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Carbon Footprint of Water Embedded in Agricultural Products Exported from California

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Environment Engineering

by

Dongfeng Li

Thesis Committee:
Professor Diego Rosso, Chair
Professor Sunny Jiang
Professor Amir AghaKouchak

2014

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ACKNOWLEDGMENTS

I would like to give my fully gratitude to my committee chair Dr. Diego Rosso. Without his guidance and patience, I could not have finished my work. He taught me not only how to research but also to be honest and creative.

I also want to express my gratitude to my committee members Dr. Sunny Jiang and Dr. Amir AghaKouchak for their support.

I want to thank Derek Nguyen. It is very helpful that I have worked with him and he gave me a lot of inspiration.

I also like to thank my parents for their support through my entire master study. Last but not least I want to thank all the people who help me during my time at UC Irvine.

ABSTRACT OF THE THESIS

Carbon Footprint of Water Embedded in Agricultural Products Exported from California

By

Dongfeng Li

Master of Science in Environment Engineering

University of California, Irvine, 2014

Professor Diego Rosso, Chair

The carbon footprint of embedded water in California's agricultural products has not been thoroughly studied before. However, related topics have been on the table to solve the sustainable development problems. This research tries to find out the energy consumption of the water embedded in the exported agricultural products from California. It also aims to figure out the nation scale distribution of the carbon footprint that was studied in this research. The results show that the water footprint of the agricultural products is around 22.3 Gm^3 and the total carbon footprint is 8.9 million metric tons of CO_2. The top three regions that have the highest water and carbon footprint are European Union 27, China, and Japan. We studied the carbon footprint by researching the water footprint of all the agricultural products. Based on the energy usage per unit water sources published by the California Energy Commission and the global average water footprint of agricultural products from previous work (Hoekstra, 2007), we calculated the carbon-equivalent of the agricultural products' carbon footprint. And based on the result that the carbon footprint of the embedded water of agricultural products is only 2% of the total carbon budget with the water footprint contributes to 25% of the total, we believe that California has

performed well in managing the energy in agriculture-water area, but it still has improvement space in the management of the water resource.

1. INTRODUCTION

The carbon footprint is defined as a measurement of the total amount of carbon dioxide emission that is directly and indirectly caused by an activity or is accumulated over the lifetime of a product. Due to its impact on the environmental issues such as global warming, the carbon footprint is the hot topic in the field of environmental science.

Virtual water trade refers to the hidden flow of water if food or other agricultural products are traded from one place to another. At the same time, virtual water is related to the carbon footprint directly and indirectly. Some studies have focused on the virtual water trade aiming to conserve water in the production of crops by increasing product export to areas with less water needs (Hoekstra and Hung, 2005). In this effort, the research on virtual water of agricultural products has the potential to reduce economic costs, where water withdrawals may have greater impacts on water-lacking regions than on water-abundant regions. However, few studies have analyzed the internal virtual water flow dynamics of the U.S. on a state or regional scale. And fewer have focused on the associated carbon footprint on a state or regional scale in the U.S.

In this study, we calculated the carbon footprint of the exporting agricultural products of California to their destinations by firstly exploring the products' water footprint.

Previous virtual water quantification studies have identified the U.S. as the leading global virtual water exporter (A. Y. Hoekstra, 2005). Close examination indicates that California is the largest agricultural producer (World Bank). Thus we hypothesize that California is the largest virtual

water exporting state in the country. Accordingly we also hypothesize that California is releasing a great amount of carbon dioxide related to the embedded water of agricultural products. And in this research, we focus on the carbon footprint associated with energy cost by the embedded water in agricultural products exported from California to other regions of the world.

2. BACKGROUND

2.1 California's Situation

Nowadays, carbon emission is a worldwide topic that hinders the development in many various sectors of human life. Every year, the United Nations would regulate the carbon budget for most of the countries. How to use the carbon budget efficiently is a mandatory issue to be managed. At the same time, water resources shortage is becoming an urgent problem all over the world, as energy deficiency is an equally critical problem. California is facing an unprecedented water crisis in history where water treatment is the largest energy use of the state taking up approximately 19 percent of the total annual electricity consumption (CEC 2005). It will cost significant financial investment to keep the water supplies sufficient for next several decades. New regulations and court decisions have resulted in the reduction of water delivery from the Sacramento-San Joaquin Delta (DWR, 2009). In some areas of the state, the quantity of underground water and surface water supplies is experiencing rapid decrease (USGCRP 2009).

The production of water for agriculture requires an enormous amount of energy. The energy-water relationship is particularly inseparable in the Southwestern arid and semi-arid regions of the United States, where significant amounts of energy are used to import water. California is exceptionally vulnerable because its water sector is the largest energy user in the state, estimated to account for 19 percent of the total electricity consumed annually (CEC 2005).

Another fact is that the annual water used in growing agricultural products in California is much greater than the total amount used by the other fields such as commercial and industrial

applications (DWR 2013). Less known is the amount of water embedded or embodied in agricultural products that are exported to other states and countries. For some certain kinds of agricultural products, California is dominating the supply of the whole U.S. market, such as almond, grape, strawberry, processed tomato, and lemon (USDA, 2012).

2.2 World Virtual Water Exchange

Table 1. A) World Virtual Water Exchange.

Country/Region	**Export To**	**Volume (MAF)**	**Volume (Gm^3)**	**Import From**	**Volume (MAF)**	**Volume (Gm^3)**
Canada	U.S.	17.02	21	U.S.	14.59	18
United States	Canada	14.59	18	China	43.78	54
	Japan	11.35	14	E.U.	10.54	13
	E.U.	17.02	21	Mexico	11.35	14
	China	11.35	14	Canada	17.02	21
				Southeast Asia	18.65	23
Mexico	U.S.	11.35	14			
European Union	U.S.	10.54	13	Russia	7.30	9
	China	4.05	5	China	38.10	47
	Southeast Asia	2.43	3	India	12.97	16
				Southeast Asia	25.94	32
				United States	17.02	21
Russia	European Union	7.30	9			

(continued overleaf)

Table 1. B) World Virtual Water Exchange.

Country/Region	**Export To**	**Volume (MAF)**	**Volume (Gm^3)**	**Import From**	**Volume (MAF)**	**Volume (Gm^3)**
China	Japan	30.00	37	European Union	4.05	5
	United States	43.78	54	Southeast Asia	21.08	26
	Southeast Asia	21.08	26			
	European Union	38.10	47			
India	European Union	12.97	16			
Japan				China	30.00	37
				Southeast Asia	16.21	20
				United States	11.35	14
Southeast Asia	European Union	25.94	32	European Union	2.43	3
	China	21.08	26	China	13.78	17
	Japan	16.21	20			
	United States	18.65	23			

(After Hoekstra, 2007)

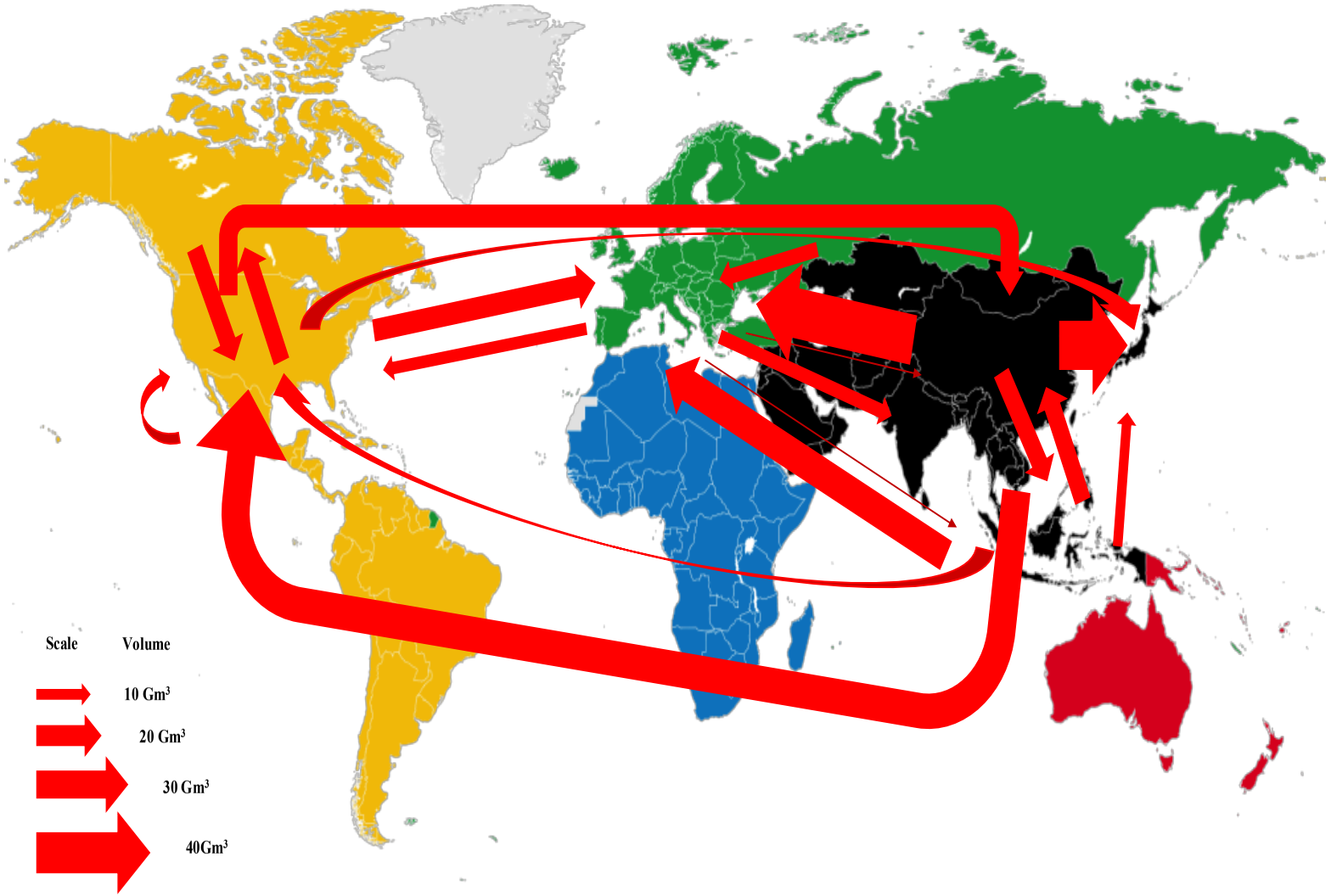

Figure 1. World Virtual Water Transferred Map in 2005 (after Hoekstra, 2007)

As shown in the virtual water transferred map and the table above, virtual water was transferred all over the world. U.S. is the largest water exporting country in the world. Another fact is that China was the largest water export country of the U.S. taking in 44% of export water footprint the states.

2.3 California GDP VS Water Footprint

Table 2. California GDP/Water Footprint Compared with the Top 20 countries.

Rank	Countries	GDP (trillions)	Water Footprint (m^3/y per capita)
1	United States	$13.14	2842
2	China	$7.30	1071
3	Japan	$5.87	1379
4	Germany	$3.58	1426
5	France	$2.78	1786
6	Brazil	$2.49	2027
7	United Kingdom	$2.42	1258
8	Italy	$2.20	2303
9	California	$1.96	3100
10	Russia	$1.85	1852
11	Canada	$1.74	2333
12	India	$1.68	1089
13	Spain	$1.49	2461
14	Australia	$1.49	2315
15	Mexico	$1.15	1978
16	South Korea	$1.12	1629
17	Southern California	$0.90	2400
18	Indonesia	$0.85	1124
19	Netherlands	$0.84	1466
20	Turkey	$0.78	1642
21	Switzerland	$0.64	1398
22	Saudi Arabia	$0.58	1849

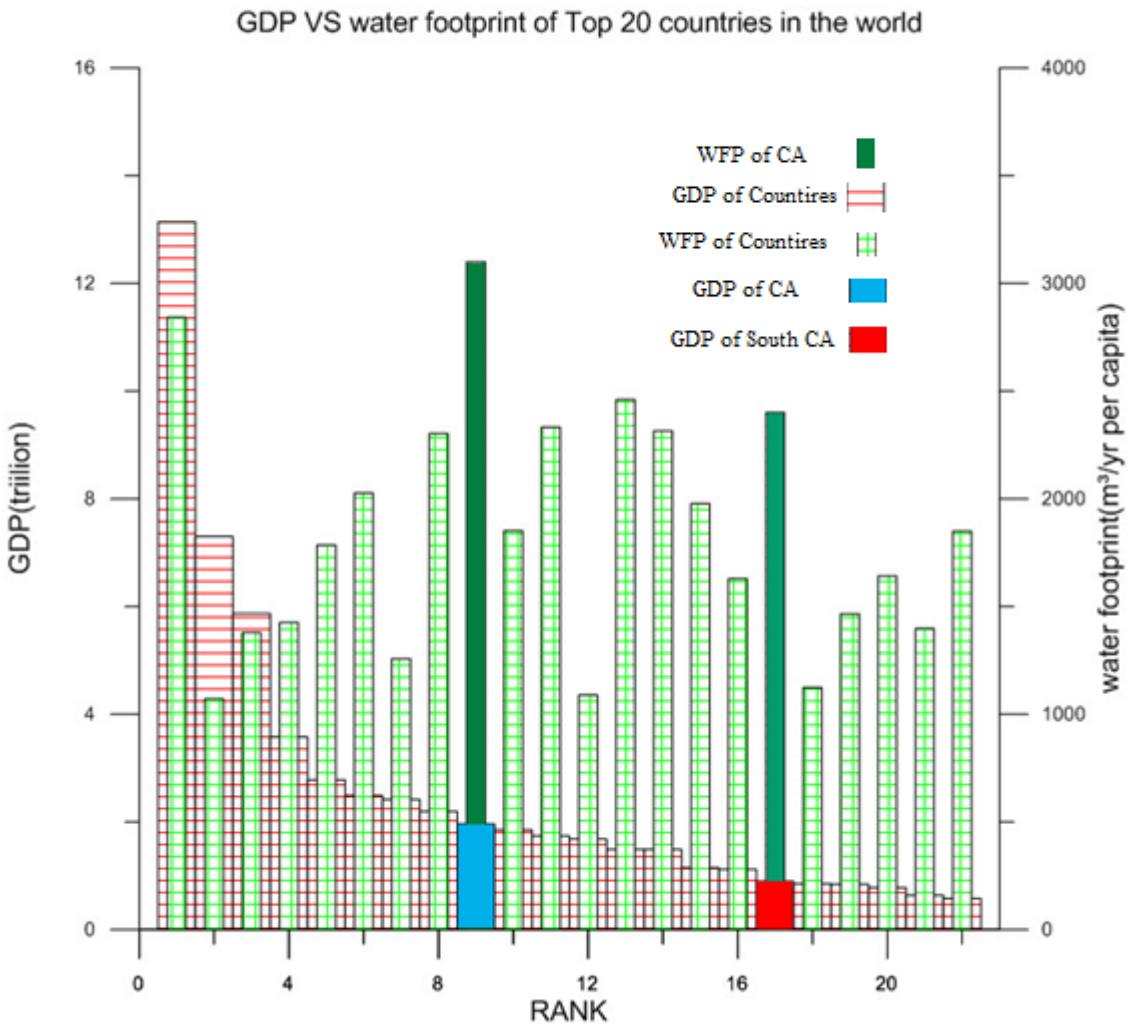

Figure 2. California GDP/Water Footprint Compared with Top 20 Countries in Year 2005 (Mekonnen, 2012)

As shown in the figure above, California made an astonishing GDP even compared to the top 10 counties in the world as listed in the Table 2, the GDP of California is ranked 9th over the top 20 countries, and Southern California is ranked 17th. However, water footprint of California is

higher than those of all the other countries. Therefore the economic development style of California is based on enormous water consumption, thus not necessarily healthy or sustainable.

2.4 California Agricultural Products Export Markets

Table 3. California Agricultural Products Main Exporting Countries and Values.

Rank	Country	Value $1 million
1	European Union	2,015
2	Canada	1,756
3	Japan	940
4	Mexico	591
5	China/Hong Kong	569
6	Korea	282
7	Taiwan	228
8	India	175
9	Turkey	124
10	Indonesia	98
11	Malaysia	97
12	Australia	92
13	Thailand	66
14	United Arab Emirates	64
15	Philippines	64

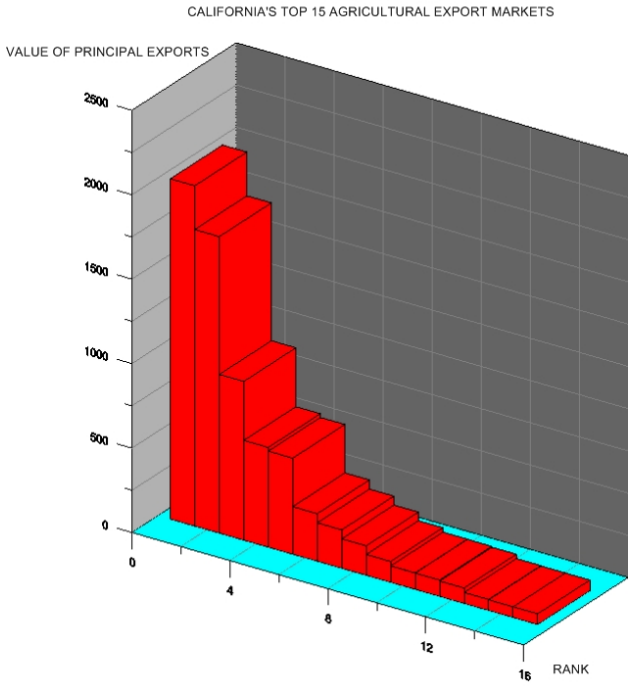

Figure 3. California Agricultural Products Main Exporting Countries and Values (2005)

Figure 3 shows that, China imported 20% of the total virtual water exported by the U.S.. Table 3 shows that the primary exporting regions of California are the E.U. and Canada, which take up 60% of total export. The countries in secondary group are Japan, Mexico, and China/Hong Kong, which take in nearly 25% of the total export from the U.S.. The other regions which import California agricultural products are the middle Asia, and the Southeast Asia.

Uncertainty exists in whether the export values are good indicators of the water resource transfer flow. That is one reason that we need to verify. Another fact is that the situation in California is unique and specific, so we should have a deeper explorer on the California scale.

2.5 California Agricultural Products Exports Scenario in 2011

Table 4. A) California Agricultural Products Exports Statistics.

Agricultural product	**Farm-gate Units**	**Farm quantity exported**	**Farm quantity produced**	**Ratio of exported to produced**
		1,000 Farm-gate Units		
Almonds	cwt.	12,513	19,500	0.64
Apples	cwt.	795	2,700	0.29
Apricots	short tons	7	63	0.11
Artichokes	cwt.	52	962	0.05
Asparagus	cwt.	4	384	0.01
Avocados	short tons	7	195	0.04
Beef and products	live weight cwt.	2,025	18,877	0.11
Blueberries	cwt.	172	330	0.52
Broccoli	cwt.	2,270	20,247	0.11
Cabbage	cwt.	164	5,070	0.03
Carrots	cwt.	2,078	19,608	0.11
Cauliflower	cwt.	797	6,460	0.12
Celery	cwt.	2,163	18,216	0.12
Cherries	short tons	27	66	0.40
Cotton	bales	732	1,341	0.55
Cottonseed and byproducts	short tons	61	565	0.11
Dairy and products	1000-cwt.	100	415	0.24
Dates	short tons	5	28	0.19

(continued overleaf)

Table 4. B) California Agricultural Products Exports Statistics.

Agricultural product	Farm-gate Units	Farm quantity Produced	Farm quantity Produced	Ratio of exported to produced
		1,000 Farm-gate Units		
Dried Plums	short tons	243	421	0.58
Dry Beans	cwt.	428	1,026	0.42
Eggs	100-dozens	79	4,406	0.02
Figs	short tons	17	39	0.43
Garlic	cwt.	769	4,080	0.19
Grapefruit	short tons	94	176	0.53
Grapes	short tons	1,896	6,612	0.29
Hay	short tons	840	6,072	0.14
Kiwi	short tons	9	41	0.21
Lemons	76lb boxes	3,019	21,579	0.14
Lettuce	cwt.	5,541	64,948	0.09
Melons	cwt.	2,287	21,188	0.11
Olives and olive oil	short tons	32	71	0.46
Onions	cwt.	3,810	19,453	0.20
Oranges and products	100-75lb boxes	296	590	0.50
Peaches and nectarines	cwt.	2,224	19,680	0.11
Pears	short tons	24	252	0.10
Peppers, bell and chili	cwt.	407	11,116	0.04
Pistachios	cwt., in shell	3,064	4,440	0.69

(continued overleaf)

Table 4. C) California Agricultural Products Exports Statistics.

Agricultural product	**Farm-gate Units**	**Farm quantity Produced**	**Farm quantity Produced**	**Ratio of exported to produced**
		1,000 Farm-gate Units		
Plums	short tons	64	160	0.40
Potatoes	cwt.	1,655	15,048	0.11
Raspberries and blackberries	cwt.	490	1,080	0.45
Rice	cwt.	22,957	44,327	0.52
Spinach	cwt.	516	6,063	0.09
Strawberries	cwt.	2,718	25,750	0.11
Sweet Potatoes	cwt.	618	5,824	0.11
Tangerines and mandarins	short tons	1,433	10,900	0.13
Tomatoes, fresh	cwt.	473	12,425	0.04
Tomatoes, processed	short tons	2,949	11,941	0.25
Turkey	liveweight cwt.	201	4,215	0.05
Walnuts	short tons	291	461	0.63
Wheat	bushels	4,117	48,235	0.09

(California Department of Food And Agriculture, 2012)

(cwt. stands for hundredweight, which is 100 pounds)

2.5California Agricultural Products Export Value

Table 5. A) CA Agricultural Product Export Values.

2012 Rank	Products	2010	2011	2012	Change in value 2011 to 2012(%)
			$1 million		
1	Almonds	2,391.70	2,828.40	3,387.30	19.8
2	Dairy Products	1,149.90	1,326.50	1,313.10	-1
3	Wine	1,007.80	1,226.20	1,273.20	3.8
4	Walnuts	819.5	1,060.40	1,112.10	4.9
5	Pistachios	719.6	777.8	1,073.30	38
6	Table Grapes	641.2	732.6	812.3	10.9
7	Rice	796.9	877.4	687.6	-21.6
8	Oranges and Products	566.4	666.1	664.4	-0.3
9	Tomatoes, Processed	492.4	573.9	574.3	0.1
10	Cotton	368.3	435.1	483.3	11.1
11	Strawberries	326.5	335.6	381.9	13.8
12	Raisins	327.4	399.2	380.3	-4.7
13	Beef and Products	293.5	365.6	373.6	2.2
14	Lettuce	337.5	346.4	345	-0.4
15	Hay	208.4	203.5	304.8	49.8
16	Seeds for sowing	295.9	325.9	303.2	-7
17	Dried Plums	173.6	174	176.8	1.6
18	Peaches and Nectarine	141.2	149	165.6	11.1
19	Raspberries and Blackberries	116	136.6	151.1	10.6
20	Lemons	147.5	145.9	145.3	-0.4

(continued overleaf)

Table 5. B) CA Agricultural Product Export Values.

2012 Rank	Products	2010	2011	2012	Change in value 2011 to 2012(%)
			$1 million		
22	Broccoli	130	105.1	124.4	18.4
23	Cauliflower	85.4	108.9	109.5	0.6
24	Carrots	111.7	115.1	104.9	-8.9
25	Flowers and Nursery	86.5	86.5	87.8	1.5
26	Onions	87.1	73.3	76	3.8
27	Spinach	51.4	60.2	69.3	15.1
28	Celery	61.7	64.5	68.5	6.1
29	Plums	68	75.7	68.1	-10.1
30	Melons	55.8	58.9	57.4	-2.5
31	Tangerines and Mandarins	39.8	65.6	50.6	-22.9
32	Blueberries	26.3	35.1	47	33.8
33	Tomatoes, Fresh	59.1	42.4	46.4	9.5
34	Grape Juice	39.4	39.7	45.6	14.9
35	Wheat	41.7	42.3	44.1	4.4
36	Grapefruit	35.2	29	38.8	33.6
37	Pears	26	35.9	37.9	5.5
38	Dates	23.6	30.3	37.2	22.7
39	Avocados	28.1	22.5	36.8	63.6
40	Dry Beans	18.7	19.1	35.4	85.2
41	Turkey	24.5	30.8	33.7	9.4

(continued overleaf)

Table 5. C) CA Agricultural Product Export Values.

2012 Rank	Products	2010	2011	2012	Change in value 2011 to 2012(%)
			$1 million		
42	Garlic	29.2	35.6	30.9	-13.3
43	Potatoes	32.1	35.8	30.4	-15.2
44	Apples	19.7	24.8	29.1	17.4
45	Olives and Olive Oil	15.3	21.1	26.5	25.4
46	Bell and Chili Peppers	29.8	27.1	24.8	-8.7
47	Sweet Potatoes	18	20.3	23	13
48	Figs	20.5	19.9	22.2	11.7
49	Asparagus	18.5	15.2	19.9	31.1
50	Kiwi	14	14.1	17.8	26
51	Apricots	13.5	16.7	17.4	4.3
52	Cottonseed and Byproduct	14.8	21	14.8	-29.6
53	Chicken	10	12	13	9
54	Eggs	4.9	8	8.7	9.3
55	Cabbage	4.4	6	6	-0.4
56	Artichokes	4.4	4.3	4.4	3.5
57	Mushrooms	4.4	3.4	2.8	-17.3
	Total Principal Agricultural Products	12,802	14,619	15,765	8
	Total Other Products and Mixtures	1,943	2,153	2,418	12
	Total All Agricultural Export	14,745	16,772	18,182	8

(California Department of Food And Agriculture, 2012)

Table 5 shows that the exports of agricultural products have been increasing from 2010-2012. Almond as the most exported agricultural product had a growth of 19%. Almond, walnut, wine, and dairy products are the top four in terms of quantity of export agricultural products. All products summed up increased expert by agricultural products 8%. Agricultural product exports provided California with economic benefits. However, considerable amount of water was consumed during the process of irrigation.

Figure 4. China Agricultural Imports From U.S. (USDA, 2013)

As shown in Figure 4 the trend of agricultural product exports from U.S. has been rapidly growing since year 2000. As one of the largest agriculture state of the U.S., California is facing an increasingly serious water and energy crisis. California exports agricultural products to more than 156 countries (Mathews and Summer 2008) and agricultural export earnings totaled $16.87 billion in 2011 (USDA 2012). A growing population is worsening the effects of multi-year droughts in many regions, threatening California's already stressed and fragile water systems.

The world population would reach 9.6 billion in 2050 (United Nations Department of Economic and Social Affairs). And the California population will across 50 million at 2050 (Department of

Finance), which accounts for a 32.4% increase from now. Therefore the food industry is expected to face the problem of food shortage, and one of the underlying causes of food shortage is the limited irrigation water resource. Furthermore, water supply including transportation, treatment, and dispensing is energy-intensive. Carbon footprint associated with such energy cost is also expected to be tremendous, thus alarming from an environmental perspective.

2.7 Carbon Budget for United States and California.

The total CO_2 emission from United States in 2012 is around 1.4 billion tons of carbon (Global Carbon Project, 2013). And the carbon budget for California is presently dominated by 115 MMTCE per year in fossil fuel emissions of CO2 to meet energy and transportation requirement. (Christopher Potter 2011) Recently, it is worth noticing that state legislation (Assembly Bill 32) requires California to reduce GHG emissions to 1990 levels by 2020 and by another 80% below the 1990 levels by 2050. But its growing population and the demand for all forms of energy will make meeting these targets a major challenge.

3. MATERIALS AND METHODS

The general methodology for this study follows the three main steps as listed below:

- Step 1 Calculate the virtual water of agricultural products
- Step 2 Calculate the energy consummation of the water treatment of all the products
- Step 3 Calculate the carbon Footprint of the Commodities

Equation 1 governs the methodology, interpreting virtual water footprint into carbon footprint.

$$C = \sum \alpha \times \beta \times (m' \times wf') \tag{1}$$

Where:

C : Total carbon footprint;

α : Converting factor from energy consummation to carbon footprint, using EPA emission Factor of 6.89551 x 10^{-4} metric tons CO_2/kWh (EPA).

β : Converting factor from virtual water footprint to energy consummation, which will be illustrated in later section.

m' : The weight of the each exported agricultural product (Department of Finance, CA, 2012)

wf' : The California average water footprint of every product.

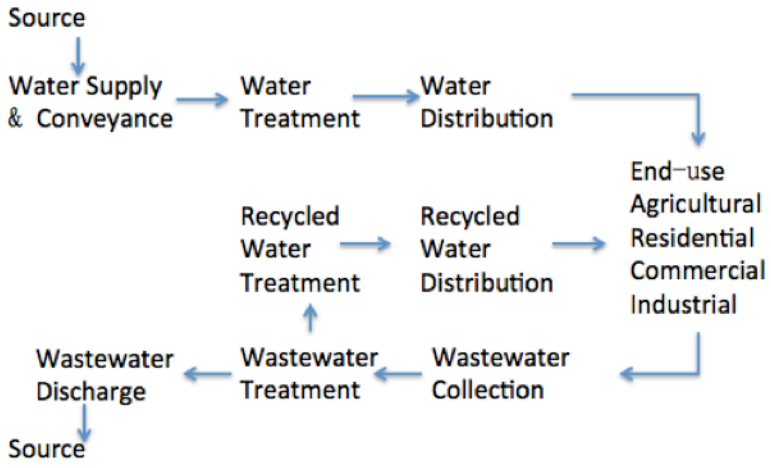

Figure 5. California's Water Use Cycle

In Figure 5, this is the California's water use cycle. Before the end-use for agricultural, the water needs the energy to be treated and distributed. In some areas, the water needs imported from the nearest water reservoir, while in other regions, it might needs to be treated before the use for agriculture.

Table 6. California Water Balance Summary in Million Acre-Feet, 2005 (Source: DWR 2014).

Water Supply	Instream	Local Projects	Local Imported Deliveries	Colorado Project	Reuse & Seepage	
2005	32	6	1	4	16	
	Federal Projects	State Project	Groundwater Extraction	Inflow & Storage	Recycled Water	Total Supplies
2005	7	3	12	0	0	82

According to the report of Department of Water Resource (DWR) in California, the water balance in 2011 is in the same situation with 2005 as shown Figure 6. And from its previous report, we got the water supply volume for agriculture of California in 2005. (Table 6)

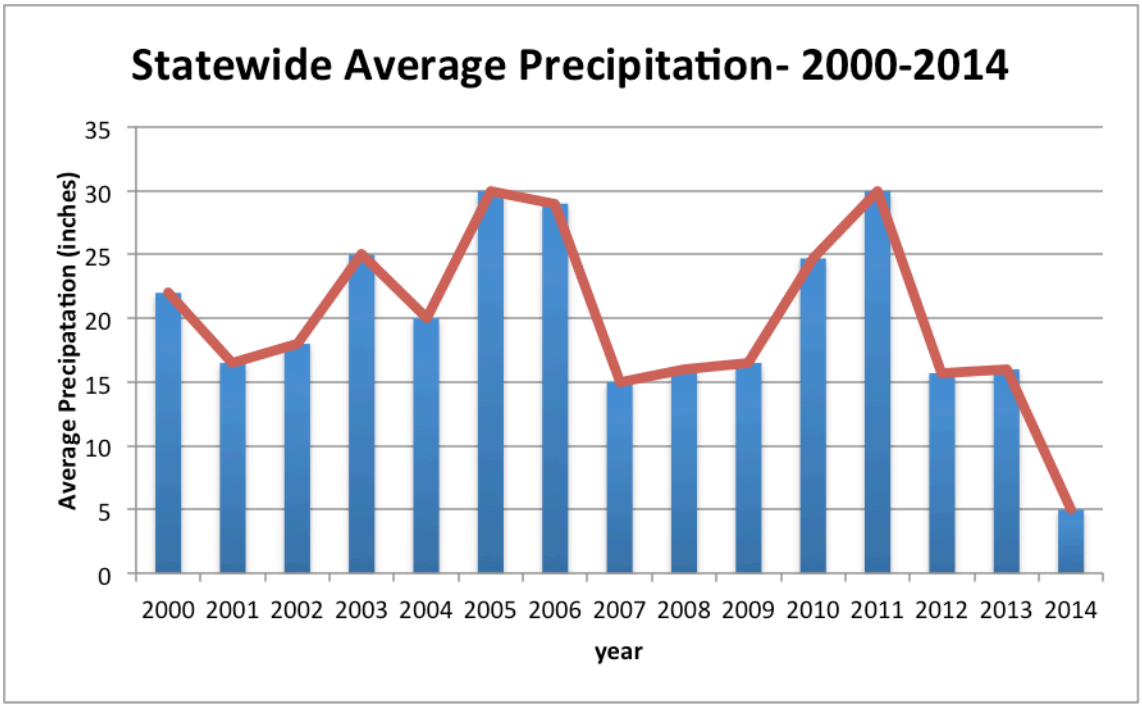

Figure 6. Statewide Average Precipitation in California (REF HERE).

Previous work by Derek (2014), Wilkinson (2010), DWR (2013) indicate that the energy requirement for local project is 2439kWh/AF. And the other the supply sources energy requirement has been summarized in Figure 7.

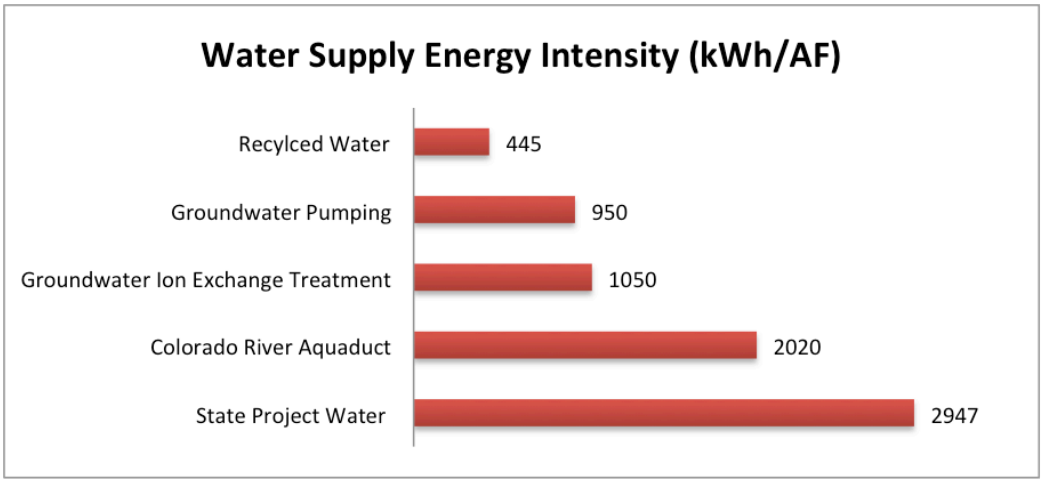

Figure 7. Energy Requirements for Southern California Water Supply Sources

For the average energy intensity, we assume that there is zero energy consumption for instream water and the water supplied by Federal projects.

Hence the energy-converting factor for California water is calculated by Equation 2, as listed below:

$$\beta = \frac{v' \times w'}{V} \tag{2}$$

Where

v' is the water volume of separate water supply.

w' is the energy requirement of the different water supply.

And v is the total water supplied in the year 2005.

As a result, the calculated value for β is 640 kWh/AF.

In order to calculate the weight of each product, information on mass proportion of each product is extracted from the export report of California Agricultural Products in 2011 (California Agricultural Products Export Report). In the report, some products that use farm unit are specified with unit conversion explained as shown in Table 7 below.

Table 7. Unit Converting Factors for Agricultural Products.

Agricultural Products	Unit Converting Factor
Cotton	218 kg/per bale
Egg	68 kg/ 100-dozons
Wheat	27.2kg/ bushels
Orange	85 lb/ box

As for wine, the quantity exported from California in the 2011 was 424.6 million liters, and the global average water footprint of the wine is 125liters/ 125ml. (A. Y. Hoekstra, 2008)

For California agricultural products average water footprint, due to the access to the irrigation and precipitation data, we can't have the precise value of it. So in this paper, we are using the global average data of the agricultural products exported from California. (M. M. Mekonnen and A. Y. Hoekstra, 2010)

Table 8. A) Global Average Water Footprint of Agricultural products from CA.

Agricultural Products	**Water footprint (m3/ton)**
Almonds	16095
Apples	822
Apricots	1287
Artichokes	818
Asparagus	2150
Avocados	1981
Beef and products	15500
Blueberries	845
Broccoli	285
Cabbage	280
Carrots	195
Cauliflower	285
Celery[1]	352
Cherries	1604
Cotton	4029
Cottonseed and byproducts	1332
Dairy and products	970
Dates	2277
Dried Plums	2180
Dry Beans	5053
Eggs	3300
Figs	3350
Garlic	589
Grapefruit	506
Grapes, all	608

(continued overleaf)

Table 8. B) Global Average Water Footprint of Agricultural products from CA.

Agricultural Products	**Water Footprint (m3/ton)**
Hay	955
Kiwi	514
Lemons	642
Lettuce	237
Melons	235
Olives and olive oil	3015
Onions	272
Oranges and products	560
Peaches and nectarines	910
Pears	922
Peppers, bell and chili	7365
Pistachios	11363
Plums	2180
Potatoes	287
Raspberries and blackberries	413
Rice	1673
Spinach	292
Strawberries	347
Sweet Potatoes	383
Tangerines and mandarins	748
Tomatoes, fresh	214
Tomatoes, processed	267
Walnuts	4918
Wheat	1828
Wine	120 l/ 125 ml

Table 9. A) Agricultural Products Destinations and Distribution.

Agricultural Products[1] and Destinations	Percent of total by destination in 2011	Agricultural Products[1] and Destinations	Percent of total by destination in 2011	Agricultural Products[1] and Destinations	Percent of total by destination in 2011
Almonds(1)		Walnuts		Rice (7)	
European Union	34	European Union	30	Japan	33
China/Hong Kong	16	China/Hong Kong	16	Jordan	5
India	10	South Korea	8	South Korea	14
United Arab Em	7	Japan	7	Taiwan	5
Canada	6	Canada	6	Canada	5
Japan	5	Turkey	10	Other destinations	41
other destinations	23	Other destinations	22		
				Oranges and Products (8)	
Dairy and Products(2)[4]		Pistachios (5)		South Korea	23
Mexico	25	China/Hong Kong	35	Canada	22
China/Hong Kong	8	European Union	34	Japan	14
Philippines	5	Canada	8	China/Hong Kong	17
Japan	6	Other destinations	24	Other destinations	23
Canada	11				
South Korea	5	Table Grapes (6)		Tomatoes, Processed (9)	
other destinations	45	Canada	28	Canada	40
		China/Hong Kong	15	European Union	8
Wine(3)		Mexico	9	Mexico	15
European Union	36	Australia	5	Japan	5
Canada	26	Indonesia	5	Other destinations	34
China/Hong Kong	14	Philippines	5		
Japan	8	Other destinations	35		
Other destinations	15				

(continued overleaf)

Table 9. B) Agricultural Products Destinations and Distribution.

Agricultural Products[1] and Destinations	Percent of total by destination in 2011	Agricultural Products[1] and Destinations	Percent of total by destination in 2011	Agricultural Products[1] and Destinations	Percent of total by destination in 2011
Cotton (10)		Beef and Products (13) [3]		Dried Plums (17)	
China/Hong Kong	27	Japan	30	European Union	33
Turkey	6	South Korea	27	Japan	17
India	8	China/Hong Kong	19	Canada	8
South Korea	11	Vietnam	8	China/Hong Kong	5
Pakistan	4	Taiwan	9	Other destinations	31
Other destinations	35	Other destinations	7		
				Peaches and Nectarines (18)	
Strawberries (11)		Lettuce (14)		Canada	49
Canada	81	Canada	92	Mexico	25
Japan	9	Other destinations	8	Taiwan	12
Mexico	5			Other destinations	14
Other destinations	6	Hay (15)			
		Japan	52	Raspberries and Blackberries (19) [6]	
Raisins (12)		South Korea	17	Canada	85
European Union	33	United Arab Emirates	17	Japan	7
Japan	12	China/Hong Kong	8	European Union	5
Canada	9	Other destinations	6	Other destinations	4
China/Hong Kong	7				
Other destinations	38				

(continued overleaf)

Table 9. C) Agricultural Products Destinations and Distribution.

Agricultural Products[1] and Destinations	Percent of total by destination in 2011	Agricultural Products[1] and Destinations	Percent of total by destination in 2011	Agricultural Products[1] and Destinations	Percent of total by destination in 2011
Lemons (20)		Cauliflower (23)		Taiwan	5
Canada	34	Canada	75	Australia	5
Japan	32	Japan	17	Other destinations	16
South Korea	5	Taiwan	5		
China/Hong Kong	8	Other destinations	8	Spinach (27)[4]	
European Union	6			Canada	99
Other destinations	21	Carrots (24)		Other destinations	1
		Canada	91		
Cherries (21)		Other destinations	9	Celery (28)	
Canada	34			Canada	79
China/Hong Kong	14	Flowers and Nursery (25)		Japan	5
Japan	18	Mexico	39	Taiwan	5
South Korea	9	Canada	41	Other destinations	21
Taiwan	8	EU-27	10		
Other destinations	18	Other destinations	10	Plums (29)	
				Canada	36
Broccoli (22)[4]		Onions (26)		China/Hong Kong	21
Canada	59	Canada	44	Mexico	17
Japan	31	Japan	17	Taiwan	8
Taiwan	9	European Union	8	Other destinations	18
Other destinations	1	Mexico	6		

(continued overleaf)

Table 9. D) Agricultural Products Destinations and Distribution

Agricultural Products and Destinations	Percent of total by destination in 2011	Agricultural Products and Destinations	Percent of total by destination in 2011	Agricultural Products and Destinations	Percent of total by destination in 2011
Melons (30)		Grape Juice (34)		Other destinations	21
Canada	82	Canada	65		
Japan	7	South Korea	11	Avocado (39)	
Other destinations	11	Japan	5	Canada	70
		Other destinations	19	Japan	23
Tangerines and Mandarins (31)				Other destinations	8
Canada	46	Grapefruit (36) [4]			
Japan	34	Japan	46	Dry Beans (40) [4]	
European Union	5	European Union	29	European Union	37
Other destinations	16	Canada	14	Mexico	5
		Other destinations	11	Canada	11
Blueberries (32)				Japan	15
Canada	38	Pears (37) [4]		Turkey	5
Japan	19	Canada	68	India	6
China/Hong Kong	5	Mexico	13	Other destinations	31
Other destinations	13	Other destinations	19		
				Garlic (42)	
Tomatoes, Fresh (33)		Dates (38)		Canada	30
Canada	82	Australia	28	European Union	10
Mexico	17	Canada	34	Mexico	14
Other destinations	1	EU-27	17	Japan	6
				Australia	10
				Other destinations	29

(continued overleaf)

Table 9. E) Agricultural Products Destinations and Distribution

Agricultural Products and Destinations	Percent of total by destination in 2011	Agricultural Products and Destinations	Percent of total by destination in 2011	Agricultural Products and Destinations	Percent of total by destination in 2011
Potatoes (43)		Japan	11	Cottonseed and Byproducts (52)	
Canada	62	China/Hong Kong	9	Mexico	31
Mexico	18	Other destinations	2	Canada	12
Other destinations	20			China/Hong Kong	31
		Asparagus (49)		Saudi Arabia	5
Olives and Olive Oil (45) [5]		Canada	50	South Korea	6
Canada	43	Japan	26	Other destinations	19
Japan	14	Switzerland	13		
Mexico	6	EU-27	10	Cabbage (55)	
Other destinations	37	Australia	5	Canada	86
		Other destinations	5	Taiwan	5
Peppers, Bell and Chili (46)		Kiwi (50)		Barbados	5
Canada	96	Mexico	27	Mexico	7
Other destinations	4	Canada	56	Other destinations	7
		Japan	5		
Sweet Potatoes (47)		Other destinations	18	Artichokes (56)	
European Union	44			Canada	85
Canada	54	Apricots (51)		Mexico	14
Other destinations	2	Canada	65	Other destinations	1
		Japan	8		
Figs (48)		Mexico	8		
Canada	49	Other destinations	19		
Mexico	29				

(continued overleaf)

Source: University of California Agricultural Issues Center.

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This series of tables show destinations that receive shares of total exports greater than or equal to 5 percent of each agricultural product in either 2011 or 2012 for which reliable data are available.

The numbers in parentheses correspond to the 2012 ranking in Table 8 Agricultural product Export Values and Rankings, 2010-2012."

2 Accurate export destination data are only available for 50 of the top 57 Agricultural Products. The Agricultural Products where export destinations are not included are apples, chickens, eggs, mushrooms, seeds for sowing, turkey and wheat.

3 " Hides and Skins" are included in the heading "Beef and Products."

4 Values were revised for 2011 based on updated production data from the U.S. Department of Agriculture/National Agricultural Statistics Service.

5 Product category "Olives and Olive Oil" is equal to the product category "Olives and Products" found in previous years' data tables.

6 "Raspberries and Blackberries" category also includes exports of mulberries and loganberries

Based on the data of agricultural product export distribution in different destinations and the total water footprint/carbon footprint of each agricultural product, the weighted water footprint for all the exported agricultural products could be computed. The associated carbon footprint from water treatment could be estimated consecutively. Furthermore, the carbon footprint of the agricultural product export to one country is simply the summation of that of each agricultural product.

4. RESULTS

Table 10. A) Water Footprints of Agricultural Products.

Agricultural Products	Water footprint (m^3)	Percent
Almonds	9.14E+09	36.59%
Apples	2.96E+07	0.12%
Apricots	8.29E+06	0.03%
Artichokes	1.91E+06	0.01%
Asparagus	3.90E+05	0.00%
Avocados	1.29E+07	0.05%
Beef and products	1.42E+09	5.70%
Blueberries	6.59E+06	0.03%
Broccoli	2.93E+07	0.12%
Cabbage	2.08E+06	0.01%
Carrots	1.84E+07	0.07%
Cauliflower	1.03E+07	0.04%
Celery[1]	3.45E+07	0.14%
Cherries	3.88E+07	0.16%
Cotton	6.43E+08	2.58%
Cottonseed and byproducts	7.36E+07	0.30%
Dairy and products	4.41E+09	17.67%
Dates	1.11E+07	0.05%
Dried Plums	4.81E+08	1.93%
Dry Beans	9.81E+07	0.39%
Eggs	1.76E+07	0.07%
Figs	5.08E+07	0.20%
Garlic	2.05E+07	0.08%
Grapefruit	4.31E+07	0.17%
Grapes, all	1.05E+09	4.19%
Hay	7.28E+08	2.92%

(continued overleaf)

Table 10. B) Water Footprints of Agricultural Products.

Agricultural Products	Water Footprint (m^3)	Percent
Kiwi	4.03E+06	0.02%
Lemons	8.79E+07	0.35%
Lettuce	5.96E+07	0.24%
Melons	2.44E+07	0.10%
Olives and olive oil	8.88E+07	0.36%
Onions	4.70E+07	0.19%
Oranges and products	7.51E+06	0.03%
Peaches and nectarines	9.18E+07	0.37%
Pears	2.04E+07	0.08%
Peppers, bell and chili	1.36E+08	0.55%
Pistachios	1.58E+09	6.33%
Plums	1.27E+08	0.51%
Potatoes	2.15E+07	0.09%
Raspberries and blackberries	9.18E+06	0.04%
Rice	1.74E+09	6.98%
Spinach	6.83E+06	0.03%
Strawberries	4.28E+07	0.17%
Sweet Potatoes	1.07E+07	0.04%
Tangerines and mandarins	3.65E+07	0.15%
Tomatoes, fresh	4.59E+06	0.02%
Tomatoes, processed	7.14E+08	2.86%
Walnuts	1.30E+09	5.19%
Wheat	7.53E+06	0.03%
Wine	4.25E+08	1.70%
Overall	2.50E+10	100%

Global Average Water Footprint Source: M. M. Mekonnen and A. Y. Hoekstra: The green, blue and grey water footprint of crops and derived crop products, Hydrol. Earth Syst. Sci., 15, 1577–1600, 2011

Table 11. A) CFP of Water for Agricultural Products Exported.

Agricultural Products	Total Energy Required (kWh)	Total CFP (metric tons CO_2)
Almonds	4.74E+09	3.27E+06
Apples	1.54E+07	1.06E+04
Apricots	4.30E+06	2.97E+03
Artichokes	9.93E+05	6.85E+02
Asparagus	2.02E+05	1.40E+02
Avocados	6.71E+06	4.63E+03
Beef and products	7.39E+08	5.09E+05
Blueberries	3.42E+06	2.36E+03
Broccoli	1.52E+07	1.05E+04
Cabbage	1.08E+06	7.45E+02
Carrots	9.54E+06	6.58E+03
Cauliflower	5.35E+06	3.69E+03
Celery	1.79E+07	1.24E+04
Cherries	2.01E+07	1.39E+04
Cotton	3.34E+08	2.30E+05
Cottonseed and byproducts	3.82E+07	2.63E+04
Dairy and products	2.29E+09	1.58E+06
Dates	5.78E+06	3.98E+03
Dried Plums	2.50E+08	1.72E+05
Dry Beans	5.09E+07	3.51E+04
Eggs	9.15E+06	6.31E+03
Figs	2.64E+07	1.82E+04
Garlic	1.07E+07	7.35E+03
Grapefruit	2.24E+07	1.54E+04
Grapes, all	5.43E+08	3.74E+05
Hay	3.78E+08	2.60E+05
Kiwi	2.09E+06	1.44E+03

(continued overleaf)

Table 11. B) CFP of Water for Agricultural Products Exported.

Agricultural Products	Total Energy Required (kWh)	Total CFP (metric tons CO_2)
Lemons	4.56E+07	3.15E+04
Lettuce	3.09E+07	2.13E+04
Melons	1.26E+07	8.72E+03
Olives and olive oil	4.61E+07	3.18E+04
Onions	2.44E+07	1.68E+04
Oranges and products	3.90E+06	2.69E+03
Peaches and nectarines	4.76E+07	3.28E+04
Pears	1.06E+07	7.29E+03
Peppers, bell and chili	7.05E+07	4.86E+04
Pistachios	8.19E+08	5.65E+05
Plums	6.57E+07	4.53E+04
Potatoes	1.12E+07	7.71E+03
Raspberries and blackberries	4.76E+06	3.28E+03
Rice	9.04E+08	6.23E+05
Spinach	3.55E+06	2.45E+03
Strawberries	2.22E+07	1.53E+04
Sweet Potatoes	5.57E+06	3.84E+03
Tangerines and mandarins	1.89E+07	1.30E+04
Tomatoes, fresh	2.38E+06	1.64E+03
Tomatoes, processed	3.71E+08	2.56E+05
Walnuts	6.73E+08	4.64E+05
Wheat	3.90E+06	2.69E+03
Wine	2.20E+08	1.52E+05
Overall	1.30E+10	8.93E+06

The results show that almond has the highest water footprint and carbon footprint (9 Gm^3 of total water footprint) among all the products. The dairy products have the second high water footprint of 4.5 Gm^3. Walnuts, beef products, rice and pistachios are ranked behind dairy products, as the third highest group with the water footprint over 1 Gm^3.

Especially, in an industrial beef production system, it takes on average three years before the animal is slaughtered to produce about 200 kg of boneless beef. The animal consumes nearly 1,300 kg of grains (wheat, oats, barley, corn, dry peas, soybean meal and other small, grains), 7,200 kg of roughages (pasture, dry hay, silage and other roughages), 24 cubic meters of water for drinking and 7 cubic meters of water for servicing. This means that to produce one kilogram of boneless beef, we use about 6.5 kg of grain, 36 kg of roughages, and 155 liters of water (only for drinking and servicing). Producing the volume of feed requires about 15,300 liters of water on average. The water footprint of 1 kg of beef thus adds up to 15,500 liters of water.

Table 12. Top 15 Countries Water Footprint.

Top 15 countries exported	Overall Water Footprint (m^3)	Percent
European Union 27	4.08E+09	18.30%
China	4.45E+09	19.96%
India	8.68E+08	3.89%
United Arab Em	2.78E+08	1.25%
Canada	4.27E+09	19.17%
Japan	2.83E+09	12.68%
Mexico	3.44E+09	15.45%
South Korea	9.77E+08	4.38%
Turkey	1.36E+08	0.61%
Taiwan	2.28E+08	1.02%
Australia	7.02E+07	0.32%
Vietnam	8.54E+07	0.38%
Philippines	3.17E+08	1.42%
Indonesia	5.31E+07	0.24%
Jordan	1.74E+08	0.78%
Pakistan	3.21E+07	0.14%
Overall	2.23E+10	100%

Table 13. Top 15 Carbon Footprint of Agricultural Product Export for Destination Countries.

Top 15 countries exported	CPF (metric tons of CO2, equivalent)
European Union 27	1.46E+06
China	1.59E+06
India	3.10E+05
United Arab Em	9.96E+04
Canada	1.53E+06
Japan	1.01E+06
Mexico	1.23E+06
South Korea	3.50E+05
Turkey	4.87E+04
Taiwan	8.17E+04
Australia	2.51E+04
Vietnam	3.06E+04
Philippines	1.13E+05
Indonesia	1.90E+04
Jordan	6.23E+04
Pakistan	1.15E+04
Overall	7.97E+06

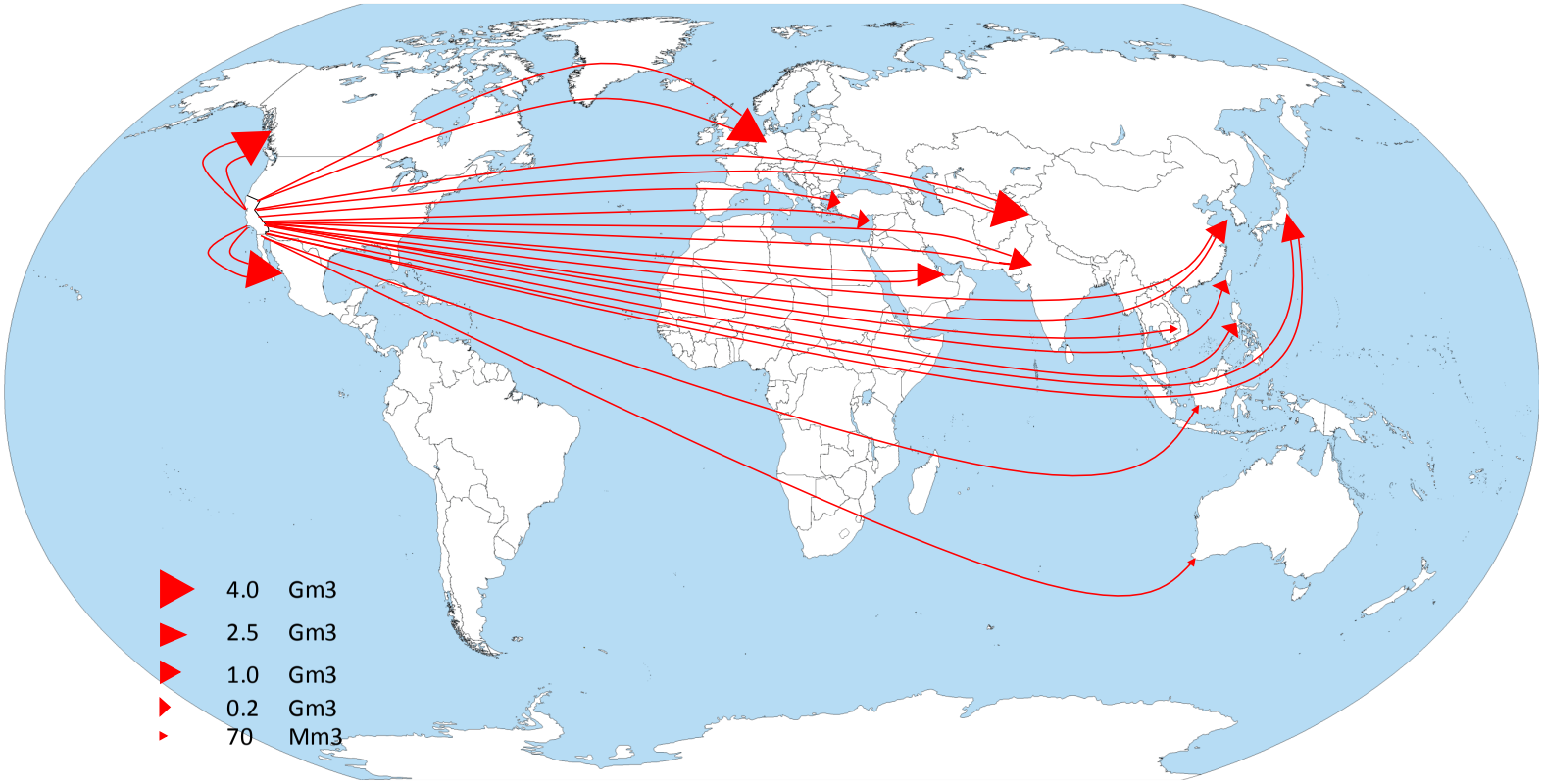

Figure 8. Water Footprint of Agricultural Products Exported

In summary the results of water footprint and carbon footprint are shown in Table 11 and Table 12. Figure 7 visualizes the water footprint of agricultural product export from California on a global scale. Several findings from the results are listed below:

1. The total water footprint of the exported agricultural products is around 22 Gm^3, which is 25% of that of the entire USA, thus a considerable portion.

2. The European United, China, Canada, Mexico, Japan are the main export water footprint destination for California, which together accounts for 86% of the total value.

3. Based on the two points above, shortage of water in California not only would have negative impacts on California, but also influence the global agricultural product commerce flow.

4. Almond is the feature agricultural products of California, which contributes 36.6% of total water footprint exported.

5. The Total carbon footprint of the water treatment of the agricultural products is around 9 million metric tons of CO_2 and 8 million of total goes to the Top 15 exported countries.

5. DISCUSSION

There are several aspects that could have changed the results of this research. Income from agriculture is 50% of California's GDP and is twice the amount of income from other industrial sectors. Being water arguably the most critical factor in agriculture, water stress is prevalent in California. In fact, water footprint in agricultural product exports was 25 Gm^3 water in 2011. California has been suffering from the droughts in recent years as shown in Figure 5. As the climate continues to warm and soil moisture deficits accumulate beyond historical levels, relevant studies suggest that sustaining water supplies in parts of the California will be a challenge (Daniel R. Cayan 2010).

Import tax is directly proportional to the total price of import products, which in author's view is biased. Products with low price/value yet high water footprint, such as beef and oranges, give the customer countries advantages over the others. With water being increasingly valuable, adjustments on import tax is needed for water resource management.

The water footprint of California agricultural products estimated in the current study should be further compared to the water footprint of the U.S.. In the study of Mekonen (2011), the total water footprint of agricultural production of USA is 800 Gm^3/yr, much bigger compared to the 25 Gm^3. However, this study focuses on not only the total quantity, but also the water footprint flow by looking at the commerce flow of each product. The import of water footprint of California should also be researched to provide an accurate understanding of the relationship between economics and environment. Furthermore, study can be expanded to the other state to

comprehensively examine the virtual water flow within the entire nation. Given that the water supply distribution in the States is vastly varied, the evaluation on water footprint flows can serve as a reference for decision making in commerce and economic management. Methodologies and results in this study can serve as preliminary results for further applications.

Carbon footprint as the other objects of this study is equally important as water footprint. In a similar way, CO_2 emission is becoming an increasingly impactful metric in many sectors of economy, and will be certainly put on the table during decision-making. Water supply in California is uniquely costly in terms of energy, standing at 19% of the total energy use of which 40% is used in agriculture (CEC 2005, DWR 2009). Therefore, the energy used in agriculture is 7.6% (product of 19% and 40%) of the total energy consumption of California.

The precipitation situation of California fluctuates from year to year, especially from 2011 to 2014, as shown in Figure 5. The California has been suffering from the worst drought in 50 years. In a drought year, instream water would be largely reduced, which means waster use in agriculture will have to rely more on other energy-intensive water supplies. Consequently, the carbon footprint for agriculture water use will be exacerbated. With year 2011 being a recent peak for precipitation, the results from this study on carbon footprint in agriculture exports, in a sense underestimated the water deficiency and energy consumption.

The total carbon footprint calculated by this study for the agricultural products exported is around 9 million metric tons CO_2, which is 2.2% of the carbon budget for California (Potter 2010). The difference between the two numbers 2.2% and 7.6%, in the author's view, is due to

primarily the fact that export is only one of the end use for agricultural products. Secondly, the use of global average value for each product's water footprint likely overlooks some of the features of regional products. In addition, inefficiency in agriculture water use for each type of product is open to exploration.

From the CEC report of 2007 (REF HERE), the largest contribution to carbon footprint is from energy for electrical power generation and the fuel for transportation.

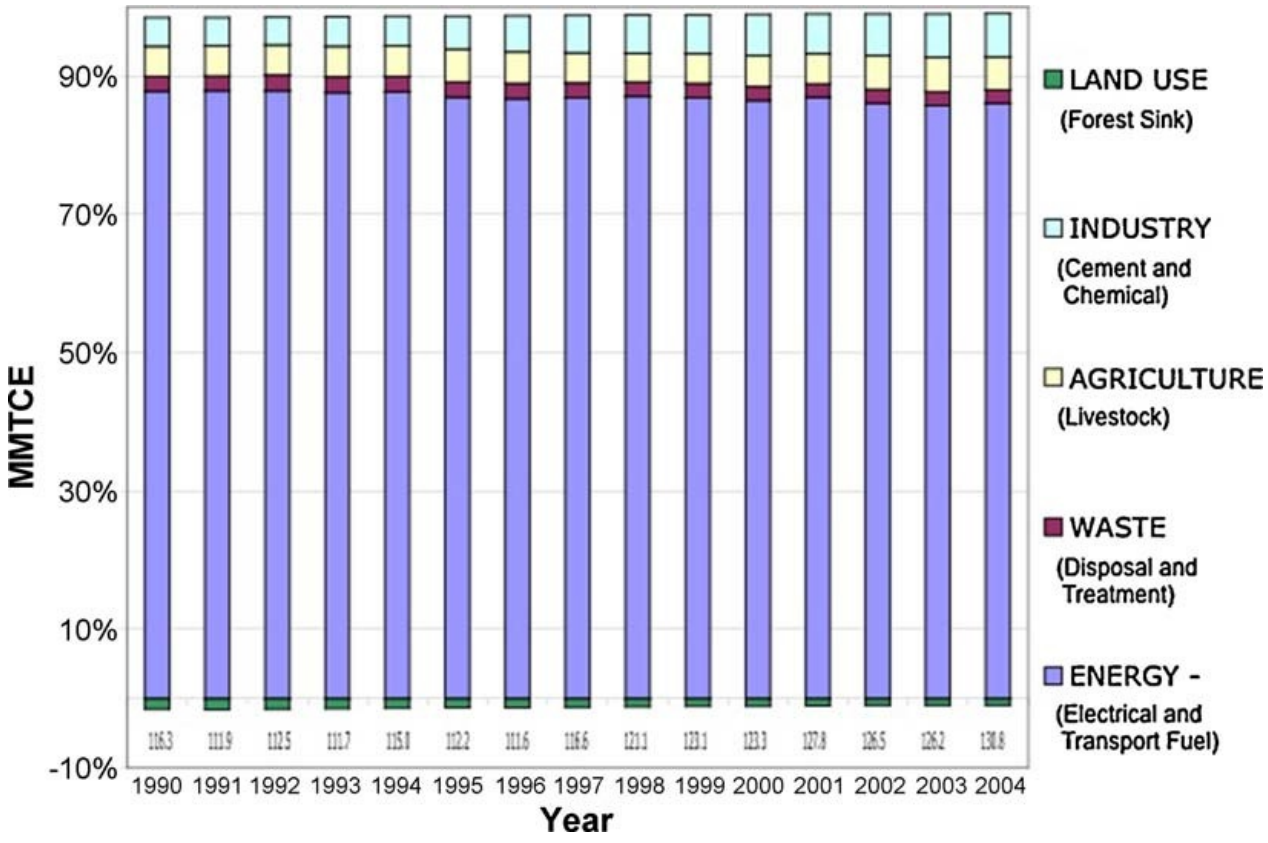

Figure 9. California GHG Inventory Summary 1990–2004 (from data compiled by the CEC, 2007). Estimated annual totals in MMTCE are provided at the bottom of each bar.

MMTCE stands for million metric tons of carbon equivalent.

The results of this study show that water footprint of agricultural product exports is 25% of the total, while the carbon footprint is 2.2% of the carbon budget. Therefore at the current stage, water consumption seems to be a more critical issue than CO_2 emission.

Nonetheless, what we considered in this research is the carbon footprint from the embedded water, but there are still many water-irrelevant activities that contribute to the total carbon footprint, such as the transportation energy and human labor carbon footprint. Hence, the carbon footprint from the entire process of agricultural production would be higher than that resulting from this research.

Another fact is that if more reclaimed water was used in agriculture, lower carbon footprint would be achieved. Reclaimed water has a lower energy requirement (445kWh/AF), compared to the ground water (950kWh/AF) (Wilkinson, 2007).

6. FUTURE WORK

Due to lack of data, global average values for each product's water footprint were used here. Further studies can increase the analysis' resolution to the county level and further. More informative results and less uncertainty should be expected when the scale of each geographical subdivision is smaller. One alternative can be resorting to the spatial distribution of precipitation, evapotranspiration and irrigation. Given the fact that precipitation combined with evapotranspiration and irrigation represents the gross water use in agriculture, and that the types of agricultural production are location-specific, hence relationships between types of agriculture production and water use can be established.

The results of this research could help fostering some new regulations to rule the management of water and energy resources in California, as well as to encourage applications of more energy-efficient water supply and water treatment technologies.

7. CONCLUSIONS

1. From the background research, the importance of researching California's specific water footprint status of agricultural market and products is obvious.
2. Due to limited availability of data, we focus our effort on trade between the top 15 countries, which shows in the result that the main carbon footprint associated with California's agricultural water exports is due to agricultural products exports to the following five regions: European Union, China, Japan, Canada, and Mexico.
3. The agricultural produce market of California is still growing at a rapid rate.
4. The total amount of the water footprint of the agricultural products is 22.3 Gm^3.
5. The agricultural products water footprint is roughly 25% of the U.S. water footprint.
6. The total carbon footprint of California's agricultural products that exported is around 8 million metric tons CO_2, corresponding to 2% of California's total carbon budget.
7. From a water conservation and resource efficiency standpoint, California must recognize the importance of implementing less energy-intensive sources of water supplies if it wishes to maintain its natural resource and economic security.

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