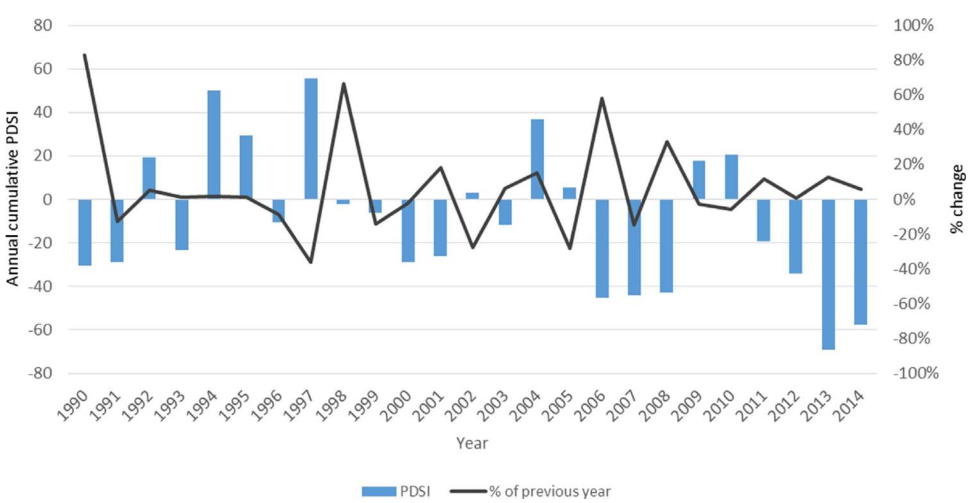


**Fig. A2.** Tangerines yield and PDSI. For both almonds and tangerines, yield data was calculated from utilized production data (in 1000 short tons) and bearing acreage data (in acres). It is expressed into tons per acre in the graphs.

**Table A2**
Results of the Wilcoxon sign-rank test.[a]

| Crop | (Paired) Observations | Wilcoxon z-statistic | Probability |
|---|---|---|---|
| Lemons | 26 | −0.73 | 0.463 |
| Tangerines | 26 | 1.50 | 0.133 |
| Dates | 26 | 0.03 | 0.972 |
| Figs | 26 | 0.87 | 0.382 |
| Kiwis | 26 | −0.80 | 0.421 |
| Olives | 26 | 0.52 | 0.600 |
| Plums | 26 | 1.99 | 0.046 |
| Prunes | 26 | −0.94 | 0.345 |
| Nectarines | 26 | 2.76 | 0.005* |
| Strawberry | 24 | −0.86 | 0.388 |
| Almonds | 26 | 1.50 | 0.133 |
| Pistachios | 26 | −0.52 | 0.600 |
| Walnuts | 26 | 0.45 | 0.649 |
| Lemons | 26 | −0.73 | 0.463 |

*Significant result.
[a] STATA-14 software used for the Wilcoxon sign-rank test.

production and bearing acreage data was collected for the years 1990–2015 for the state of California from United States Department of Agriculture, National Agricultural Statistics Service, Annual Citrus and Non-citrus Fruit and Nut reports. As bearing acreages varies from year to year, yield (production per acre) was calculated for each crop.

As an indicator of drought, the PDSI [Palmer Drought Severity Index (Palmer, 1965)] was used. The monthly PDSI data for California were obtained from NOAA's Climate Divisional Database (nCLIMDIV).[1] As agricultural production data are annual figures, the cumulative PDSI was calculated by adding the monthly PDSI figures in a year. Negative values of the cumulative PDSI indicate dry years and positive values indicate wet years.

Visual inspections of plots displaying cumulative PDSI and yield, see for instance Figs. A1 and A2, did not show any clear relation between drought (low cumulative PDSI values) and yields. To substantiate the visual observations, the relation between the PDSI and yields was investigated using the Wilcoxon signed-rank test (Wilcoxon, 1945), which is appropriate for data sets that are not normally distributed. The test is used to assess if population means differ significantly. In this case, the sample was split in years with low and high PDSIs and it was tested if the median yield differs. As shown in Table A1, for all crops except nectarines the hypotheses that the median yield in years with a high and a low PDSI significantly differs is rejected. Further inspection[2] of the results for nectarines show that the relation is opposite of what is expected: in dry years yields are on average higher. Nectarines may actually benefit from deficit irrigation and hence dry weather (Thakur and Singh, 2013) (Table A2).

## Appendix B

Data sources for Figs. B1–B5 and Table B1

1. Citrus Crops: Lemons and Tangerines (Number of Crops = 2)

- 1990–1993: Citrus Fruit Summary, September 1993.Agricultural Statistics Board, United States Department of Agriculture, National Statistics Service.
- 1993–1995; Citrus Fruit Summary, September 1996.Agricultural Statistics Board, United States Department of Agriculture, National Statistics Service.
- 1996–1999; Citrus Fruit Summary, September 1999. Agricultural Statistics Board, United States Department of Agriculture, National Statistics Service.
- 1999–2002: Citrus Fruit Summary, September 2003. Summary of 2002.Agricultural Statistics Board, United States Department of Agriculture, National Statistics Service.
- 2002–2004: Citrus Fruit Summary, September 2005.Summary of 2004. Agricultural Statistics Board, United States Department of Agriculture, National Statistics Service.
- 2005: Citrus Summary, Sept. 2008, Summary of 2007. Agricultural Statistics Board United States Department of Agriculture, National Statistics Service.
- 2006: Citrus Summary, Sept 2009. Summary of 2008. Agricultural Statistics Board, United States Department of Agriculture, National Statistics Service.
- 2007: Citrus Summary, Sept 2010. Summary of 2009. Agricultural Statistics Board, United States Department of Agriculture, National Statistics Service.
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[1] https://data.noaa.gov/dataset/noaas-climate-divisional-database-nclimdiv.
[2] Spearman's rank correlation coefficient for nectarine yields and annual cumulative PDSI shows a negative significant relationship (rho = −0.71; p = 0.000).

Service.

- 2012: Citrus Summary, Sept 2015, Summary of 2014. Agricultural Statistics Board, United States Department of Agriculture, National Statistics Service.
- 2013–2015: Citrus Summary, Sept. 2016, Summary of 2015. Agricultural Statistics Board, United States Department of Agriculture, National Statistics Service.

2. Non Citrus Fruits and Nuts: Dates, Figs, Kiwifruit, Olives, Plums, Prunes, Nectarines, Strawberries, Almonds, Pistachios and Walnuts (Number of Crops = 11)

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- 1999–2002: Non Citrus Fruit and Nut Summary, July 2003, Agricultural Statistics Board. United States Department of Agriculture, National Statistics Service
- 2002–2004: Non- Citrus Fruit and Nut Summary, July 2005, Agricultural Statistics Board. United States Department of Agriculture, National Statistics Service
- 2005: Non-citrus Fruit and Nut Summary, July 2008. Agricultural Statistics Board. United States Department of Agriculture, National Statistics Service.
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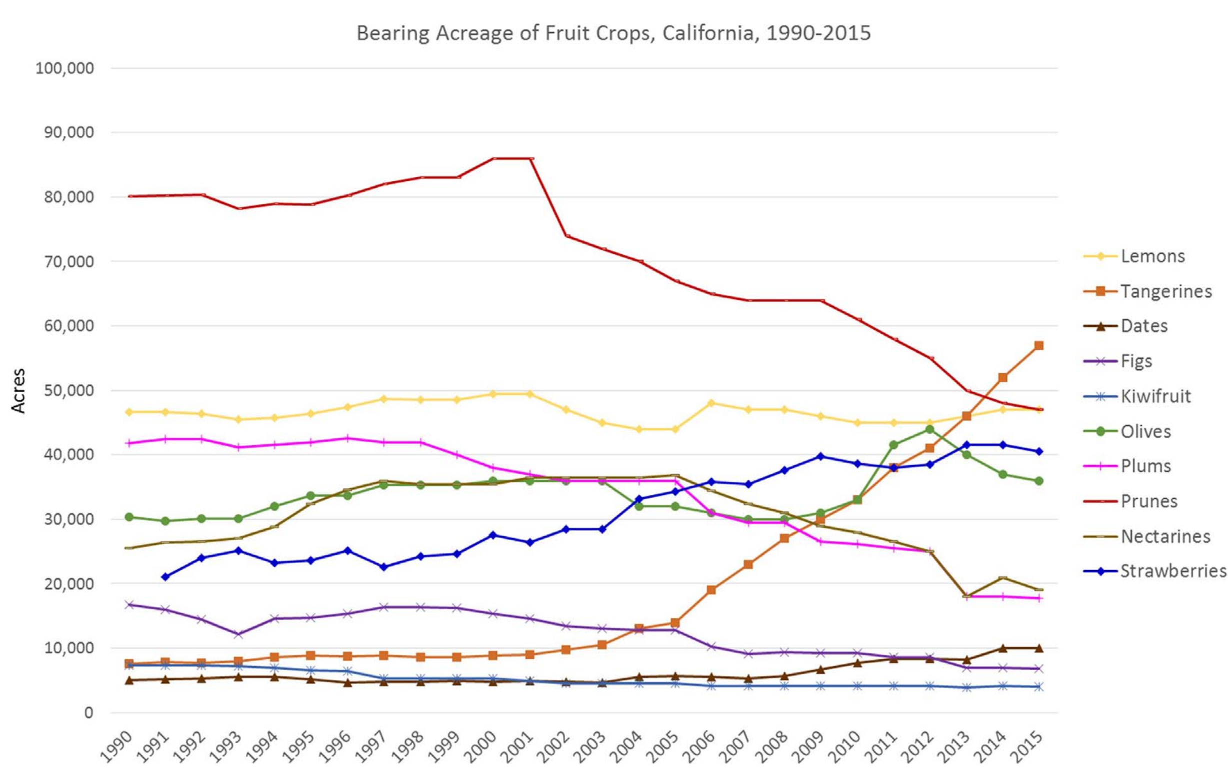


**Fig. B1.** Bearing acreage of fruit crops in California from 1990 to 2015.

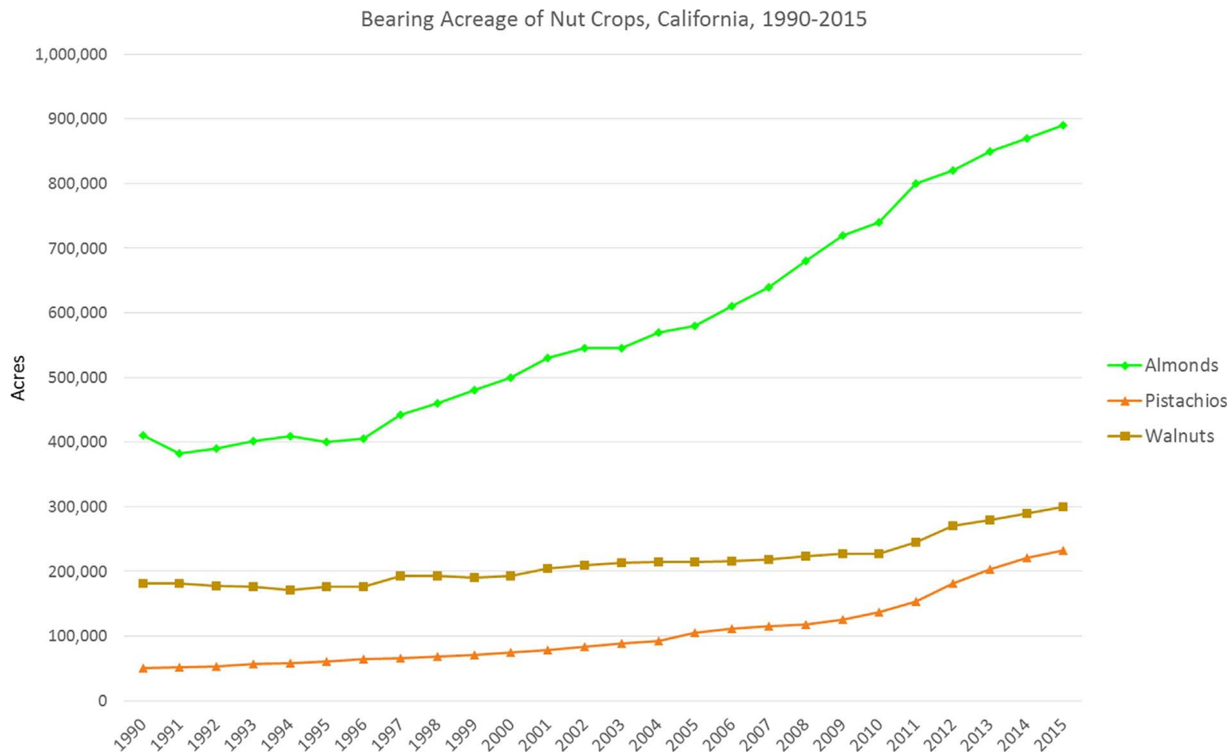


**Fig. B2.** Bearing acreage of nut crops in California from 1990 to 2015.

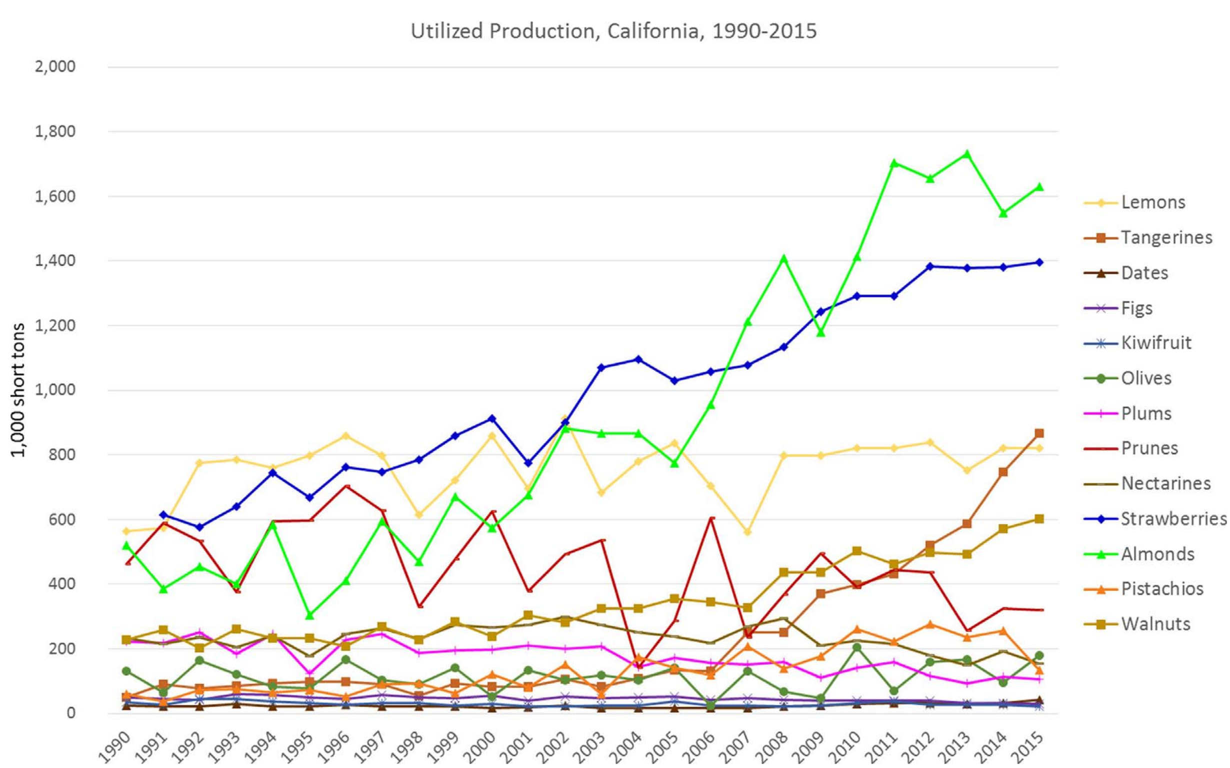


**Fig. B3.** Utilized production in California from 1990 to 2015. Notes: Utilized production includes quantities/volumes of fresh and processed volume of production of the crop. Lemons: Net box weight is 76 lbs (pounds) through 2009/10; Beginning in 2010/11 Net box weight is 80 lbs. Tangerines: Net box weight is 75 lbs (pounds) through 2009/10; Beginning in 2010/11 Net box weight is 80 lbs.

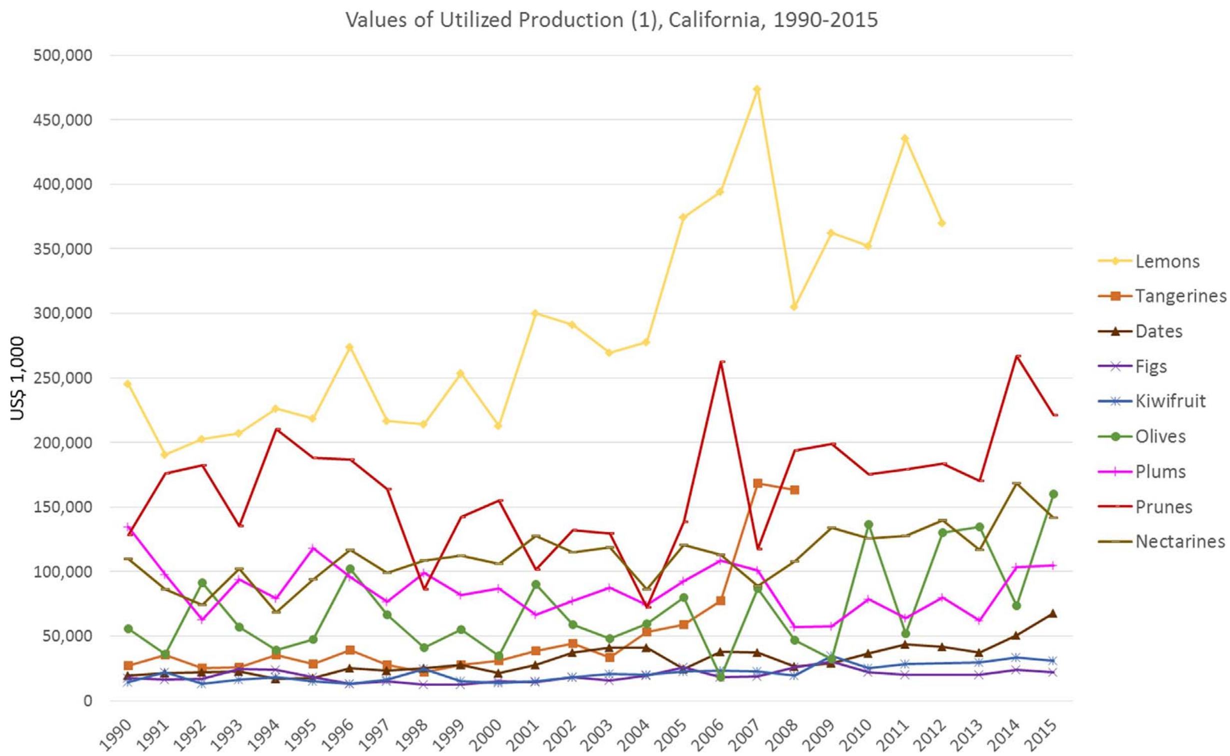


**Fig. B4.** Values of utilized production in California from 1990 to 2015 for crops with a value below US$500 million after 2010. Note: some figures for lemons and tangerines are said to have been withheld to avoid providing information on individual operations.

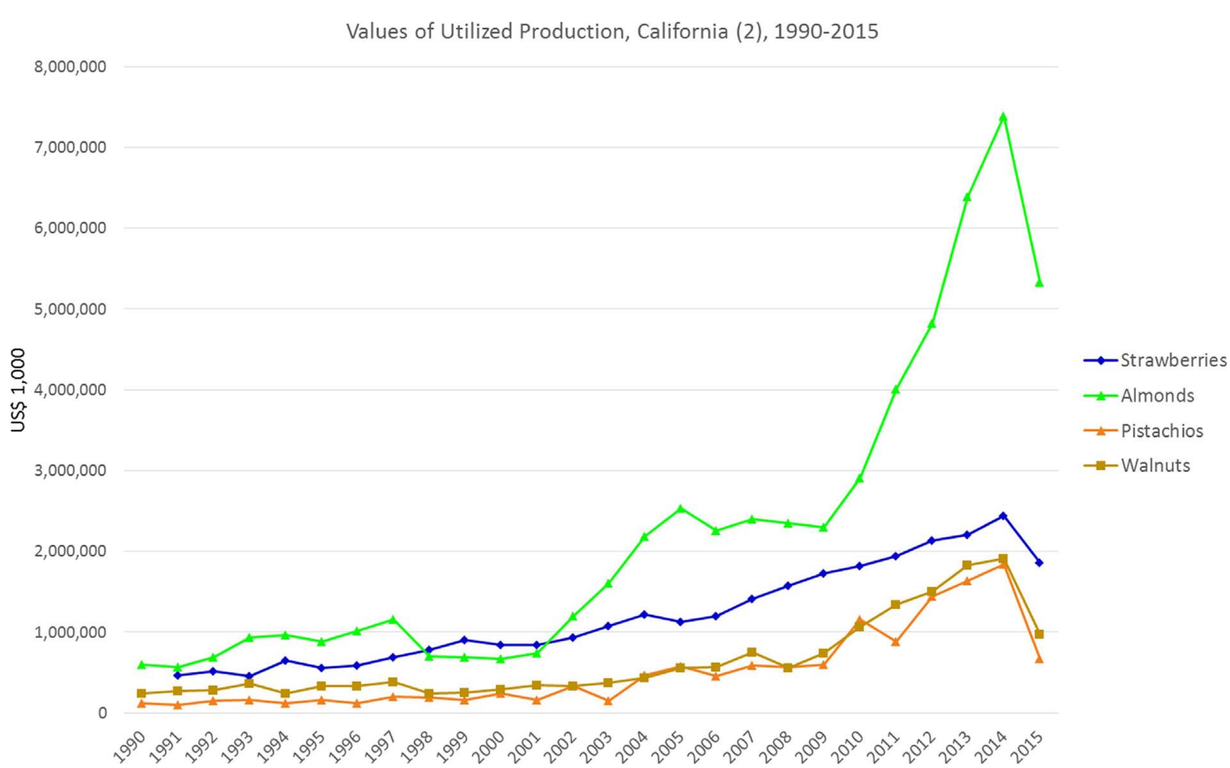


**Fig. B5.** Values of Utilized Production in California from 1990 to 2015 for crops with a value above US$500 million after 2010.

**Table B1**
Crop Yields in California, 1990–2015 (in 1000 short tons per acre).

| Year | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lemons | 12.06 | 12.29 | 16.70 | 17.30 | 16.63 | 17.20 | 18.12 | 16.39 | 12.70 | 14.89 | 17.35 | 14.04 | 19.40 |
| Tangerines | 6.41 | 11.73 | 10.23 | 10.78 | 10.90 | 11.08 | 11.21 | 10.23 | 6.54 | 10.90 | 9.38 | 9.17 | 10.82 |
| Dates | 4.80 | 4.23 | 3.96 | 5.27 | 4.18 | 4.23 | 5.56 | 4.38 | 4.63 | 4.53 | 3.63 | 4.02 | 5.04 |
| Figs | 2.97 | 2.82 | 2.92 | 4.98 | 3.88 | 3.40 | 2.95 | 3.51 | 3.09 | 2.90 | 3.63 | 2.73 | 3.94 |
| Kiwis | 4.66 | 3.67 | 6.30 | 6.19 | 5.43 | 4.83 | 4.31 | 6.00 | 6.23 | 4.53 | 5.75 | 4.69 | 5.13 |
| Olives | 4.33 | 2.19 | 5.48 | 4.05 | 2.63 | 2.30 | 4.93 | 2.95 | 2.55 | 4.02 | 1.47 | 3.72 | 2.86 |
| Plums | 5.33 | 5.14 | 5.90 | 4.49 | 5.94 | 2.95 | 5.35 | 5.86 | 4.45 | 4.90 | 5.18 | 5.68 | 5.58 |
| Prunes | 5.78 | 7.34 | 6.64 | 4.80 | 7.53 | 7.58 | 8.78 | 7.65 | 3.97 | 5.77 | 7.27 | 4.40 | 6.65 |
| Nectarines | 9.10 | 8.14 | 8.91 | 7.56 | 8.40 | 5.43 | 7.14 | 7.33 | 6.48 | 7.72 | 7.52 | 7.53 | 8.22 |
| Strawberries | N/A | 29.10 | 24.08 | 25.48 | 31.92 | 28.28 | 30.24 | 33.04 | 32.48 | 34.95 | 33.04 | 29.40 | 31.62 |
| Almonds | 1.26 | 1.01 | 1.17 | 1.00 | 1.43 | 0.76 | 1.02 | 1.34 | 1.02 | 1.40 | 1.15 | 1.28 | 1.62 |
| Pistachios | 1.19 | 0.74 | 1.40 | 1.33 | 1.12 | 1.23 | 0.82 | 1.38 | 1.38 | 0.87 | 1.63 | 1.03 | 1.83 |
| Walnuts | 1.25 | 1.43 | 1.14 | 1.48 | 1.36 | 1.33 | 1.18 | 1.39 | 1.18 | 1.48 | 1.24 | 1.50 | 1.34 |

| Year | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lemons | 15.20 | 17.70 | 19.00 | 14.65 | 11.96 | 16.98 | 17.35 | 18.22 | 18.22 | 18.67 | 16.35 | 17.45 | 17.45 |
| Tangerines | 7.86 | 8.37 | 9.64 | 6.91 | 10.92 | 9.31 | 12.38 | 12.05 | 11.37 | 12.68 | 12.78 | 14.38 | 15.23 |
| Dates | 3.81 | 2.98 | 3.02 | 3.22 | 3.08 | 3.67 | 3.49 | 3.77 | 3.96 | 3.70 | 3.72 | 3.34 | 4.36 |
| Figs | 3.77 | 3.97 | 4.08 | 4.16 | 5.25 | 4.61 | 4.30 | 4.45 | 4.50 | 4.50 | 4.71 | 4.77 | 4.44 |
| Kiwis | 5.33 | 5.49 | 8.04 | 6.05 | 5.64 | 5.24 | 5.69 | 7.74 | 8.74 | 6.45 | 6.90 | 6.80 | 5.78 |
| Olives | 3.28 | 3.25 | 4.44 | 0.76 | 4.42 | 2.23 | 1.49 | 6.24 | 1.72 | 3.64 | 4.15 | 2.57 | 4.97 |
| Plums | 5.81 | 4.00 | 4.75 | 5.10 | 5.15 | 5.42 | 4.21 | 5.39 | 6.27 | 4.60 | 5.19 | 6.28 | 5.90 |
| Prunes | 7.44 | 2.01 | 4.28 | 9.30 | 3.67 | 5.75 | 7.75 | 6.39 | 7.66 | 7.93 | 5.10 | 6.75 | 6.79 |
| Nectarines | 7.48 | 6.90 | 6.48 | 6.34 | 8.30 | 9.52 | 7.24 | 8.04 | 8.15 | 7.20 | 8.33 | 9.19 | 8.16 |
| Strawberries | 37.51 | 33.04 | 30.00 | 29.56 | 30.34 | 30.15 | 31.23 | 33.50 | 34.01 | 35.90 | 33.22 | 33.24 | 34.46 |
| Almonds | 1.59 | 1.52 | 1.34 | 1.57 | 1.90 | 2.07 | 1.64 | 1.91 | 2.13 | 2.02 | 2.04 | 1.78 | 1.83 |
| Pistachios | 0.68 | 1.87 | 1.35 | 1.06 | 1.81 | 1.18 | 1.41 | 1.91 | 1.45 | 1.51 | 1.16 | 1.16 | 0.58 |
| Walnuts | 1.53 | 1.52 | 1.65 | 1.60 | 1.50 | 1.96 | 1.93 | 2.22 | 1.88 | 1.84 | 1.76 | 1.97 | 2.01 |

## Appendix C. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.envsci.2017.09.012.

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