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Water-indexed benefits and impacts of California almonds

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ABSTRACT

California almonds have been the focus of recent media scrutiny because of the large amount of water required to grow individual nuts and, by extension, for the industry as a whole. With almond orchard acreage doubling in the last two decades and becoming California's most extensive irrigated crop, the questions arise: what are the benefits and impacts derived from this use of scarce water? Can we use this information to make decisions about growing and consuming this particular crop? We first use a water footprint approach to estimate total impact on water per unit of almond production in California, including variation in the water footprint over time (2004–2015) and across the production area. We then compare almonds to a set of other foods and crops grown in California using water footprint values and three other dimensions: nutritional value, per-unit-weight economic value, and total economic value. The water footprint of California almonds averaged 10,240 liters per kilogram kernels (or, 12 liters per almond kernel), with substantial variation over the time period analyzed. Water footprint values also varied twofold across the production area, with the smallest water footprint being in the southern counties of California's Central Valley. In relation to dietary benefits, almonds were among the top three foods analyzed providing the greatest nutritional benefit per unit weights, however they had the highest water footprint value per unit weight. The direct economic benefits of almond production based on market sales were also greater than for any other major crop in California, however almonds again had the largest water footprint on a per-unit and aggregate basis. We find that nutritionally and economically indexed water footprint indicators provide information to better-inform discussions on the benefits and impacts of growing almonds using California's limited water resources, relative to other crops. Such composite indices can be used in combination with more local and contextual information on water availability/scarcity, existing impacts, and agricultural conditions to better optimize water use within single crops, such as the almond industry, and among crops within a region. We propose that this approach should be used to inform political- and value-weighted decisions about agricultural water allocation in California and beyond.

1. Introduction

California is one of the world's most productive agricultural areas, and California's almond industry is an important and growing sector of the state's economy. California dominates the global almond market by growing about 80% of the world's almonds produced in any given year (USDA-FAS, 2015). Within California, the land area containing almond orchards in 2015 was nearly 450 thousand hectares (CDFA, 2016), representing an 81% increase over a decade prior. Almonds are the top economic-value export crop for California farms, accounting for 25 percent ($5.1B USD) of California's farm exports in 2015 (CDFA, 2017) and indirectly contributing $21.5 billion to California's economy in 2014 (Sumner et al., 2015).

Almonds are known for their nutritional value, providing a dense supply of protein, fats, fiber, and micro-nutrients (Chen et al., 2006; King et al., 2008). The oils and fats in almonds may be useful in reducing blood cholesterol (Hyson et al., 2002) and reduced risk of cardiovascular disease (Estruch et al., 2013) and diabetes (Martínez-González et al., 2008). There have been previous estimates of nutritional water productivity calculated as energy, protein, calcium, fat, Vitamin A, and iron output per unit of water input (Renault and Wallender, 2000); our study considers these and other macronutrients and compares almonds to alternative dietary sources of these nutrients.

Balancing the environmental impacts (e.g., from water use) of food production with nutritional benefits of foods is increasingly discussed in the press and can be affected by various actors, ranging from governments to individual consumers. Successful and sustainable food products are likely to be those that demonstrate contributions to tasty and healthy diets, economic benefits at the scale of production and consumption, and are demonstrably less environmentally damaging to

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produce than other foods that provide similar benefits. Water footprints are one way to compare crops and foods based on the volume of water consumptively used in their production, as discussed in Section 2.1. When expressed relative to economic and health outcomes, water footprint information can help inform both production and consumption choices and potential management of growing conditions (e.g., available water). Indicators and composite indices of water use and crop benefits can provide important information about agricultural efficiency and could be used at global-to-local geographic scales to make decisions about which crops to grow with limited water availability (e.g., Brauman et al., 2013).

Economic and dietary benefits of almonds must be compared against the impacts of production, including the use of surface and ground water (Vanham et al., 2018). Given the recent multi-year drought in California, water usage of all varieties is undergoing increased scrutiny (e.g. Holthaus, 2014). Moreover, water availability is expected to decrease given groundwater aquifer subsidence as well as decreased snowpack in the Sierra Nevada mountain range, an important storage source for California's water system (Belmecheri et al., 2016). As water in California becomes less abundant, or less available due to competing demands, the water use by irrigated crops will need to be balanced against the economic and nutritive benefits of those crops.

Estimates of the impacts of water use by crops, however, typically account for only the water used per unit of crop produced (e.g. the commonly referenced "one gallon per nut" for almonds (Park and Lurie, 2014)), a measure which fails to account for the full economic and dietary impacts of the crop. Although global and regional estimates of almond water footprints exist in the literature (Mekonnen and Hoekstra, 2011), there has never been a detailed examination of the water footprint of almonds within the crop's primary growing area, California, nor with respect to agricultural decision-making. In this article, we examine variations in almond water footprints across the production area and over time, in order to improve understanding of how the footprint for this crop could be managed. We also provide a comparison of the almond water footprint (impact) with other crops with respect to their nutritional and economic benefits, in order to improve optimization of crop decision-making.

2. Methods

2.1. Water footprints

Water footprint assessment (Hoekstra et al., 2011; Hoekstra and Mekonnen, 2012) accounts for the water consumptively used to create a product at all levels of the production and consumption of goods. Consumptive water use includes the water from managed sources, termed "blue water," effective rainfall or "green water" and pollution impacts to ground and surface water, termed "grey water." The water footprint ideally also includes qualitative information about water consumption, such as the geographic source of the water in question and whether or not the source of the water is external or internal to the geographic area of interest.

We calculated California's almond water footprint for years 2004–2015 on a countywide basis following methods presented in Hoekstra et al. (2011) and using locally relevant data sources. Almond acreage and production data by county were obtained from the County Agricultural Commissioners' Reports, available from the California Department of Food and Agriculture (CDFA, 2016). Consumptive green and blue water use factors were derived from the California Department of Water Resources' Cal-SIMETAW model (Orang et al., 2013). Factors for almonds were calculated as follows: green water = county-wide average rates of effective precipitation and blue water = total evapotranspiration minus effective precipitation. For grey water footprint calculations, estimated nitrogen application and uptake rates were obtained from Brown (2015) and statewide governing standards were from the California State Water Resources Control Board (CSWRCB, 2010).

2.2. Nutritional value of water footprints

We compared the nutritive content of 43 different California food crops in terms of 11 different nutrients, based on the nutrient-rich foods (NRF) index (Fulgoni et al., 2009). The NRF index rates foods based on their nutritional content in nine nutrients to encourage (protein, fiber, vitamins A, C and E, calcium, iron, magnesium, and potassium), and three to limit (saturated fat, added sugar, and sodium). As most raw agricultural products are not substantial sources of added sugar, we omitted it from the analysis. We assumed that nutrient composition was similar among varieties of almonds and no attempt was made to correct for proportions of each variety in the total crop by year or region. Data for nutrient content of different crops was obtained from the USDA National Nutrient Database for Standard Reference (USDA, 2016).

Almonds and other food crops were first ranked by their water footprint (liters of water per kilogram of product), where a rank of one was given to the smallest water footprint. Crops were also ranked by their content of each nutrient category (mg per 100 g of product), where a rank of one was given for the most desirable values, i.e. the largest value of nutrients to encourage (e.g., protein) and the smallest value of nutrients to limit (e.g., saturated fat). As no widely accepted method exists for weighting each nutrient category, a simple averaging of each crop's 11 rank values was used to create a composite score. This approach allows for comparison among crops, however conclusions should not be drawn about the magnitude of these differences. A simple ratio of absolute water footprint values to nutrient values (liters water per milligram nutrient) was also calculated and is available in the Supplementary Material for this article; these ratios are better suited for evaluating the magnitude of differences among crops.

2.3. Economic value of water footprints among crops

We compared almonds to 44 other California crops (the same 42 food crops plus alfalfa hay and wine grapes because of their economic importance) using a ratio of water footprint to direct economic value. Direct economic value is defined here as total farm-gate sales, whereas the overall economic value of an industry could include indirect activities by support industries, as well as induced economic effects associated with employment, finance, and other economic impacts. Sumner et al. (2015) provide a more complete assessment of economic impact of California almonds, however sufficient and comparable assessments among other crop industries do not exist for creating comparative indicators, one of the main motivations of our study. Therefore we focus on direct economic benefits only.

For analyzing direct economic effects of almonds in comparison to other crops, we calculated three different indicators. First, to give a farm-level perspective, we ranked the per-unit-weight water footprints (l/kg) of the 45 crops and compared this ranking to their ranked farm-gate market prices ($/kg). As with the nutritional value indicators (Section 2.2), we selected a ranking approach in order to show relative differences among crops rather than absolute values. We obtained water footprint factors (liters of water per metric ton of product) for California products from Mekonnen and Hoekstra (2011), who give factors averaged over the 1996–2005 period. We also used their water footprint estimate for almonds in this calculation in order to maintain consistency in estimation methods and therefore comparability between products. Farm-gate prices were obtained from County Agricultural Commissioners' Reports (CDFA 2016) and averaged over the 2004–2015 period. Second, because prices fluctuate with market conditions and water footprints fluctuate with climatological and growing conditions, we calculated this ratio over time for almonds using our own almond water footprint calculations, as described previously in Section 2.2. Third, to give a statewide water management perspective, we compared the same 45 crops in terms of their total crop water footprint and their total farm-gate market value.

3. Results

3.1. The water footprint of California almonds

3.1.1. Temporal variation in the California almond water footprint

Between 2004 and 2015, the average water footprint of one kilogram of raw California almond kernels was 5290 liters blue water, 570 liters green water, and 4,380 liters grey water (total = 10,240 l/kg kernels). At 1.2 grams per kernel (USDA, 2016), each California almond has an average water footprint of about 12 liters, of which the blue water portion is 70% greater than previous media estimates (Park and Lurie, 2014). Using global-level data, Mekonnen and Hoekstra (2011) estimated that the water footprint of one kilogram of California almonds was slightly higher: 4026 liters blue water, 2321 liters green water, and 6,637 liters grey water (total = 12,984 l/kg kernels). We found a lower overall water footprint, but with key differences between the types of water: less green and grey water, but higher blue water in our study. This likely reflects the resolution of data available to construct a global dataset (Mekonnen and Hoekstra, 2011) and the particular dependence on irrigation in California's agricultural sector.

During the 12 years analyzed, the water footprint of California almonds has varied considerably, having decreased by as much as 22% in 2011 but rising back to 2004 levels by 2015 (Fig. 1). The initial decreases appear to have been driven primarily by better orchard yields, as technology improved and almond orchards were developed in regions of the state with better growing conditions (as discussed in the next sub-section 3.1.2). The more recent increase in the almond water footprint, however, appears to be driven by increased blue water requirements, possibly associated with drought and higher temperature conditions, as well as water impacts associated with increasing the area of new almond orchards that do not yet produce high yields.

3.1.2. Regional variation in the California almond water footprint

Water footprints among the 16 almond-growing counties across California varied by nearly twofold (Fig. 2). Over the 12-year period analyzed, Sutter and Yuba counties, had the highest average total (green, blue and grey) almond water footprints, at over 16,468 and 16,400 liters per kilogram, respectively. Kern and Fresno counties had the lowest, at 9351 and 9225 liters per kilogram, respectively. There was a general trend of higher water footprints among northern counties and lower water footprints among southern counties. This pattern is associated with a hotter climate and therefore better yields in the southern part of the state. Thus, even though evapotranspiration rates for almond orchards are lower in the cooler, northern climate, decreased yields have a greater effect on water footprint values. Conversely, actual almond production (yield) in the southern counties outweighs the higher evapotranspiration rates, resulting in a lower water footprint value.

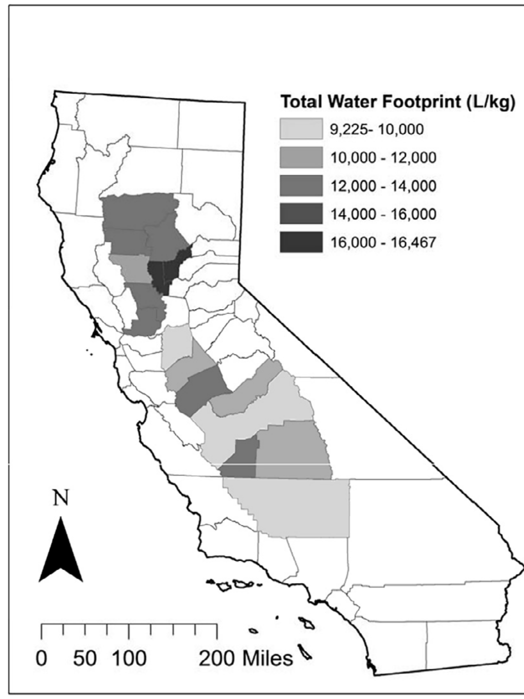

Fig. 2. Variation among California counties in the average (2004–2015) water footprint of almonds.

3.2. Water footprint and nutritional value

To inform decisions at the individual consumer level, we compared almonds to other major California crops in terms of their nutritional benefit per unit water footprint. Out of the 43 crops selected for this comparison, almonds ranked 43rd in terms of water footprint and 3rd in terms of average nutrient rank, where a lower rank is considered more desirable. Figure 3 shows all 43 crops plotted by water footprint rank (horizontal axis) and average nutrient rank (vertical axis; note that the minimum value is 10), where proximity to the origin of the graph represents smaller water footprint and greater nutritional value. Using

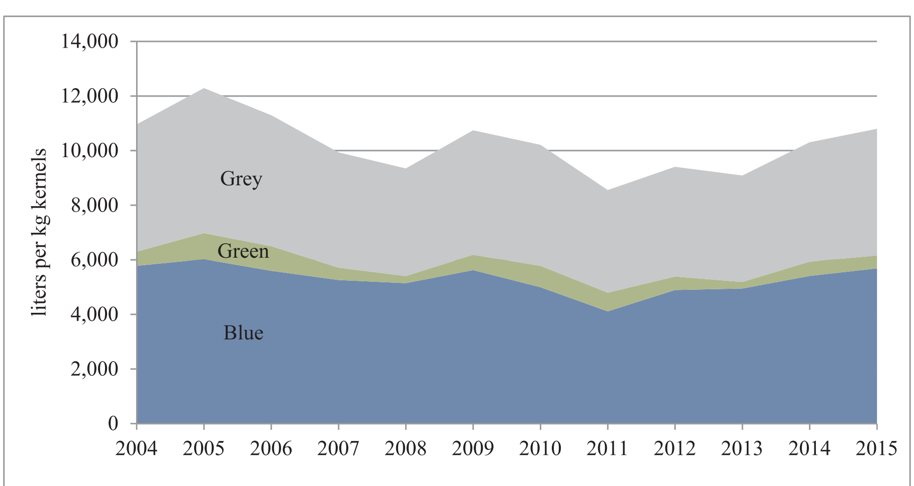

Fig. 1. Temporal variation in the water footprint of California almonds.

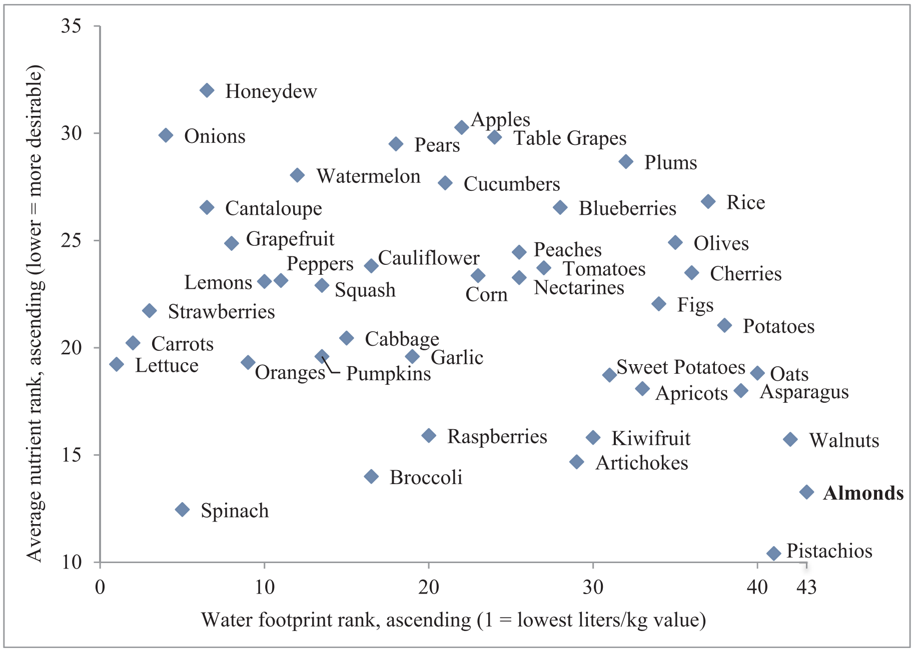

Fig. 3. Major California crops ranked by water footprint values (horizontal axis) and average rank of 11 nutrient categories (vertical axis; note that the minimum value is 10). "Almonds" is bolded.

this approach, almonds appear similar to other tree nut crops (walnuts and pistachios), however several other specialty crops (spinach, broccoli, raspberries, artichokes, and kiwifruit) rank similarly in relative nutrient content but rank better in terms of water footprint.

In general, this comparison illustrates the tradeoffs between water intensity and nutritional value of grower-selected crops and, consumer-preferred foods. Some products that have low water footprints may have low nutritional value (e.g. honeydew and onions), while others may have high water footprints yet still provide a highly nutritious food (e.g. almonds and other tree nuts). In terms of nutritional value, almonds rank at or near the top of all California crops in seven of the 11 nutrient categories, with the exceptions of vitamins A and C, as well as saturated fat.

3.3. Water footprint and economic value

3.3.1. Comparison of crop water footprint and price per unit weight

To inform decisions at the individual grower level, we compared the water footprint of almonds and other crops to the average farm-gate prices received for those crops over the 2004–2015 period. Almonds ranked last in terms of water footprint but ranked first in terms of direct economic value, where a lower rank is considered more desirable. Figure 4 shows all 43 crops plotted by water footprint rank (horizontal axis) and average (2004–2015) farm-gate price (vertical axis), where the origin of the graph represents the highest value per unit water footprint. Almonds appear at the bottom-right corner, indicating a high-water use, high-value crop, along with other tree nut crops and some berries.

In general, a clear trend can be seen in Fig. 4 from top-left to bottom-right, indicating a somewhat rigid tradeoff between higher economic returns and higher water footprints. Few crops – notably spinach, strawberries, raspberries and blueberries – appear to have higher ratios of economic value to water footprint. For actual values of these ratios, see the Supplementary Material for this article.

3.3.2. Temporal variation in almond water footprint indexed to economic value

In addition to comparing the economic values over multiple crops, another way to view the economic efficiency of water usage by the almond industry is to track the ratio of farm-gate revenue to water footprint ($ per cubic meter) over time (Fig. 5). By this measure, the economic productivity of water for almond production has varied substantially, initially declining in the mid-2000 s before more than doubling in recent years. This occurred as the total value of the almond crop in California has increased substantially (black dotted line in Fig. 5) while also impacting less water per unit of production (as shown in Fig. 1).

3.3.3. Comparison of total crop water footprint and total market value

To inform decisions at the state scale, we compared almonds to other California crops in terms of their total water demand and their total direct economic value. Figure 6 plots the total statewide water footprint of each crop against the total farm-gate market value for the year 2014. Note that contrary to Figs. 3 and 4, axis units are not ranked but in absolute terms in order to demonstrate the magnitude of water demands and economic values of different crops in California. A dashed line plotted along the $\$1/m^3$ ratio is also shown to aid in comparing crops using this indicator.

As shown in Fig. 6, the majority of agricultural products are clustered around the origin, indicating both low total water footprint and low total sales value. Almonds are positioned at the opposite corner of the chart, with nearly triple the total water footprint of the next highest crop water footprint (walnuts) and nearly double next highest aggregate crop sales value (wine grapes). In addition to highlighting the difference in magnitude of total water used and total economic value among California crops, Fig. 6 also depicts the economic productivity of water consumption among crops.

The dashed line, while somewhat arbitrarily placed at $1 in sales per m^3 of water demand, provides a benchmark level of productivity with which to compare crops in 2014. A majority (37) of the 45 crops fell above the dashed line, indicating higher economic productivity per unit water footprint. Many of these crops had a smaller impact on overall statewide total water consumption and crop sales. Still others had a larger economic impact while maintaining a smaller water impact, i.e. a greater productivity ratio. For example, five crops – wine grapes, table grapes, strawberries, pistachios, and oranges – together accounted for 35% of total sales but only 13% of the total water footprint associated with the 45 selected crops in 2014. Conversely, four

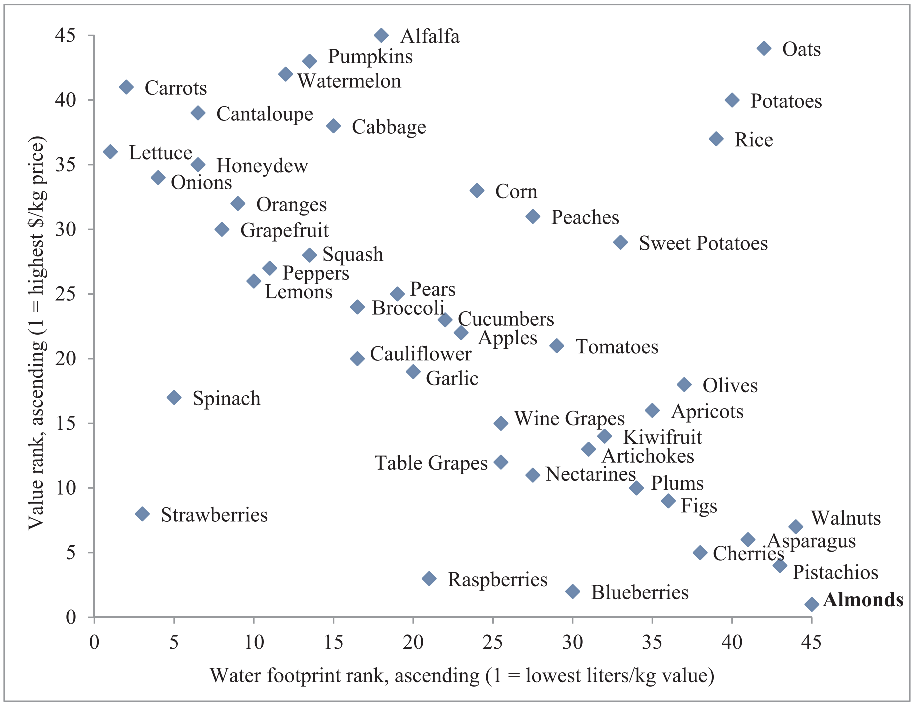

Fig. 4. Major California crops ranked by water footprint values (horizontal axis) and ranked by average (2004–2015) farm-gate price (vertical axis). "Almonds" is bolded.

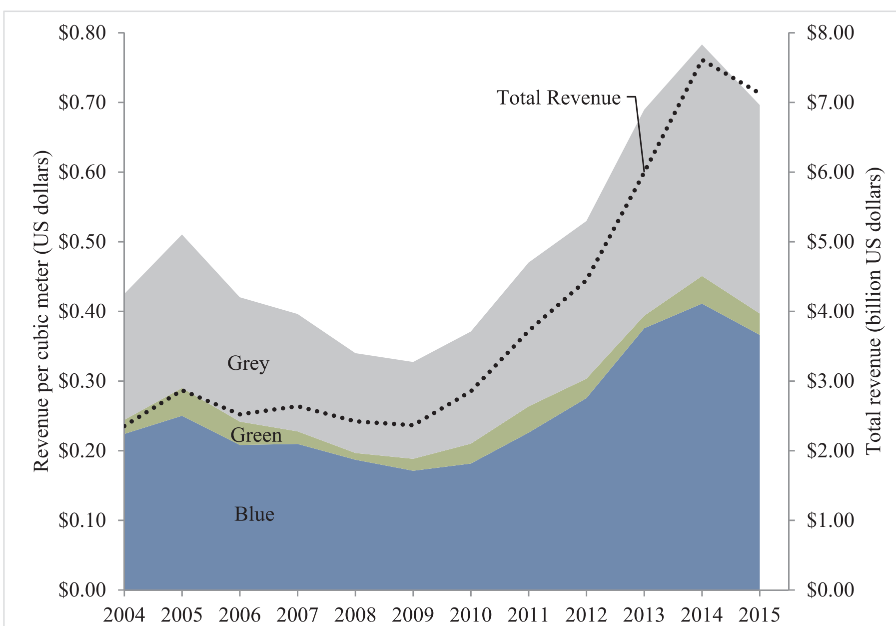

Fig. 5. 2004 to 2015 California almond revenue per cubic meter water footprint, by blue, green, and grey water (left-hand vertical axis), and total almond revenue (right-hand vertical axis).

major crops falling below the dashed line – almonds, walnuts, alfalfa, and rice – accounted for 41% of total sales but 73% of the total water footprint. Almonds alone accounted for 25% of total sales and 42% of the total water footprint.

4. Discussion

To inform a growing debate about the impact of almond production on water in California, we provided a calculation of the almond water footprint, detailed regional and inter-annual variation in water footprint, and compared the nutritional and economic benefits of almonds and other crops with their water footprint. The water footprint is a useful tool for determining total impacts from food/crop production in an area like California (Fulton et al., 2014) and, when scaled to benefits, could be a decision-support tool for individual and institutional decisions about water impacts. Our calculation of the California almond water footprint for 2004–2015 was lower than the global average and also lower than previous California estimates using global-scale data (Mekonnen and Hoekstra, 2011). We found that the almond water footprint has varied considerably (22%) over the last decade and can vary by up to 2–fold across its production range in California's Central Valley. Almonds have a larger water footprint per unit weight than most other foods/crops, but when normalized to nutritional contributions or market value, was on par or better than most common foods/

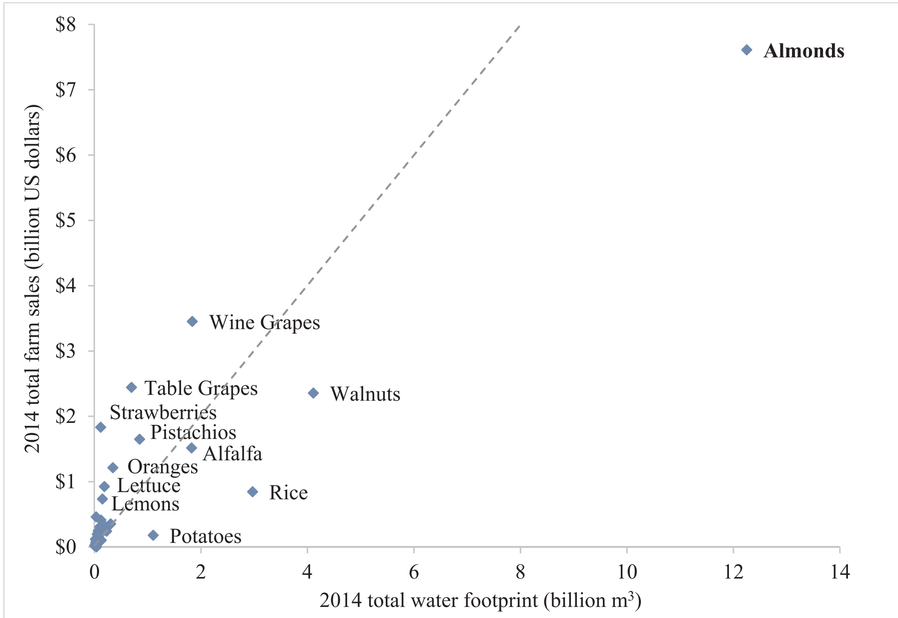

Fig. 6. Comparison of 2014 total water footprint with 2014 total market value of each agricultural product within California. The dashed line corresponds to $1/m^3 water footprint. “Almonds” is bolded.

crops.

Water footprint calculations indicate that over 10 cubic kilometers of water were consumptively used to produce the statewide almond crop in 2015. On a per-nut basis, the total water footprint of almonds is 3-to-4 times higher (blue water is 1.7 times higher) than previous media estimates (e.g., Philpott and Lurie, 2015). The water footprint of almonds decreased during the initial period of our study due to increasing overall yields and expansion of almond acreage in areas of the state with particularly high yields, however most of these gains were undone in recent years due to an increased dependence on blue water during drought conditions, and the grey water impacts of an expanded orchard area with younger trees. To the extent that the overall almond water footprint has decreased, these findings should not be taken as an indicator of increasing sustainability of almond production, as many of these high-yield regions face water scarcity, stressed groundwater aquifers, and high energy and greenhouse gas impacts of water supply (Klein and Krebs, 2005; Williams et al., 2015; Marston and Konar, 2017). Assessing these factors through a systematic water footprint sustainability assessment or lifecycle assessment would be an important step toward sustainability in the almond industry. In addition, sustainability of individual crops in an agricultural region should be based upon the water impact (i.e., water footprint) compared to the total water available, not just water footprint per unit weight, or value (Tom et al., 2016).

The higher water footprint per unit weight for almonds grown in northern counties compared to southern counties may seem counterintuitive when one thinks about the growing conditions in the northern counties being milder than in the hotter, drier southern counties. Evapotranspiration of applied water (ETaw) rates in parts of the southern counties range from one to two feet greater than in northern counties. Nevertheless, the hotter, drier conditions in the southern counties help make almond crop yields so much greater that they outweigh the effect of higher ETaw values on the overall water footprint.

With respect to the health benefits of almonds, we extend previous studies of the nutritional productivity relative to water use (e.g. Renault and Wallender, 2000) and argue that typical methods of comparing water impacts of almonds to the weight produced does not account for the unique nutritional contributions of almonds. The water footprint of almonds indexed to their nutritional benefit is favorable compared to several other prominent California crops such as rice, olives, and cherries. More generally, our results are consistent with other research that shows that a plant-based diet leads to less of an environmental impact, including water use, energy use, pesticides, and fertilizer (Pimentel and Pimentel, 2003; Hoekstra, 2010; Marlow et al., 2015).

In terms of economic impacts, the impact of the almond industry is felt in a variety of ways, and accounts for economic activity in California both directly and indirectly. We found that the direct economic impact of almond production per unit water footprint may be less than for other high-value crops (e.g. berries) and greater than for lower-value foods like oats. This information can be useful to inform decisions at the individual grower scale. To support state-scale decisions about the value obtained from crop-specific water allocation and use, it will be informative to conduct more comprehensive analyses of direct and indirect economic benefits for other foods/crops (see e.g. Li et al., 2017).

It is important to note that our study does not contain a water footprint sustainability assessment. Such an assessment would identify actual environmental and social impacts from consumptive water use for almond production (Pfister and Hellweg, 2009). This study provides volumetric water footprint estimates for California almonds in connection with their economic and nutritional values as a basis for comparison with other crops and crop products. These comparisons can inform a broader discussion of the role of water in agricultural production but should by no means be considered a comprehensive basis for assessing its sustainability.

Our study points towards future areas of research. To better assess and track the overall sustainability of California's almond industry, our findings can be integrated with other assessments of impacts and benefits. Studying the environmental and social impacts of various water supplies around California can improve decisions about water use, beyond the typical volumetric-basis. Efforts to calculate energy use and greenhouse gas emissions of the almond industry can be incorporated to examine trends as well as tradeoffs and synergies in particular management practices (Marvinney et al., 2015). Finally, we did not address California's virtual imports or exports of water. The concept of water footprint can be used to compare virtual transfers of water among geographic areas, and the analysis in this paper can account for California's unique contributions to global almond production.

With increasing legislative oversight and competition for available water, California may move towards more active intervention among all of the potential uses and users of that water. In the future in California and beyond, this may lead to crop-specific prioritization within the agricultural sector or economic optimization of available water allocations and impacts (Davis et al., 2017). The concepts in this paper are intended to encourage the inclusion of nutritional and economic scaling of almonds' water footprint (and other foods) into any future decision-making, with an eye towards the sustainable management of California's water for future generations.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2017.12.063.

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