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A growing produce bubble: United States produce tied to Mexico's unsustainable agricultural water use

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E-mail: sarah_hartman@berkeley.edu**Keywords:** water resources, sustainability, diet, water and food security, agriculture and irrigation systemsSupplementary material for this article is available [online](#)

Abstract

Global analyses have revealed virtual drains and gains of water between trading countries, with Mexico ranking as one of the countries with the fastest increase in unsustainable water consumption in agriculture for export markets, since 2000. It is unclear, however, how Mexico has reshaped its crop production and associated reliance on freshwater resources to satisfy growing domestic and international markets, especially the United States (US). While the Mexico-US partnership has been identified as one supported by unsustainable irrigation water, the spatial understanding of its strain on water resources has remained at the national scale and without context of the crops driving the change. In this analysis, we focus on the evolution of Mexican agriculture since 1994, the year the North American Free Trade Agreement was enacted, to identify hotspots of water unsustainability in crop production in the domestic and US supply chain. Using a global process-based crop water model, we find that between 1994 and 2015, rainwater (or 'green' water) and irrigation (or 'blue') water consumed in the production of crops increased by one fourth nationally, while water in crops exported to the US doubled. Virtual export of blue water embodied in the trade of berries increased five orders of magnitude; a substantial growth in blue water export was also associated with trade to the US of cereals, fruits, nuts, vegetables, pulses, and tubers. Our results show that in Mexico irrigated water plays an increasingly prominent role in export agriculture, and that many healthy crops that dominate US imports from the world are grown in water scarce Mexican municipalities relying on unsustainable irrigation practices. This serves as a warning for the sustainability of future Mexican healthy food supplies, both for the domestic market and for export to the US.

1. Introduction

The 2020 'State of Food Security and Nutrition in the World' painted a grim reality of global progress made towards ensuring safe, nutritious, and sufficient food for all people, also casting doubt on achieving sustainable, healthy diets (FAO *et al* 2020). Healthy diets are defined by the United Nations as diets that include foods from several food groups and with a diversity within groups (FAO *et al* 2020). Sustainable diets are those with 'low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations' (FAO 2012). The 2030 Agenda for Sustainable Development

combines these definitions to focus on healthy and sustainable diets, thereby highlighting the critical need to assess sustainability of food supply chains today and into the future (FAO/WHO 2020).

At the same time, availability and affordability of high quality, healthy diets have increased in high-income countries, such as the United States, even as severe food insecurity rose and overall nutrient quality decreased in lower income countries, such as Mexico (FAO *et al* 2020). Meanwhile, in recent years, Mexico has exported its greatest ever quantity of fruits, vegetables, and nuts to the United States (US) (FAO 2020). While these food groups by themselves do not wholly encapsulate a healthy diet per the United

Nations definition, they are necessary components of one. The associated changes in crop demand to satisfy US diets have reshaped the Mexican agricultural landscape in terms of domestic production, trade with other countries, and domestic natural resource use.

The proliferation of agricultural trade between Mexico and the United States is in part a result of the North American Free Trade Agreement (NAFTA). Effective January 1994, NAFTA loosened restrictions on agricultural trade, among other commodities (NAFTA 1994). NAFTA partner countries received preferential duty treatment on goods, and importantly, gained duty-free status for crops over a staged process. Duties were eliminated based on crop categories and season, first in 1994, and incrementally by 1998, 2003, and 2008. Compared to the pre-NAFTA era, continental market integration increased for all agricultural sectors, including grains and oilseeds, fruits and vegetables, sugar and sweeteners, and processed foods (Zahniser *et al* 2015).

Changes in crop demand and production type have implications for water resources. Global crop water requirement (CWR) models have been used broadly to calculate freshwater withdrawals for agricultural production and to quantify virtual water trade (VWT) flows between countries (Allan 1996, Mekonnen and Hoekstra 2011, Konar *et al* 2013, D'Odorico *et al* 2019). Virtual water is the water consumed to produce a commodity; although it is not physically present in that commodity in its terminal location, it is virtually traded as that commodity is exported to another region or country (Allan 1996). VWT of staple crops, such as rice and wheat, have been attributed with net water savings due to the re-distribution of crop production from less water-efficient countries to more efficient countries (Konar *et al* 2013). At the same time, the global redistribution of food crops and associated water and nutrient resources is not—to date—optimal (Davis *et al* 2017). Analysis of global unsustainable virtual water flows in agricultural trade reveals that 52% of global irrigation is unsustainable, with 15% of it virtually exported between countries (Rosa *et al* 2019). For this analysis, 'unsustainable' is defined as situations where local surface and ground water (termed 'blue water') consumption for irrigation exceeds locally available blue water resources. Available resources are the amount of surface and subsurface runoff remaining after preserving environmental flows, which are often taken as 80% of runoff (Richter *et al* 2012).

Mexico is a major player in global unsustainable virtual water flows, ranking as the country with the third highest increase in unsustainable agricultural water consumption between 2000 and 2015, due to expansion of irrigated agriculture (Rosa *et al* 2019). Unsustainable water consumption in Mexican agricultural exports increased by 89% during this time, with a notable uptick in the export of unsustainably produced fruits and vegetables to the United States.

Water use for Mexican agricultural export has also been attributed to groundwater depletion in production, national consumption, and exports (Dalin *et al* 2017). The post-NAFTA era is marked by an increase in intracontinental trade and a tightening of North American VWT (Dalin *et al* 2012).

In this study, we investigate how agricultural exports from Mexico to the US changed since NAFTA was enacted in 1994, thereby reshaping the patterns of crop production, irrigation, and unsustainable water use in Mexico. To that end, we examine the evolution of crop water consumption for Mexican domestic production and virtual water export to the US at a spatial and temporal resolution never examined before. We quantify water requirements for 58 primary crops and compare them to regional sustainability classifications for the year 2000 to identify crops and municipalities that are contributing to unsustainable water consumption and export. By tracking state- and municipality-level shifts, we analyze a unit of measurement that has direct value for local to regional policy makers and identify which growing regions have rapidly and oftentimes unsustainably transformed to accommodate the US export market.

2. Methods

This study analyzed the annual CWRs of Mexican production of 58 key crops that comprise over 96% of harvested hectares and 95% of production mass for food crops in Mexico between 1986 and 2016. The 58 crops represent 91% of all non-animal agricultural export from Mexico to the United States between 1986 and 2016 based on bulk metric ton (1000 kg, hereafter referred to as 'ton'). Production data came from the Agri-Food and Fisheries Information Services (SIAP) of the Mexican government and are reported at the state level from 1980 onwards and the municipal (or county) level from 2003 onwards (SIAP 2020). The database reported crop seed mass separately; we do not consider seeds in our analysis. Trade data are from the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) and reported at the national level from 1986 onwards as US import from Mexico (FAO 2020). Where temporally possible, analysis was conducted at the municipal level, with municipalities representing the smallest administrative unit in Mexico.

To analyze trends, the 58 crops were grouped into nine crop categories that follow FAOSTAT commodity groupings: cereals, fruits, vegetables, nuts, pulses, tubers, fodder crops, oil-bearing crops, and other crops not included elsewhere (2020). The crops selected for the other crops category did not fit into the other designated categories but are present in Mexican production and export. Sub-categories within fruits and vegetables were also created—berries,

citrus fruits, tropical fruits, other fruits, brassicas and leafy v. (vegetables), fruiting vegetables, and other vegetables—based on FAO primary food commodities of plant origin groups (FAO and WHO 2006). A summary chart of the groupings can be found in the supplementary materials (available online at stacks.iop.org/ERL/16/105008/mmedia).

CWRs, and blue and green water consumption were quantified using the WATNEEDS model, a global process-based crop water model (5 arcmin; ~ 10 km resolution), applied to the municipalities of Mexico (Chiarelli *et al* 2020). This model has been previously used to assess irrigation water requirements (Davis *et al* 2017, Chiarelli *et al* 2018, Rosa *et al* 2018). The model's structure and validation are presented in Chiarelli *et al* (2020). Model values for crop parameters accounting for planting and harvesting dates and the growing period were taken from (Chapagain and Hoekstra 2004) where not already available in the WATNEEDS model. Daily soil water balance during each crop's growing season was used to calculate municipal-level, spatially explicit CWRs for rainfed (green water) and irrigated (blue and green water) crops (mm yr^{-1}) for every year from 1986 to 2016. State-level CWRs are area-averaged sums of the requirements for the municipalities they contain (equation (1)).

State average CWR (volume/area) values were aggregated from estimates at the municipality level:

$$\text{CWR}_s = \sum_m \text{CWR}_m \frac{A_m}{A_s} \quad (1)$$

where A_m is the area of municipality m within the total state's area, A_s .

Crop water consumption was then calculated by dividing the CWR value calculated in the WATNEEDS model by the yield for each crop, then by multiplying the resulting value by the production of that crop in that year (equation (2)). The yield is calculated using SIAP data for each corresponding year, location, and modality (irrigated or rainfed). For the purposes of this study, we assume that CWRs are met for all crops in all years, meaning that the crops are not operating under deficit irrigation.

Water consumption (volume) of crop i is determined as:

$$\text{WC}_i = \frac{\text{CWR}_i}{Y_i} \times \text{Production}_i \quad (2)$$

where Y_i (mass/area) is the yield of crop i in that location and Production_i is the production mass of crop i .

Blue, green, and all (blue plus green in the case of irrigated agriculture) water consumption were calculated for every crop, location, and year combination. Water consumption change was calculated as the change between the average of the final three years

and the average of the initial three years, with the reported change happening between the middle year of the initial and final three years. This was done to smooth out any variation from year-to-year that may be due to incomplete reporting in one year.

Export data from FAOSTAT were used to quantify Mexican export to the US (FAO 2020), with missing data imported from the United States Department of Agriculture (USDA) Foreign Agricultural Service Global Agricultural Trade System (GATS) database where needed (USDA/FAS 2020). FAOSTAT primary product extraction rates were used to determine the amount of exported primary product originating from the 58 primary crops in the SIAP database (FAO n.d.). Where available, the Mexico-specific extraction rate was used.

While SIAP has a dataset of subnational direct crop export since 1999, this dataset is sparse until 2015, at which point it reports only 18 of the 58 crop categories in our study and at far lower quantities of export than reported in FAOSTAT, likely due to how 'export' is defined (i.e. presence of a middleman processor in Mexico before export) and availability of municipal-level data. For this reason, state- and municipal-level 'export' values are here estimated as the amount of domestic production that contributes to the export market as a best approximation of export given limited existing data. These values were calculated by taking a proportional average of the location's production to the national production, thereby conserving flows at the national scale and distributing their impacts equally among producing regions of each exported crop (equation (3)):

$$\begin{aligned} & \text{Export proportion}_{\text{location, crop}} \\ &= \frac{\text{Production tons}_{\text{location, crop}}}{\text{National production tons}_{\text{crop}}} \\ & \times \text{National Export tons}_{\text{crop}}. \end{aligned} \quad (3)$$

Here, the local export proportion is the amount of the national export of a crop that originates in the specified location, calculated as the proportion of the national production that originates in that location times the national export of the specified crop. In cases where export tons exceeded the amount of national production, the export proportion is simply the location's proportion of the national production. Municipal- and state-level water consumption for export are then determined on a crop-wise basis as the respective water consumption for that crop times its export proportion. This provides a modelled value of the amount of water resources that are contributing to export from every municipality or state.

Finally, trends in irrigated crop production and associated water requirements were compared to (Rosa *et al* 2018)'s global map (at 30×30 arcmin resolution) of sustainable and unsustainable irrigation areas available only for the year 2000. In this map, local water consumption was determined by

combining calculated blue crop water consumption values with local blue water consumption for municipal and industrial uses. Local water availability was computed based on estimates of runoff and flow accumulation minus the water used for other needs (municipal and industrial) and the environmental flows. The unsustainable areas are defined as areas where irrigation practices in 2000 require water exceeding the locally sustainable amount required to maintain local environmental needs assuming 80% of runoff is reserved for environmental flows. Contrastingly, sustainable water use occurs in locations where available blue water resources exceed blue water consumption. This model does not differentiate between water sourced from surface versus ground water. The growth trends of irrigated crop production and water requirements calculated as part of this study were compared to year 2000 sustainable and unsustainable classifications for Mexico in ArcGIS using the Intersect Analysis Tool. Areas were then classified based on whether (a) their 2000 water use was sustainable or unsustainable, and (b) the irrigated crop water consumption calculated in this study was increasing, decreasing, or exhibited no change. No change was defined as an irrigation water consumption change of $<|5|\%$ over the study period.

3. Results

3.1. Domestic production

For the 58 selected crops in this study, harvested area increased by +2.6% and +0.9% per year until 1994 and 2016 respectively (figure 1). In these cases, growth is faster prior to 1994 than post 1994, with growth in the selected crops outpacing all agricultural growth in Mexico. Both rainfed and irrigated agriculture grew at a rate of roughly 0.9% each year in terms of harvested area and +4.3% in terms of production output. The time between 1994 and 2016 also saw a national increase in crop yields for many primary crops, especially fruits and vegetables. This included a doubling of irrigated crop yield of eggplant; cucumber; tomato; asparagus; papaya; cassava; strawberries; watermelon; and melons, other (incl. cantaloupes). Unsurprisingly, the time period brought about agricultural expansion in Mexico.

While at the national level harvested area and production quantity increased modestly, crop categories saw broader ranges of increase and decrease (see table in supplementary materials). Increases in irrigated land area and production tons (respectively) were led by fodder crops (+115%, +152%), nuts (+104%, 204%), tubers (+63%, +120%), vegetables (+53%, +153%), and fruits (+41%, +94%), due to an expansion of agricultural land use, spatially or temporally, and increasing crop yields. In the case of cereals, irrigated area increased while rainfed area decreased, with the irrigated production (in tons) increasing more than the rainfed production in these

categories. For oil-bearing crops, irrigated area and production decreased while rainfed area and production increased. Irrigated and rainfed area increased for fruit, nuts, and tubers, with irrigated production change outpacing rainfed production. Irrigated and rainfed area increased for fodder crops and vegetables, with rainfed production change outpacing irrigated production change. Pulses harvested area and production generally decreased with the exception of rainfed production, which stayed roughly constant.

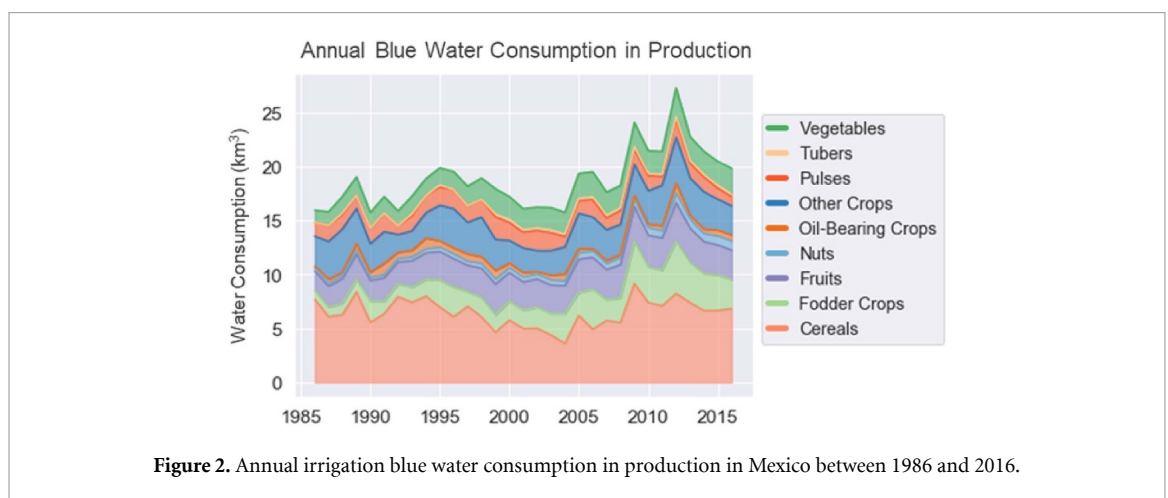
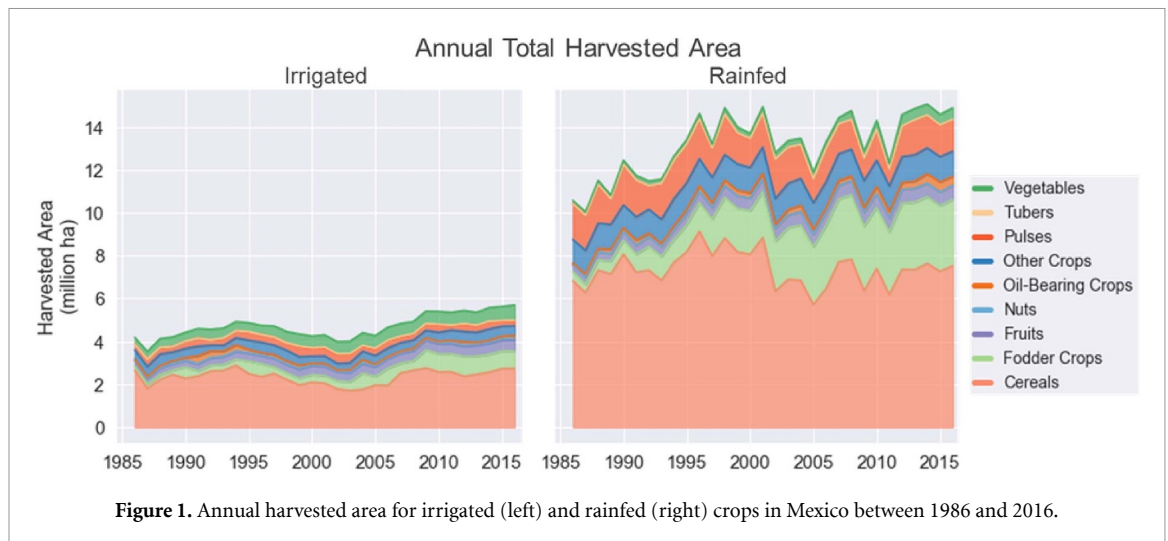
Within crop categories, specific crops led the increases in agricultural production. Irrigated pineapple and raspberry production increased by four orders of magnitude, followed by a quadrupling or more of eggplant, papaya, asparagus, strawberries, spinach, and grapefruit production. Crops that at least doubled in irrigated production include sweet corn, green maize, watermelon, cauliflowers and broccoli, cucumber, nut, chilies and peppers, lemons and limes, seed cotton, green bean, onion, and cassava. Blueberries, which were not extensively grown until 2009, increased by five orders of magnitude since then.

This study estimates that the current irrigation water consumption for the selected crops changes from $18.68 \text{ km}^3 \text{ yr}^{-1}$ in 1994 to $17.09 \text{ km}^3 \text{ yr}^{-1}$ in 2000 and up to $20.57 \text{ km}^3 \text{ yr}^{-1}$ in 2015 (years are three-year averages) (figure 2). This finding is in overall agreement with previous studies (Rosa *et al* 2018, 2019). Between 1994 and 2016, average annual blue water consumption increased for nuts (+107%, $+0.42 \text{ km}^3 \text{ yr}^{-1}$), fodder crops (+73%, $+1.32 \text{ km}^3 \text{ yr}^{-1}$), tubers (+60%, $+0.09 \text{ km}^3 \text{ yr}^{-1}$), vegetables (+40%, $+0.65 \text{ km}^3 \text{ yr}^{-1}$), other crops (+20%, $+0.50 \text{ km}^3 \text{ yr}^{-1}$), and fruits (+12%, $+0.31 \text{ km}^3 \text{ yr}^{-1}$) (figure 2). Blue water consumption decreases were concentrated in the remaining categories: oil-bearing crops (−30%, $-0.21 \text{ km}^3 \text{ yr}^{-1}$), pulses (−29%, $-0.44 \text{ km}^3 \text{ yr}^{-1}$), and cereals (−10%, $-0.77 \text{ km}^3 \text{ yr}^{-1}$). Overall, blue water consumption increased 14%, at 2% per year until 1994, and 10%, at 0.05% per year, between 1994 and 2015.

3.2. Export

Export of the 58 select crops to the United States has grown in bulk quantity since 1987 at a faster rate than Mexican export to the world. While export from Mexico was nearly stagnant between 1987 and 1994 (an annual decrease of 1.8% to the world and 0.7% to the US), it has increased since at an annual rate of 9% to the world and 14% to the US. The Mexico-US trade relationship not only dominates Mexican agricultural exports, but it is strengthening with time.

In recent years, the US has received on average 80% of Mexico's global export of the selected crops (i.e. the categories of: nuts, groundnuts, sugar cane, and vegetables and fruit), grown under either rainfed or irrigated conditions. For comparison, that



number was 59% in 1994. For the three-year averaged 2014–2016 period, irrigated agriculture represented 58.4% of Mexican export to the US (based on primary extraction rates), with the remaining agriculture being rainfed, and Mexico exported 11.5% of its total domestic production to the US. The crops that have continued to be dominated by Mexican export to the US, holding at least 90% of Mexico's global export market share, are: vegetables and fruit (specifically, cabbage; green maize; lettuce; tomato; cauliflowers and broccoli; cucumber; chilies and peppers; oranges; lemons and limes; watermelon; mangoes, mangosteens, and guavas; strawberries; blueberries; papaya), and fodders.

In terms of US trade partners, Mexico was the US's single largest supplier of fruits, with Mexican exports to the US accounting for over 88% of all of the US's imports of fruits in 2016 (FAO 2020). Mexico also accounted for 33% of US nut imports and 31% of US vegetable imports in 2016. While overall per capita domestic supply of fruits decreased in the US between 1994 and 2016, the per capita Mexican export of fruits to the US increased (FAO 2020). The per capita domestic supply of nuts increased in the US, as did

the per capita Mexican export of nuts. The per capita US domestic supply and Mexican export of vegetables decreased.

Total blue water consumption in exports saw a pronounced change. Overall, blue water consumption for US export-oriented crops increased 36.5%, at 5.2% per year from 1987 to 1994, and 79.4%, at 3.8% per year, between 1994 and 2015. Annual exports to the US and associated annual virtual water flow increased (between 1994 and 2015) for all categories of irrigated crop excluding oil-bearing crops and other crops, with the greatest growth in irrigated blue water required for export in fruits (+173%, +0.58 km³ yr⁻¹), cereals (+690%, +0.53 km³ yr⁻¹), vegetables (+98%, +0.37 km³ yr⁻¹), and nuts (+3689%, +0.13 km³ yr⁻¹) (figure 3(c)). Blue water consumption for pulses, fodder crops, and tubers also increased over the period, but accounted for only 0.02 km³ of total annual blue water export increase, representing roughly 1% of the total increase.

Not only is bulk quantity of export and associated water to the US increasing (figure 3(a)), but the fraction of Mexico's total irrigated agricultural production and water resources that is going to the US

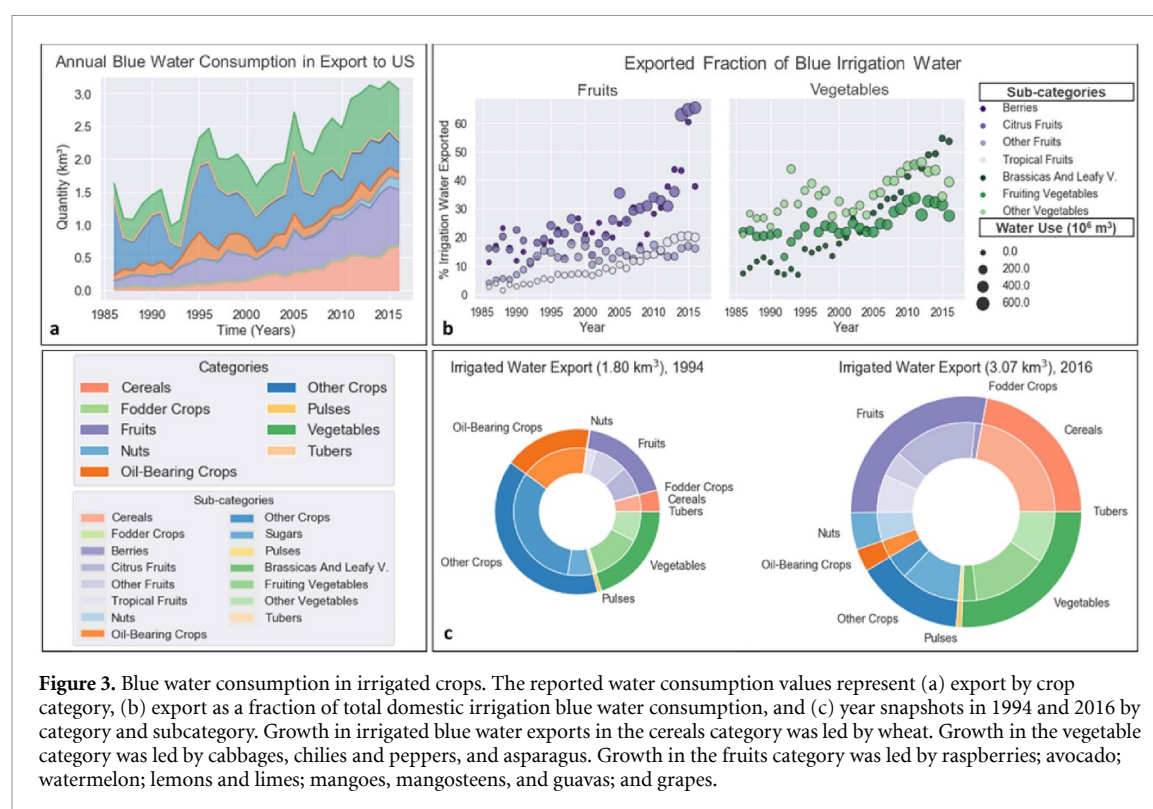


Figure 3. Blue water consumption in irrigated crops. The reported water consumption values represent (a) export by crop category, (b) export as a fraction of total domestic irrigation blue water consumption, and (c) year snapshots in 1994 and 2016 by category and subcategory. Growth in irrigated blue water exports in the cereals category was led by wheat. Growth in the vegetable category was led by cabbages, chilies and peppers, and asparagus. Growth in the fruits category was led by raspberries; avocado; watermelon; lemons and limes; mangoes, mangosteens, and guavas; and grapes.

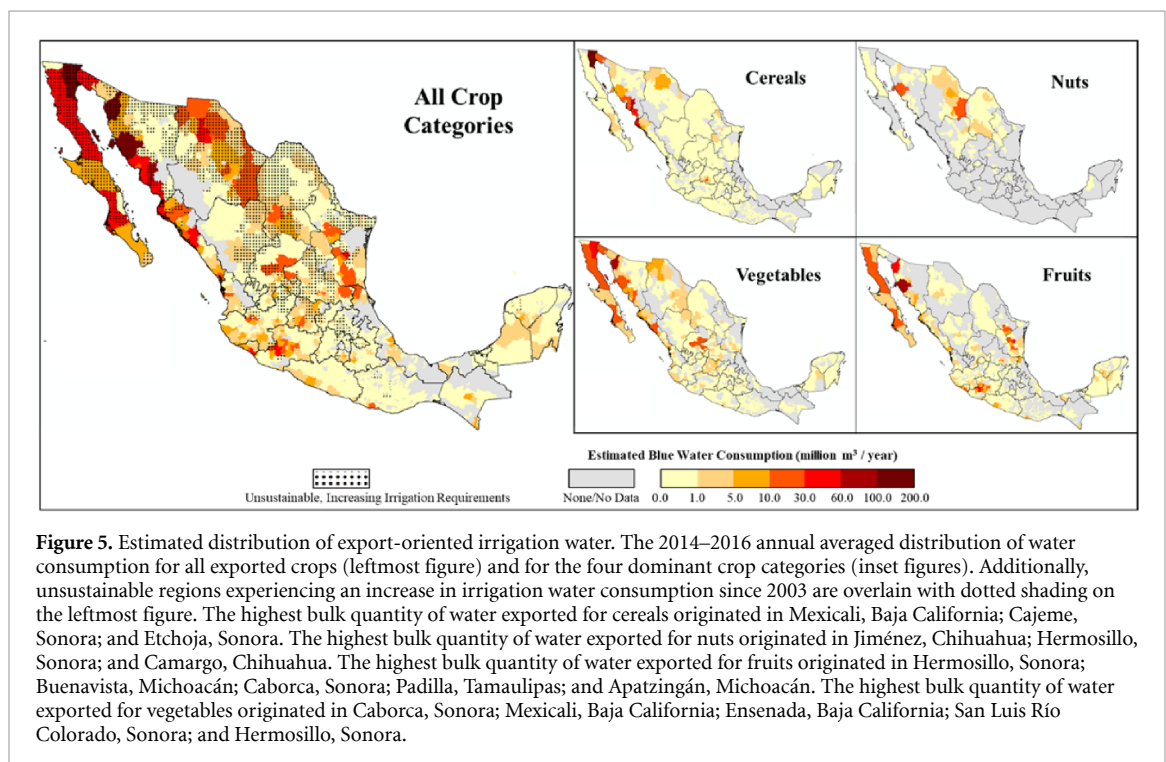
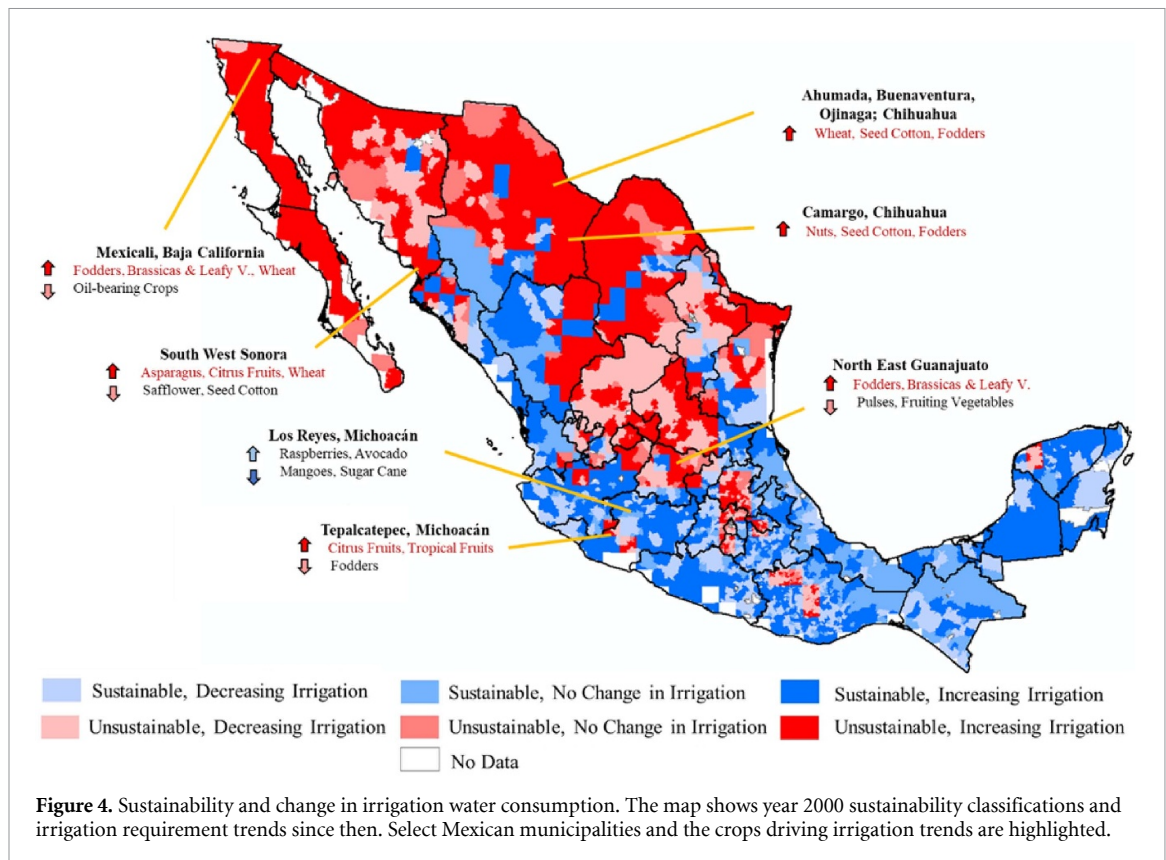
has increased for the categories of fruits, vegetables, and nuts. In recent years, at least 20% of domestic irrigation water required to grow fruits and vegetables are associated with produce exported to the US (figure 3(b)). This compares to an average value of 15.1% for all selected crops. For some subcategories, such as berries, citrus fruits, and brassicas and leafy vegetables, the fraction of domestic production going to US export has surpassed 50% in recent years. This means that Mexican production of specific subcategories and their associated water requirements are increasing to directly serve the US export market.

Irrigated agriculture for specific crop commodities has grown alongside increasing demand for export to the US. The largest percentage of growth of blue water consumption for exported crops is seen in the avocado trade, with growth of magnitudes of four to seven-fold increase depending on the municipality. US avocado imports from Mexico represented 91% of US global imports in 2016, up from 3% in 1994 (USDA/FAS 2020). Raspberries also see a growth at a magnitude of five to six. US raspberry imports from Mexico represented 98% of US global imports in 2016, up from 1% in 1994 (USDA/FAS 2020). Lettuce grows at a magnitude of four. US lettuce imports from Mexico represented 82% of US global imports in 2016, up from 36% in 1994 (USDA/FAS 2020). For some crops, single growing regions dominate the domestic production and therefore export of the crop. For example, estimated virtual export of blue water to grow cauliflowers and broccoli originating in Guanajuato has increased by 621% since 1994, with the production in Guanajuato

representing 62% of national blue water consumption for the crop group in recent years. Similarly, estimated virtual water export of blue water to grow avocados in Michoacán has increased five orders of magnitude, with Michoacán representing 72% of national blue water consumption for avocados in recent years. Lastly, estimated virtual export of blue water in asparagus grown in Sonora has grown 200% since 1994 with Sonora production representing 68% of the national blue water consumption in recent years. A summary chart of specific crop commodities for export and their growth can be found in the supplementary materials.

3.3. Sustainability of irrigation water requirements trends

From a water quantity perspective, water resource management can be sustainable if water consumption does not exceed local availability, which is defined as the difference between (surface and groundwater) runoff and environmental flows (i.e. the minimum surface runoff that should be sustained to conserve aquatic habitat). When these conditions are not met, water consumption for human activities occurs at the expenses of environmental flows (i.e. aquatic habitat) or groundwater stocks and is therefore ‘unsustainable.’ Water sustainability assessments across Mexico show that in the year 2000, 986 of Mexico’s 2448 municipalities were at least partially unsustainably using their water resources. Of that, almost half (462) of municipalities that were at least partially unsustainably managing water resources in 2000 saw an increase in water consumption for



irrigated agricultural production between 2003 and 2016 based on three year averages of their trends during the reported municipal period (2003–2005 vs 2014–2016) (figure 4).

Nearly the entire northern and central regions of Mexico had unsustainable water use in 2000 and exhibit an increasing trend in irrigation water

consumption since then (figure 5). This region has historically been home to much of the country's irrigated agriculture (Ochoa-Noriega *et al* 2020, SIAP 2020). Contrastingly, the southern portion of the country has long been rainfed dominant. For some municipalities that lie in the 2000 unsustainable zone, the increase in water consumption represents the

emergence of irrigated agriculture altogether in places that were previously only rainfed, and for crops that are dominant in domestic food consumption, such as wheat, beans, and corn. Twenty-nine unsustainable municipalities started using irrigation after 2003, 17 of which were municipalities in the southern state of Oaxaca. The municipalities with the greatest increase in unsustainable irrigation water consumption from previously only (or mostly) rainfed crops are Matamoros, Tamaulipas; Valle Hermoso, Tamaulipas; and Sierra Mojada, Coahuila. All are in the northern portion of the country. Some areas that were sustainable in 2000 are also experiencing an increase in irrigated agriculture water consumption. Seven sustainable municipalities expanded from rainfed only to include irrigated agriculture, all of which were in the south of the country. The crops that led the irrigation water consumption increase in unsustainable municipalities that already had irrigation in 2003 varied by region. The rapid increase in irrigation water consumption for export-oriented agriculture impacted growing regions throughout the country, oftentimes in municipalities with unsustainable water management in 2000.

4. Discussion

The agricultural landscape of Mexico has changed greatly since 1986 and after the enactment of NAFTA in 1994. Overall irrigated and rainfed lands have increased, as well as the pace of agricultural output, with implications for irrigation water consumption. Crop yields have increased, indicating that the per ton amount of green water consumed for the same crop at the beginning and end of the study period has decreased. The increase in yields, however, may result from the intensification of irrigation and associated increase in blue water consumption to meet the irrigation water requirements. In some cases, irrigated agriculture has expanded geographically into rainfed lands, with crops that are traditionally rainfed being irrigated. At the same time, the country's export to the US has increased, drawing upon the strained water resources of Mexico. As agriculture and export-oriented industry grow, three observations are clear.

First, the US consumer's voracious demand for fruits, vegetables, and nuts is ostensibly linked with, yet exacerbating, the exploitation of water resources in Mexico. This poses a threat to food system sustainability in Mexico and the US alike. Growth in export of agricultural products and associated water requirements to the US is most pronounced in the sub-categories of fruits and vegetables, especially berries, citrus fruits, and brassicas and leafy vegetables. These sub-categories are also largely sourced from regions with unsustainably used water resources (for all uses including agricultural). The thirsty nut industry in Chihuahua grows in an unsustainably irrigated, arid part of the county while fruits blossom

on wet, yet increasingly water-strained Michoacán farms. The very crops that have come to define the US diet, such as asparagus from Sonora, leafy greens and strawberries from Baja California, and broccoli from Guanajuato, are sourced from municipalities with unsustainable use of water resources. Further, avocado and raspberries are becoming increasingly present in a few municipalities of Michoacán that were sustainable in 2000 but may become strained as the luxury-crop industry concentrates there. The results of this study show that the year-round US domestic supply of produce favorites is made possible through trade irrespective of associated unsustainable irrigation practices.

Second, VWT impacts regions and not necessarily countries. While the traditional VWT lens assesses transfers between countries, this neglects to recognize that agribusiness is heterogeneous within a country. In Mexico, agricultural output of export-oriented crops and associated water requirements is concentrated along Mexico's northern border with the US, its coasts, and its temperate central highlands. These regions, and the people who live there, are most impacted by local water insecurities arising from overuse of water supply for agriculture. While an assessment of the costs (externalities such as environmental degradation and water insecurity) and benefits (such as financial or connectivity boosts) of the local agribusiness on local people is beyond the scope of this study, the spatial heterogeneity of water resource strain throughout the country indicates that impacts are not evenly distributed.

Third, irrigation expansion within the country is not exclusively detrimental, provided that it occurs in areas where the irrigation water requirements can be sustainably met. The expansion of irrigation into previously only rainfed areas in southern Mexico appears to be contributing to greater predictability of water resources to grow crops for local consumer markets. Irrigation in these areas serves as a tool for resilience as climate change makes seasonal variability of rainfall less predictable (Gornall *et al* 2010). The emergence of irrigation in the tropical south of the country is mostly for staple crops (with the exception of irrigated oil palm), contrasting the heavy irrigation regions in central and northern Mexico that produce, among others, irrigation-only export crops such as asparagus, brassicas, berries, and nuts. Sustainable irrigation expansion within rainfed agricultural regions of Mexico is necessary and possible to feed a growing population amid climate change (Rosa *et al* 2020).

Our study shows through biophysical modeling that the historic trends in irrigation in Mexico are leading to the unsustainable production of crops concentrated in the northern, central, and coastal regions of Mexico. While irrigation expansion happening in the rainfed-dominant south is not currently a threat to sustainability, the irrigation expansion happening

elsewhere in Mexico is unsustainable and therefore represents a threat to future generations and ecosystems alike. The increase in water demand has grown most sharply for commodity products ripe for export, especially to Mexico's largest agricultural trade partner, the United States. The results of this study reveal the spatial and temporal heterogeneity of Mexico's agricultural production and associated export to the US, whose restrictions were incrementally lifted with the enactment of NAFTA. The modern result of trade policies and agribusiness' crop decisions has established an export-oriented agricultural industry buoyed by unsustainably consumed water resources. For the US, this endangers surety of future food supplies, especially for crops that the US sources primarily from Mexico. Studies have also found that the agricultural industry in Mexico relies on short-term land leasing that exhausts local resources including soil nutrients and water resources, resulting in environmental degradation (González 2014, 2020). The land use practices further challenge a landscape with agriculture-induced environmental externalities including pollution of water bodies, decreased biodiversity, and climate change (Ochoa-Noriega *et al* 2020).

While this study quantifies the spatial and temporal changes in agricultural production and associated water consumption and compares it to year 2000 water sustainability classifications, it does not assess sustainability yearly for the entire study period or evaluate different scenarios for preservation of environmental flow (assumed to be 80% for this study). Local water availability is constantly changing as water stocks are consumed and replenished for different anthropogenic and nature-based uses, as well as a result of local water balance fluctuations (Falkenmark and Rockström 2005). Also, this study does not take into account changes in policies at the municipal, state, or national level that may have influenced the proliferation of export-agriculture in Mexico since 1994. Nor does it calculate the comparative impact of expansion of manufacturing and mining, both heavy consumers of water resources in Mexico.

Despite these limitations, this analysis is able to highlight a pattern of increased irrigation across the country since the enactment of NAFTA in 1994 at a spatial resolution never explored before. In some regions, the unsustainable and increasing consumption of water resources is driven by foreign market demands fueled by increasing demand in high-income places such as the United States. In other regions, the emergence of irrigated agriculture is indicative of irrigation infrastructure that will provide resilience as precipitation patterns change due to climate change. As the agricultural landscape evolves, Mexico is characterized by a mosaic of sustainable and unsustainable crop lands that strive to satisfy domestic and foreign demands.

5. Conclusion

The NAFTA of 1994 solidified an agricultural and social transformation in Mexico that began with the Green Revolution (Harwood 2020). In the years since, Mexico has continued to undergo agricultural expansion, with a portion of its food and associated resources destined to supply the US consumer market. In this study, we considered the agricultural transformation of a country at the smallest administrative unit to elucidate impacts on regional sustainability of water resources for export-oriented irrigation agriculture and domestic markets. Our biophysical analysis of the CWRs for irrigated agriculture furthers an understanding of the relationship between local water consumption for agriculture and sustainability of subsequent food consumption at the terminal location. As one of the most water unsustainable trade relationships in the world, the Mexico-US trade relationship is characterized by agriculture that exploits local resources to feed people in areas disconnected from the local agricultural consumption of water resources. It is a classic example of the ability of VWT to decouple producer and consumer through institutional means such as trade.

Our findings indicate that irrigated agriculture practices grew throughout Mexico, with irrigation in the north, coasts, and central regions associated with export agriculture and irrigation in the south associated with newly established irrigation for local consumption. Water consumption in production and export increased since 1994. This occurred at a faster rate for export, especially for crops such as avocado, raspberries, asparagus, and broccoli. Some of these crops, both for domestic consumption and export to the US, originated in municipalities with unsustainably consumed water resources.

By providing a spatially and temporally explicit map of water consumption for the major crops of Mexico, this study lays the groundwork for future work examining the localized role of the export industry in determining both domestic and foreign food supply sustainability. Future research should focus on the hotspot growing regions identified in this study that have seen rapid transformations of specific crop commodities, such as the berry industry of Michoacán, the broccoli industry of Guanajuato, and the nuts industry of Chihuahua. In each of these locations, more work is needed to understand the social and ecological impacts of irrigated agricultural expansion, thereby furthering the scientific understanding of disproportionate socio-environmental impacts at varying scales.

Improved spatial and temporal understanding of irrigated CWRs and associated exports can be beneficial for policy makers and farmers, especially as climate change and shifting consumer preferences alter the sustainability and type of crop that is grown

respectively. This analysis provides a warning for the major agricultural regions of the world of the delicate challenge between sustainably managing resource-limited supply and global consumer-driven demand for produce. While irrigated Mexican fruits, vegetables, and nuts are increasingly components of the US year-round diet, this shift often induces an unsustainable use of water resources in Mexico, the country that contributes to most of the US produce imports.

Data availability

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors declare no conflict of interest.

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