Water footprint analysis of temporary crops produced in São Carlos (SP), Brazil

Análise da pegada hídrica das culturas temporárias produzidas no município de São Carlos/SP

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ABSTRACT

This paper aims to evaluate the water footprint (WF) of temporary crops produced in the municipality of São Carlos, Brazil, between 2004 and 2017. The WF calculation was developed following the Water Footprint Network approach (WFN) and using CROPWAT model. The results were compared with the world averages and other studies that analyzed the same crops. We applied statistical tests to verify data behavior over the years and calculated correlation coefficients between WF components and crop yields. The results indicated low values of total WF for sugarcane (total average of 166.2 m³ ton⁻¹) and tomato (total average of 97.2 m³ ton⁻¹), while rice (total average of 5212.4 m³ ton⁻¹) and groundnut (total average of 3865.8 m³ ton⁻¹) showed the opposite. In general, WF components do not follow a monotonic trend, a normal distribution can be assumed and there is a statistically significant difference when comparing our findings with global mean values. These results ratify the importance of local WF studies, especially in Brazil, considering its importance in global agricultural market and the respective use of water resources.

Keywords: Water security; Agricultural production; Water scarcity; Water use.

RESUMO

Este trabalho visa avaliar a pegada hídrica (PH) das culturas temporárias produzidas no munícipio de São Carlos/SP, no período entre 2004 e 2017. O cálculo da pegada hídrica foi desenvolvido seguindo a metodologia da Water Footprint Newtwork (WFN) e o modelo CROPWAT. Os resultados foram comparados com as médias mundiais e outros estudos que analisaram as mesmas culturas. Foram aplicados alguns testes estatísticos para verificar o comportamento dos dados ao longo do tempo e calculou-se os coeficientes de correlação entre as componentes de pegada hídrica e as produtividades de cada cultura. Os resultados indicam baixos valores de PH total para a cana-de-açúcar (valor médio total de 166.2 m³ ton⁻¹) e tomate (valor médio total de 97.2 m³ ton⁻¹), enquanto arroz (valor médio total de 5212.4 m³ ton⁻¹) e amendoim (valor médio total de 3865.8 m³ ton⁻¹) apresentam valores elevados. Em geral, os componentes da PH não seguem uma tendência monotônica; uma distribuição normal dos dados pode ser assumida ao longo dos anos; e existe uma diferença estatisticamente significativa entre quando comparando os resultados calculados e os valores médios globais. Tais resultados ratificam a importância da realização de estudos locais de pegada hídrica, especialmente no Brasil, considerando sua importância no mercado agrícola global e o respectivo uso da água para tal fim.

Palavras-chave: Segurança hídrica; Produção agrícola; Escassez de água; Uso da água.

INTRODUCTION

Freshwater use is increasing worldwide because of population growth and economic demands, and many regions around the globe are already experiencing frequent or severe water shortages. According to the Organisation for Economic Co-operation and Development (2019), 70% of the planet's freshwater is used by agriculture. This economic activity exerts pressure on water resources as a result of human demand for food. It is important to understand how water resources are incorporated into agriculture, both in terms of direct consumption and pollution generation. One way to check this is by determining the water footprint (WF). This indicator aims to determine the water volume used, directly and indirectly, in the production chain of a given product (Hoekstra, 2003; Hoekstra et al., 2011).

The WF is usually divided into three components: the green (WF_{green}), blue (WF_{blue}) and gray water footprint (WF_{gray}), accounted considering the indirect and direct use. In the context of agricultural production, indirect use refers to water consumed in complementary products used during the crop growing, as seeds, fertilizers, pesticides, sowing and harvesting operations, and others, which were not accounted here. Direct use refers to water consumed by the plant itself, during its growing, which we determined in this study. Each component of WF refers to:

- WF_{green} refers to the water consumption resulting from rainfall, which does not generate runoff, and is stored or remains temporarily in the soil or the vegetation. (Hoekstra et al., 2011);

- WF_{blue} refers to groundwater or surface freshwater consumption, evaporated and incorporated into the product, during production. (Hoekstra et al., 2011);

- WF_{gray} is the volume of water needed to assimilate the pollutant load generated by the activity, for example, fertilizers and pesticides (Hoekstra et al., 2011).

Mekonnen & Hoekstra (2011) were the pioneers in determining the water footprint for agricultural production at a global level. The authors analyzed 126 crops between 1996 and 2005, using a high-resolution approach. However, the uncertainty involved in a global study, without the appropriate geographical specifications, have encouraged regional and local studies in recent years (Lovarelli et al., 2016). Vanham (2013), Mekonnen et al. (2015), Zhang et al. (2016) and Hoekstra & Mekonnen (2016) conducted regional and country studies and obtained agricultural water footprint values to verify how commodity-exporting countries can be considered virtual water exporters, sending water resources embedded in exported agricultural products. In Brazil, Silva et al. (2016) determined the water footprint of agricultural and livestock activities for all states, concluding that Brazil is a virtual water exporter. Scarpare et al. (2016) calculated sugarcane water footprint in the Tietê/Jacaré watershed in São Paulo state, where high production of this crop occurs. To the best of our knowledge, this study represents a unique sub-national water footprint assessment in Brazil.

At the municipal level, there are no studies that assessed the water footprint in Brazil. The main reason is the lack of local climate data in most municipalities. Another missing analysis is the evaluation of the temporal evolution of the agricultural water footprint, which can allow to observe the annual values of this indicator and to identify possible causes of the variation, linked to climate, productivity or crop management.

This study aimed to evaluate the water used by temporary crops produced in the municipality of São Carlos, São Paulo state (SP), Brazil, through direct water footprint estimation between 2004 and 2017. Besides, this study may become a reference for municipalities with similar climatic characteristics and similar agricultural production, in terms of crops and yields, especially in tropical areas (Burt & McDonnell, 2015).

MATERIAL AND METHODS

Study area

This study was conducted in the municipality of São Carlos (Latitude 22° 0' 55" S, Longitude 47° 53' 28" W, altitude: 854 m), situated in São Paulo (SP) state, Brazil, (Figure 1). This municipality has a humid subtropical climate (Cwa, Köppen), with a hot and wet summer and a dry winter (Alvares et al., 2014). The average annual rainfall and temperature are 1486 mm yr^{-1} and 19 °C, respectively (Cabrera et al., 2016). Cerrado (Brazilian savanna) is the predominant biome (São Carlos, 2019).

São Carlos has a total area of 1,136.93 km², divided in 67.25 km² of urban area and 1,069.68 km² of rural use. Approximately 730 km² of the rural area is occupied by farms, where agricultural and livestock activities are developed. Forestry and preservation areas are also observed in the municipality area (Instituto Brasileiro de Geografia e Estatística, 2018).

The object of study is the temporary crops cultivated in the rural areas of São Carlos. Temporary crops are those which are both sown and harvested during the same agricultural year, sometimes more than once. In São Carlos, we found sugarcane, maize, soybean, tomato, cassava, rice, beans, and groundnut as temporary crops. Only temporary crops were evaluated because of their predominance, ranging from 77.98 (263.66 km²) to 91.84% (383.25 km²) of the planted area. Permanent crops occupy the remaining fields (Instituto Brasileiro de Geografia e Estatística, 2018). Table 1 shows the planted area of the crops analyzed in this study and the occupation rate, considering the total area used for temporary crops and the municipality area.

Water footprint calculation

The direct water footprint of crops was calculated following the Water Footprint Assessment Manual, (Hoekstra et al., 2011). The total water footprint of the crops is the sum of three components: blue, green and gray water footprint (WF_{blue}, WF_{green}, and WF_{gray}), as shown in Equations 1, 2 and 3, respectively.

$$WF_{blue} = \frac{CWU_{blue}}{Y} \tag{1}$$

$$WF_{green} = \frac{CWU_{green}}{Y} \tag{2}$$

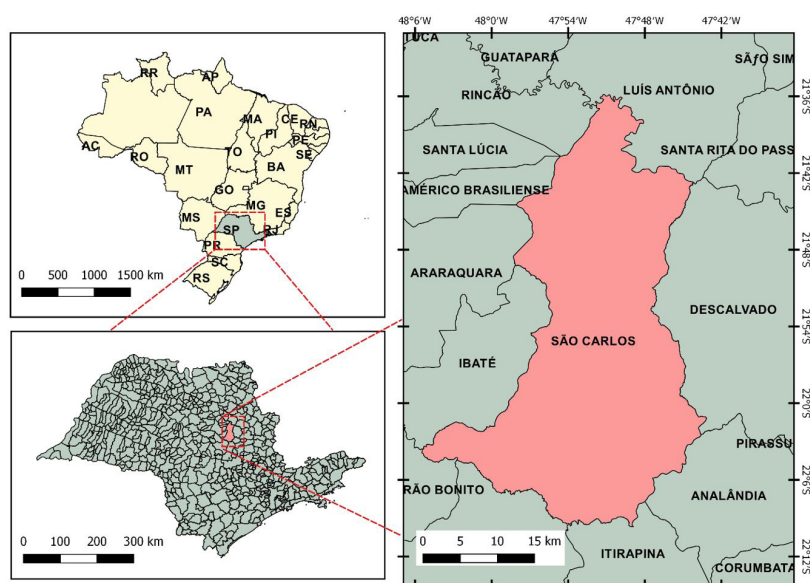$$WF_{gray} = \frac{(\alpha \times AR)/(c_{máx} - c_{nat})}{Y} \tag{3}$$

Figure 1. Map showing the location of São Carlos municipality, São Paulo (SP) state, Brazil.

Table 1. Crops planted area (ha) in São Carlos (SP) during the study period. The percentages indicate the relation between the crop planted area and the total area for temporary crops and the relation between the crop planted area and the municipality total area, respectively.

C	2004	2005	2006	2007	2008	2009	2010
1	23867	24220	23867	23000	23000	38084	37943
	83.7% / 20.99%	85.4% / 21.30%	85.5% / 20.99%	87.2% / 20.23%	87.0% / 20.23%	94.0% / 33.5%	98.1% / 33.37%
2	3580	3080	3580	2900	3000	2000	300
	12.6% / 3.15%	10.9% / 2.71%	12.8% / 3.15%	10.4% / 2.55%	11.3% / 2.64%	4.94% / 1.76%	0.78% / 0.26%
3	1000	1000	400	400	400	400	400
	3.51% / 0.88%	3.52% / 0.88%	1.43% / 0.35%	1.43% / 0.35%	1.51% / 0.35%	0.99% / 0.35%	1.03% / 0.35%
4	10	15	15	12	12	9	9
	0.04% / 0.01%	0.05% / 0.01%	0.05% / 0.01%	0.04% / 0.01%	0.05% / 0.05%	0.02% / 0.01%	0.02% / 0.01%
5	9	6	9	9	9	9	9
	0.03% / 0.01%	0.03% / 0.01%	0.03% / 0.01%	0.03% / 0.01%	0.03% / 0.01%	0.02% / 0.01%	0.02% / 0.01%
6	25	25	25	25	25	---	---
	0.09% / 0.02%	0.09% / 0.02%	0.09% / 0.02%	0.09% / 0.02%	0.09% / 0.02%		
7	30	30	20	20	---	---	---
	0.11% / 0.03%	0.07% / 0.02%	0.07% / 0.02%	0.07% / 0.02%			
8	---	---	---	---	---	---	---
T	**28521**	**28376**	**27916**	**26366**	**26446**	**40502**	**38661**
	100% / 25.09%	100% / 24.96%	83.7% / 24.55%	100% / 20.99%	100% / 23.26%	100% / 35.62%	83.7% / 34.00%
C	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
1	38084	32967	32967	32500	34500	35000	35000
	98.0% / 33.50%	91.6% / 29.00%	91.25% / 29.00%	91.27% / 28.59%	86.32% / 30.34%	91.96% / 30.78%	91.32% / 30.78%
2	350	2500	2700	1900	1700	1500	1800
	0.90% / 0.31%	6.94% / 2.20%	7.47% / 2.37%	5.34% / 1.67%	4.25% / 1.50%	3.94% / 1.32%	4.70% / 1.58%
3	400	500	400	700	700	1500	1500
	1.03% / 0.35%	1.39% / 0.44%	1.11% / 0.35%	1.97% / 0.62%	1.75% / 0.62%	3.94% / 1.32%	3.91% / 1.32%
4	12	12	12	10	10	12	10
	0.03% / 0.01%	0.03% / 0.01%	0.03% / 0.01%	0.03% / 0.01%	0.03% / 0.01%	0.03% / 0.01%	0.03% / 0.01%
5	12	10	25	30	38	30	15
	0.03% / 0.01%	0.03% / 0.01%	0.07% / 0.02%	0.08% / 0.03%	0.10% / 0.03%	0.08% / 0.03%	0.04% / 0.01%
6	25	20	20	20	20	20	---
	0.06% / 0.02%	0.06% / 0.02%	0.06% / 0.02%	0.06% / 0.02%	0.05% / 0.02%	0.05% / 0.02%	
7	---	---	5	---	---	---	---
			0.01% / 0.004%				
8	---	---	---	450	3000	---	---
				1.26% / 0.40%	7.51% / 2.64%		
T	**38883**	**36009**	**36129**	**35610**	**39968**	**38062**	**38325**
	100% / 34.20%	100% / 31.67%	100% / 31.78%	100% / 31.32%	100% / 35.15%	100% / 33.48%	100% / 33.71%

C = Crops; 1 = Sugarcane; 2 = Maize; 3 = Soybeans; 4 = Tomato; 5 = Cassava; 6 = Rice; 7 = Beans; 8 = Groundnut; T = total area of temporary crops. Source: Instituto Brasileiro de Geografia e Estatística (2018).

Table 2. Planting and harvesting dates considered in the CROPWAT model.

Crop	Planting order	Plant date	Harvest date	Stage (days)
1	----	01/09	31/08	365
2	1st planting	01/09	03/01	125
	2nd planting	01/02	05/06	125
3	----	01/11	24/01	85
4	----	01/02	25/06	145
5	----	01/09	29/03	210
6	----	01/10	28/01	120
7	1st planting	01/09	19/12	110
	2nd planting	01/01	20/04	110
	3rd planting	01/05	18/08	110
8	1st planting	01/09	08/01	130
	2nd planting	01/02	08/06	130

1 = Sugarcane; 2 = Maize; 3 = Soybeans; 4 = Tomato; 5 = Cassava; 6 = Rice; 7 = Beans; 8 = Groundnut. Source: Companhia Nacional de Abastecimento (2019a) and Empresa Brasileira de Pesquisa Agropecuária (2019a).

where: CWU_{blue}: blue component in crop water use (m³ ha⁻¹); CWU_{green}: green component in crop water use (m³ ha⁻¹); Y = crop yield (ton ha⁻¹); α = leaching-runoff fraction; AR = chemical application rate to the field (kg ha⁻¹); c_{max} = maximum acceptable concentration for the pollutant considered (kg m⁻³); and c_{nat} = natural concentration for the pollutant considered (kg m⁻³). Here, the water footprint values are expressed in water volume per mass (m³ ton⁻¹).

The crop water use (CWU_{blue} and CWU_{green}) was determined using the CROPWAT 8.0 model (Allen et al., 1998). The model analyzes the amount of rainwater incorporated by the crop (the green component of the water demand), as shown in Equation 4, and the irrigation demand (the blue component of the water demand), as shown in Equation 5.

$$CWU_{blue} = 10 * \sum_{d=1}^{lgp} ET_{blue} \qquad (4)$$

$$CWU_{green} = 10 * \sum_{d=1}^{lgp} ET_{green} \qquad (5)$$

where: lgp: length of growing period (days); d: day of planting; ET_{green}: green water evapotranspiration (mm day⁻¹); and ET_{blue} = blue water evapotranspiration (mm day⁻¹).

These two parts together provide crop evapotranspiration. The calculation of these components considered the crops under optimal development conditions, using only climatic and crop data, once there is not a detailed information about irrigation schedule in a local scale.

Data collection

Climate data were collected at the Climatological Station of the Water Resources and Applied Ecology Center (CRHEA) from the University of São Paulo (USP), and consist of maximum and minimum temperature, humidity, wind speed, insolation, and rainfall.

The crop data used were: crop coefficient (K_c); length of growth stage; and root depth. They were obtained from the global CROPWAT defaults (Allen et al., 1998). Cassava was an exception because we used data from the Food and Agriculture Organization (2019).

São Carlos temporary crop yield data (Y) were obtained from the Instituto Brasileiro de Geografia e Estatística (2018). The data are available between 2004 and 2017 for sugarcane, maize, soybean, tomato, cassava, rice, beans, and groundnut.

Table 2 indicates the planting and harvesting crops calendar adapted from the Brazilian Grain Plantation and Harvest Calendar (Companhia Nacional de Abastecimento, 2019a) and Brazilian Agricultural Research Corporation (Empresa Brasileira de Pesquisa Agropecuária, 2019a) proposals. These dates were included in the CROPWAT model. The climatic data incorporated in the CROPWAT model followed the planting and harvesting calendar, from September of the first year to August of the following year, to cover all cultures growth.

For the WF_{gray}, the nitrogen application rate was obtained from Empresa Brasileira de Pesquisa Agropecuária (2019a, 2020a, 2020b, 2020c, 2020d, 2020e, 2020f, 2020g), which indicates the average values used in Brazilian territory. We used only one value for crop, during the study period (Table 3), because there is not a historical data available. The leaching-runoff fraction (α) was assumed to be 10% (Chapagain et al., 2006). The maximum concentrations of pollutants (c_{max}) were obtained from Resolution nº 357/2005 of the National Council of the Environment (CONAMA) (Brasil, 2005). For nitrate, the maximum concentration allowed is 10 mg L⁻¹. Natural concentrations (c_{nat}) were assumed to be zero due to the lack of local data, following the suggestion of Hoekstra et al. (2011)., We used only nitrogen rates to calculate WF_{gray}, according to several studies found in the literature, which also allowed us to compare our results with those found in these studies (Bulsink et al., 2010, Mekonnen & Hoekstra, 2011; Liu et al., 2012).

Data analysis

We calculated the water footprint of the crops for each year of the study period (2004 to 2017) and analyzed the years where the results showed more discrepancy. The main base for results comparison was the global WF results (Mekonnen & Hoekstra, 2011) (Table 4). Although they were estimated with data from 1996 to 2005, their findings can be used as a reference, considering the lack of similar results with global data. We also checked other recent studies (from 2009 to 2019) that analyzed the same crops in different places of the world, for approximation and validation of the results.

We applied statistical tests to verify the water footprint behavior over the years. Groundnut results was excluded from this analysis, considering that this crop was planted only in two years and this was not enough to use the tests correctly.

First, we tested data distributions for normality, using the Shapiro-Wilk test, with a 95% confidence interval ($\alpha=0.05$). If the test confirms the null hypothesis, the sample analyzed comes from a normal population. Otherwise, the alternative hypothesis indicates that the sample does not follow a normal distribution.

When the normal distribution has been confirmed, we applied two additional parametric tests: t-Student and the one-way analysis of variance (ANOVA) with Tukey test. If data do not follow normal distribution, these two tests were not applied. The t-student compares the mean results found in this study with the global mean values, (Mekonnen & Hoekstra, 2011), determining if the two data sets are significantly different from each other. If the test confirms the null hypothesis, there is no difference between the sample (our results) and population (global values) means. Otherwise, the alternative hypothesis indicates a significant difference between the sample and the population means. A 95% confidence interval was also considered.

The ANOVA was applied to compare means of two different crops, considering the same WF component. The null hypothesis indicates that the samples are from populations with the same mean values. Additionally, the Tukey test was applied to perform multiple comparisons between different crops in the same WF component.

We also used Mann-Kendall, a non-parametric test (Kendall & Stuart, 1967; Mann, 1945), to check a monotonic upward or downward trend of each water footprint component. The null hypothesis indicates that the data originate from a population of independent and identically distributed measurements, with no trend. The alternative hypothesis indicates that data follows a monotonic trend, upward or downward. This test was applied only for the five crops with data in the whole period study (sugarcane, maize, soybean, tomato and cassava).

Table 3. The application rate of nitrogen compounds, in kg ha^{-1}.

Crop	Fertilizer application rate considered (kg/ha)
1. Sugarcane	87.5
2. Maize	60
3. Soybeans	10
4. Tomato	92.5
5. Cassava	30
6. Rice	85
7. Beans	105
8. Groundnut	13

Source: Empresa Brasileira de Pesquisa Agropecuária (2019a, 2020a, 2020b, 2020c, 2020d, 2020e, 2020f, 2020g).

Table 4. Water footprint values, in m³ ton^{-1}, calculated by Mekonnen & Hoekstra (2011). Columns indicate global values (minimum, mean and maximum, with the country and province/state of occurrence), national (mean) and sub-national (SP state).

Crop	WF component	Global values			Brazil	
		Minimum	Mean	Maximum	Mean	SP State
1. Sugarcane	Green	11	139	10749	122	115
		Egypt – Al Minya		American Samoa		
	Blue	0	57	507	5	4
		Indonesia - Papua		Nigeria - Jigawa		
	Gray	0	13	266	10	10
		Zambia		Afghanistan - Badghis		
	Total	11	209	11522	137	128
2. Maize	Green	33	947	21289	1621	1510
		Kuwait – Al'Asimah		Botswana - Southern		
	Blue	0	81	8593	1	0
		Bangladesh – Chittagong		Sudan – An Nil al Azraq		
	Gray	0	194	5316	125	113
		Central African Republic – Haut Mbombou		Dominica		
	Total	33	1222	35198	1746	1622
3. Soybeans	Green	208	2037	36975	2181	2114
		Egypt – Al Buhayrah		Tajikistan - Kulyab		
	Blue	0	70	161176	1	1
		Russian Federation		Tajikistan - Khudzhand		
	Gray	0	37	89528	15	14
		Pakistan		Tajikistan – Kulyab		
	Total	208	2144	287680	2197	2129

Source: Mekonnen & Hoekstra (2011).

Table 4. Continued...

Crop	WF component	Global values			Brazil	
		Minimum	Mean	Maximum	Mean	SP State
4. Tomato	Green	0.1	108	3234	68	71
		Brunei Darussalam		Somalia - Banaadir		
	Blue	0	63	1777	19	14
		Zimbabwe - Midlands		Somalia – Shabeellaha Dhexe		
	Gray	0	43	474	7	7
		Zambia		Cuba – Ciudad de la Habana		
	Total	0.1	214	5486	94	92
5. Cassava	Green	47	550	3685	433	476
		Saint Lucia		Cayman Islands – G. Cayman		
	Blue	0	0	459	1	0
		Brazil - Amazonas		Niger - Agadez		
	Gray	0	13	267	17	14
		Tanzania - Kilmanjaro		Guyana – M.-Berbice		
	Total	47	564	4412	451	490
6. Rice	Green	49	1146	8822	1943	2222
		Egypt – Al Qalyubiyah		Brunei - Temburong		
	Blue	0	341	7405	356	96
		Ecuador – Mor. Santiago		Iraq - Maysan		
	Gray	0	187	2145	104	107
		Central African Republic – Haut Mbombou		Kyrgyztan – Jalal-Abad		
	Total	49	1673	18372	2403	2425
7. Beans	Green	234	3945	12362	2761	2039
		Libya – Al Jufrah		India – Daman and Diu		
	Blue	0	125	4771	62	54
		Bangladesh - Chittagong		Cyprus - Kyrenia		
	Gray	0	983	19259	440	225
		Ethiopia		United States - Nevada		
	Total	234	5053	36392	3264	2318
8. Groundnut	Green	72	2469	14267	2777	2815
		Israel - HaMerkaz		Angola - Zaire		
	Blue	0	150	8956	3	1
		Myanmar – Chin State		Sudan – Janub Darfur		
	Gray	0	163	3931	12	12
		Venezuela		Namibia - Luderitz		
	Total	72	2782	27154	2793	2828

Source: Mekonnen & Hoekstra (2011).

Finally, we calculated the linear correlation coefficient between WF components and the yields of each crop. This coefficient can vary between -1 (negative correlation) and +1 (positive correlation), which indicates that variables are inversely or directly proportional, respectively. Values close to 0 indicate no linear relationship. We searched to visualize and delineate how crop productivity could influence each WF component. We expect negative values for these coefficients, once the yields are inversely proportional to WF components, as can be seen in Equations 1, 2, and 3. The values variation can indicate how strong the relation of both variables are and how it can probably influence in each other.

RESULTS AND DISCUSSIONS

Water footprint calculation by crop and comparison of the results

Table 5 summarizes the water footprint results in terms of mean and standard deviation values, for each temporary crop analyzed in this study. These values can be compared with the main global results (Mekonnen & Hoekstra, 2011), highlighted in Table 4 (minimum, mean and maximum global values / Brazilian mean and SP state values). We also consulted other studies for further discussion.

In summary, this study allowed us to estimate the temporary crops water footprint in a Brazilian municipality, using preferentially local data. Sugarcane, tomato, soybeans and maize showed WF values below or near the global and national averages, which can reveal a good adaptation to local conditions. On the other hand, rice, beans and groundnut presented high values of WF, what it can mean a non-adaptation, and its cultivation is not recommended in São Carlos, considering water use. We highlight that the blue WF was overestimated, when comparing to the other studies. This probably happened because CROPWAT assumes optimal growth conditions, without water restriction.

The results and comparisons for each crop are discussed separately, in the following topics.

Sugarcane

Figure 2 shows the results for sugarcane, the crop with the highest planted area (average of 31071 ha) and the highest yield (average of 83 ton ha^{-1}) in São Carlos/SP. The sugarcane

Table 5. Mean and standard deviation of the water footprint components, in m³ ton⁻¹, for the analyzed crops in this study.

Crop	WF$_{green}$	WF$_{blue}$	WF$_{gray}$	WF$_{total}$
1. Sugarcane	109.8 ± 7.6 [a]	45.9 ± 13.1 [a]	10.5 ± 0.3 [a]	166.2 ± 9.4[a]
2. Maize	1203.4 ± 234.3	395.5 ± 178.4 [b]	124.0 ± 26.6	1722.8 ± 392.2[b]
3. Soybeans	1127.1 ± 274.3	118.0 ± 84.3 [ab]	38.9 ± 8.7	1284.1 ± 317.4[b]
4. Tomato	56.2 ± 15.4 [a]	23.0 ± 16.0 [a]	18.0 ± 5.8 [a]	97.2 ± 32.2[a]
5. Cassava	317.5 ± 35.9 [a]	19.5 ± 18.4 [a]	18.6 ± 2.2 [a]	355.7 ± 41.3[a]
6. Rice	2546.7 ± 312.5	2217.9 ± 538.2 [c]	447.9 ± 54.3	5212.4 ± 740.9
7. Beans	5524.3 ± 1018.7	2220.0 ± 676.1 [c]	840.0 ± 78.3	8584.4 ± 692.4
8. Groundnut	2911.9 ± 515.2	894.5 ± 493.4	59.4 ± 10.5	3865.8 ± 1019.1

WF$_{green}$: green water footprint; WF$_{blue}$: blue water footprint; WF$_{gray}$: gray water footprint. Identical lower-case letters indicate no significant difference between means in the same column by the Tukey means comparison test (P >0.05).
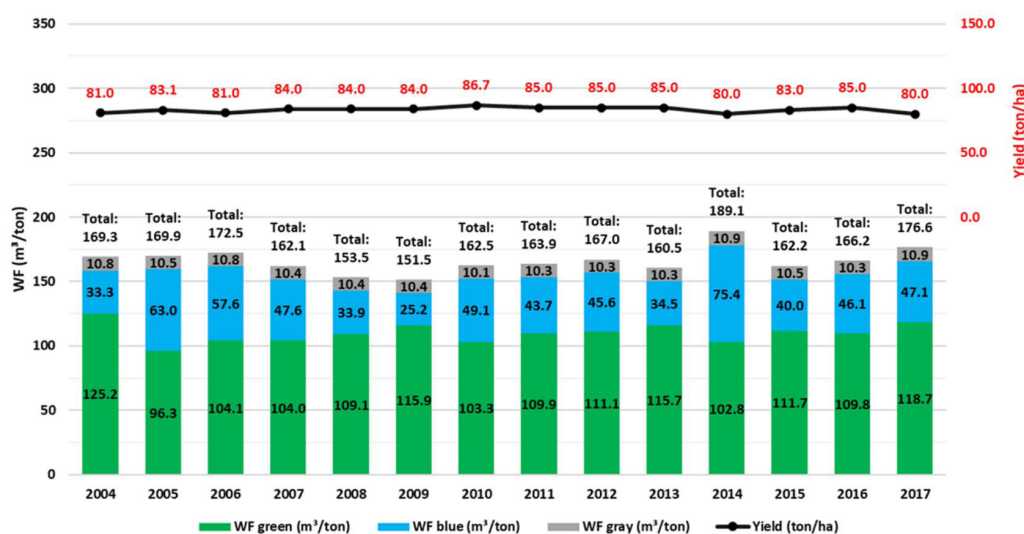
Figure 2. Sugarcane water footprint, in São Carlos/SP, between 2004 and 2017. The green part of the graph represents the green water footprint (WF$_{green}$), the blue part represents the blue water footprint (WF$_{blue}$) and the gray part represents the gray water footprint (WF$_{gray}$). The sum of the three plots is the total water footprint (WF$_{total}$). The graph also shows the crop yield over the years.

yield variation is minimum, varying from 80 to 86.7 ton ha⁻¹, and cannot be indicated as a modifying factor of the water footprint. The significant increase in sugarcane production from 2009, due to the growth in the planted area (see Table 1), did not affect productivity.

Comparing the results with the global results (Mekonnen & Hoekstra, 2011), the total values of water footprint (average of 166.2 m³ ton⁻¹) are lower than the world average (209 m³ ton⁻¹) for all years. Both results are near to the world minimum WF (11 m³ ton⁻¹) and far from the maximum WF (11522 m³ ton⁻¹) for sugarcane, according to Table 4 (Mekonnen & Hoekstra, 2011). Analyzing the plots separately, the results are also lower than the global mean values. Only the blue water footprint exceeds the global average (57 m³ ton⁻¹) in 2005 (63 m³ ton⁻¹) and 2006 (57.6 m³ ton⁻¹). There was a small variation of the gray component compared to the global average. Our results are also close to the Brazilian values identified in the global study (Mekonnen & Hoekstra, 2011), for green and gray components. The exception is the blue WF, that was nine time bigger. As we considered an optimal development condition for crops growing, with no restriction of irrigation, we can expect that this component achieve bigger values.

Scarpare et al. (2016) calculated sugarcane water footprint in the Tietê/Jacaré watershed, where part of São Carlos' territory is

inserted. They found 145, 38 and 18 m³ ton⁻¹ as the average results for green, blue and gray components, respectively, considering sugarcane as the semi-permanent culture, which was harvested for five consecutive years, with different yields, different irrigation, and fertilization scenarios, during this cultivation period. With different assumptions, their results are close to the values obtained in this study, with negligible deviations, even for the blue component, which was the critical value, when comparing with the Brazilian results calculated in the global study (Mekonnen & Hoekstra, 2011). This fact highlights the importance of local studies, with local data, to analyze the water use in agriculture, from WF concept. Also, both results indicate that sugarcane has a good adaptation to the regional climate and how this crop presents a low water footprint, especially in São Paulo state, where high productivity is achieved.

Anache et al. (2019) estimated sugarcane evapotranspiration at a study site in Itirapina/SP, a municipality near São Carlos/SP, with similar climate conditions. They found values for evapotranspiration of 801 ± 212 mm year⁻¹, considering water balance components, monitored over 5 years (2012 to 2016). Evapotranspiration is an important element for green and blue WF determination, and therefore their results are important to validate our calculations. For this study, sugarcane annual evapotranspiration modeled by CROPWAT was, on average, 1296 ± 53 mm year⁻¹ This difference

can be explained by the years considered in each study. Anache et al. (2019) used data from 2012 and 2016, when occurred a historical dry in the state of São Paulo (2014 and 2015), reducing water availability for crops, and consequently, evapotranspiration rates also reduced. Our study, on the other hand, considers a longer period (2004-2017), so this drought was compensated by years of high rainfall rates (2004, 2009 and 2011), which raised the average evapotranspiration rate. Another cause is the use of different values of K_c applied in both studies. This comparison highlights how rainfall is important to agriculture and how it can affect the evapotranspiration, and consequently, green and blue WF values.

Maize

Figure 3 shows the results for maize, the second most planted crop in São Carlos/SP (2206 ha). The 2009 water footprint results show a great discrepancy with the other years. This may be because in 2009 the harvested area was lower than the planted area, causing a production loss by an external factor, for example, climate anomaly or disease. However, crop yields were still good, contributing to the water footprint reduction that year. On the other hand, there may have been a data collection problem, leading to yield values higher than those found in other years. The crop yield increase in 2009 was also observed in soybean and tomato crops.

The total water footprint values (average of 1722.8 m³ ton⁻¹) were higher than the global averages (Mekonnen & Hoekstra, 2011), 1222 m³ ton⁻¹, in most years. Both results are closest to the minimum total WF (33 m³ ton⁻¹) than the maximum total WF (35198 m³ ton⁻¹) in the world. Observing the plots separately, the greatest differences appear in the blue water footprint, indicating a high irrigation demand or an overestimation in this component, caused again by modeling assumptions. Another possible explanation is the planting and harvesting calendar used, which considered two crops, with one of them in the dry season, requiring more irrigation water. That deviation also occurs when comparing our result for blue WF to the national and state averages, found

in the global study, which can reinforce these two hypotheses. Considering the green component, consecutive plantings can lead to high values of a green water footprint because precipitation water is incorporated into the crop during the year. The maize gray water footprint (average of 124.0 m³ ton⁻¹) was lower than the global average (194 m³ ton⁻¹) in all years.

Gerbens-Leenes & Hoekstra (2012) calculated the water footprint for maize in the main producing countries, which includes Brazil, considering data from 1996 to 2005. They confirmed that Brazilian maize has total water footprint values (approx. 1800 m³ ton⁻¹) higher than the global means, as seen in São Carlos. However, these authors showed that the blue component in Brazil is one of the lowest among the other evaluated countries. This result does not correspond with the values obtained in this study, where blue WF showed a high discrepancy with global means. These authors considered actual irrigation in WF calculation rather than irrigation requirement, which explains this difference. However, this approach is valuable when irrigation information is available, in a more detailed way, which was not the case during our study.

Soybean

The soybean total water footprint values (1284.1 m³ ton⁻¹) were lower than the global average (2144 m³ ton⁻¹), as shown in Figure 4. Again, we observe that the São Carlos total WF values are below the global average and closer to the minimum result at global scale (208 m³ ton⁻¹) and far from the maximum (287660 m³ ton⁻¹) The green component was 45% smaller than the world average (2037 m³ ton⁻¹), suggesting favorable water availability conditions for the crop. The planting and harvesting calendar used for soybean was only one crop per year. Thus, the positive variations of the green component are not the result of new planting in sequence. The blue water footprint results varied greatly (0 to 265.7 m³ ton⁻¹) during the years, but the average value (118.0 m³ ton⁻¹) is not so far to the global average (70 m³ ton⁻¹), which deviation is again linked to the no water restriction of CROPWAT modeling. The mean
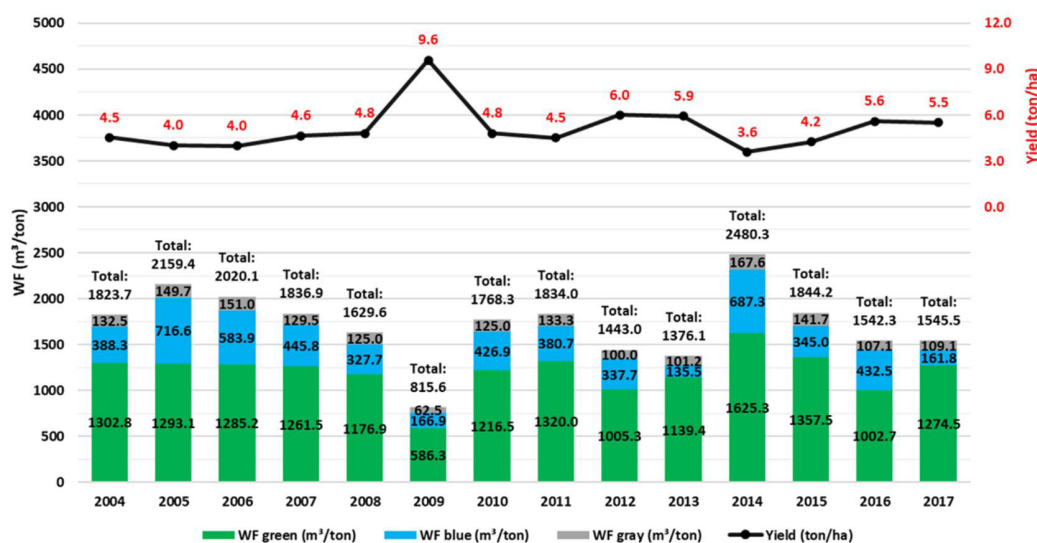

Figure 3. Maize water footprint, in São Carlos/SP, between 2004 and 2017. The green part of the graph represents the green water footprint (WF_{green}), the blue part represents the blue water footprint (WF_{blue}) and the gray part represents the gray water footprint (WF_{gray}). The sum of the three plots is the total water footprint (WF_{total}). The graph also shows the crop yield over the years.

gray WF (38.9 m³ ton⁻¹) is almost the same of the global mean value (37 m³ ton⁻¹). Considering the Brazilian values, obtained in the global study, we observe that our green component is almost a half smaller, while blue and gray components presents elevated deviations. The explanation for blue component is the same of the other crops. In terms of gray component, soybean demands little or no use of nitrogen compounds for fertilization when planted in the Cerrado biome (Mendes et al. 2007). However, its common to visualize this application in small properties, what justifies the consideration of little application rate (Empresa Brasileira de Pesquisa Agropecuária, 2020c).

Zhuo et al. (2014) calculated soybeans WF in a region near Beijing, China. Their average results are similar to those of São Carlos for the green component (1195.6 m³ ton⁻¹ versus 1127.1 m³ ton⁻¹). For gray component, we observe a great deviation (266.4 m³ ton⁻¹ in China versus 38.9 m³ ton⁻¹ in São Carlos, 37 m³ ton⁻¹ in the global average and 15 m³ ton⁻¹ in Brazilian average). The authors considered

an application fertilizer rate of 47.6 kg ha⁻¹, almost five times of that was considered in this study. Another significant factor is the low soybean yields in China (approx. 1.7 ton ha⁻¹), while in São Carlos it is higher than 2.1 ton ha⁻¹. Regarding blue WF, soybeans produced in São Carlos demand half of the irrigation required in China (118.0 m³ ton⁻¹ versus 354.3 m³ ton⁻¹).

Tomato

Figure 5 shows the tomato water footprint results. The WF_{blue} average value was 23 m³ ton⁻¹, 56.2 m³ ton⁻¹ for WF_{green} and 18.0 m³ ton⁻¹ for WF_{gray}. None of the three plots exceeded the global mean values and also remains close to the lowest values of each component in the world (Table 4, Mekonnen & Hoekstra, 2011). Considering Brazilian results in the global study, São Carlos tomatoes presented more consumption of blue and
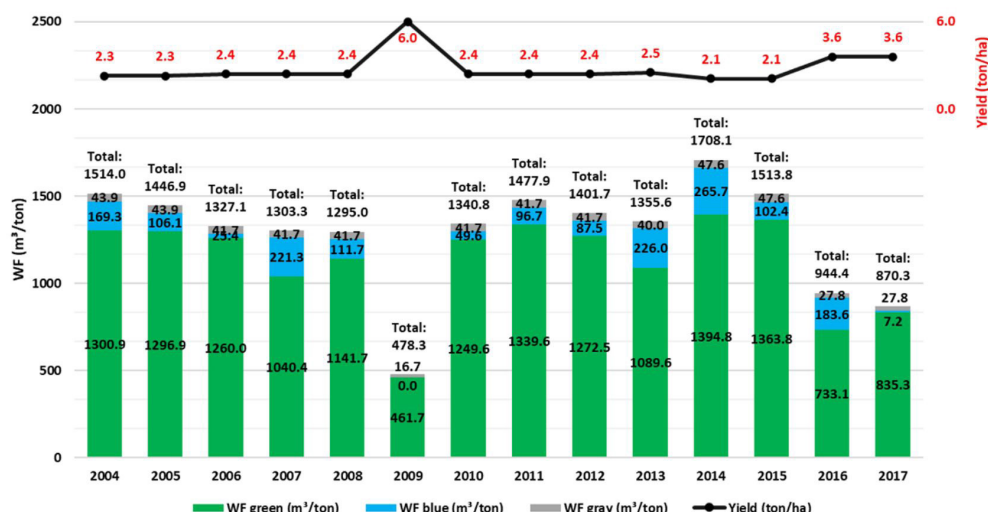

Figure 4. Soybean water footprint, in São Carlos/SP, between 2004 and 2017. The green part of the graph represents the green water footprint (WF_{green}), the blue part represents the blue water footprint (WF_{blue}) and the gray part represents the gray water footprint (WF_{gray}). The sum of the three plots is the total water footprint (WF_{total}). The graph also shows the crop yield over the years.
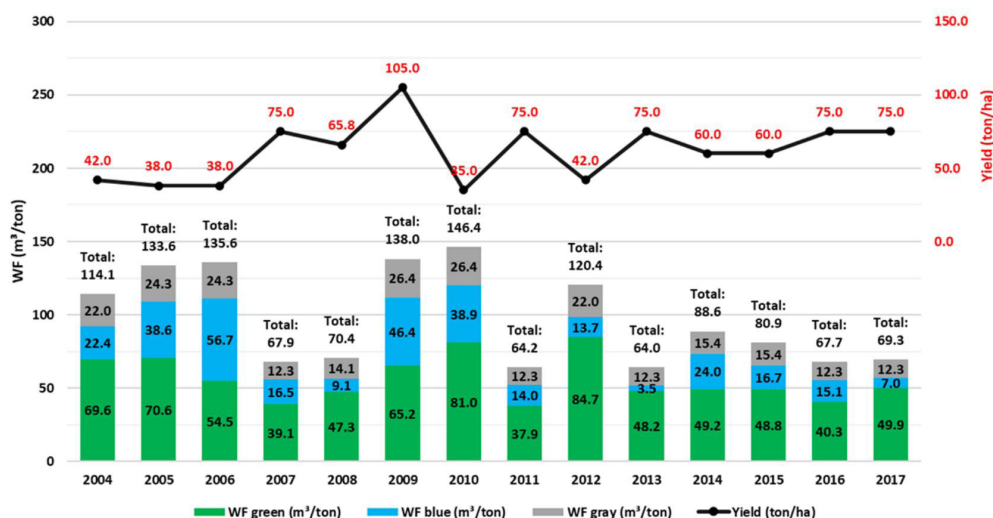

Figure 5. Tomato water footprint, in São Carlos/SP, between 2004 and 2017. The green part of the graph represents the green water footprint (WF_{green}), the blue part represents the blue water footprint (WF_{blue}) and the gray part represents the gray water footprint (WF_{gray}). The sum of the three plots is the total water footprint (WF_{total}). The graph also shows the crop yield over the years.

grey water, while the green component was below the national and state average.

According to the historical record we generated, it could be observed that 2007 and 2016 show the lowest water footprint total values, 67.9 and 67.7 m³ ton⁻¹ respectively, due to the high crop yields. It should be mentioned that 2009 was not considered in this evaluation, because of the possible data failure, as already commented. From 2013 to 2014, yield values decreased from 75 to 60 ton ha⁻¹ and green water footprint values remained remarkably close (48.2 and 49.2 m³ ton⁻¹). In these same years, the blue component varied considerably, from 3.5 to 24 m³ ton⁻¹, possibly compensating the crop water demand, not supplied by the green component, once low rainfall was observed in 2014.

Chapagain & Orr (2009) determined WF for the Spanish production of tomatoes, considering both open (in fields) and covered (greenhouses) systems. They reached, as a national average result, 13.6, 60.5 and 7.2 m³ ton⁻¹ for the green, blue and gray components, respectively. Aldaya & Hoekstra (2010) calculated WF for industrial tomatoes, for pasta and pizza consumption in Italy. They obtained, also at a national level, average results of 35, 60 and 19 m³ ton⁻¹ for the green, blue and gray components, respectively. We note a difference in blue WF, compared to São Carlos tomatoes. Italian tomatoes consume more water from irrigation than the Brazilian case, where the green component is dominant, indicating a good adaptation to the region. For gray WF, we can see a considerable variation, due to different fertilizer inputs, indicating intensive use of chemicals in this crop (Rinaldi et al., 2006).

Cassava

Figure 6 presents the cassava water footprint results. The total average value was 355.7 m³ ton⁻¹, lower than the world average, 564 m³ ton⁻¹ and well bellow of the maximum value observed around the globe (4412 m³ ton⁻¹) (Mekonnen & Hoekstra, 2011). Considering national and regional results in the global study, we observe similarity with our results in green and grey components, while blue WF remains overestimated.

The growth of crop yield from 15 ton ha⁻¹ in 2012 to 20.4 ton ha⁻¹ in 2013 caused a decrease in WF$_{green}$ from 348.4 to 262.4 m³ ton⁻¹. The green component has the lowest variation compared with the world average (550 m³ ton⁻¹). For the blue water footprint, the world average and the Brazilian average value are minimum, below 1 m³ ton⁻¹. Here, the values remained between 0 m³ ton⁻¹ and 60 m³ ton⁻¹, which indicates more dependency of irrigation and a lack of enough rainfall for this culture, when compared to other regions (like Amazon in Brazil, where the blue component is zero). The gray water footprint values (average of 18.0 m³ ton⁻¹) were similar to the global mean value (13 m³ ton⁻¹), Brazilian mean value (17 m³ ton⁻¹) and SP state mean value (14 m³ ton⁻¹).

Kongboon & Sampattagul (2012) analyzed this crop production in Northern Thailand. They found average values of 192, 232 and 85 m³ ton⁻¹ for the green, blue and gray components, respectively. The Thai cassava WF is very close to the global average (Mekonnen & Hoekstra, 2011), regarding the total value, but with larger differences in their components. The blue component is very high and exceeds the green water footprint. In our results, there is a lower irrigation demand. For the gray component, Thai values are bigger than the results found in our study.

Rice

Figure 7 shows the water footprint results for rice. There is intensive use of water resources in rice cultivation, because this crop is heavily dependent on irrigation, with 85% of the world's production being cultivated in flooded lands (Bouman et al., 2007). In 2007, 2008 and 2014, the blue water footprint (2518.5, 2197.5 and 3534.8 m³ ton⁻¹ respectively), exceeded the green water footprint (2186, 2137.5 and 2850.3 m³ ton⁻¹, respectively). In 2014, where the blue water footprint superiority was more evident, the lowest rainfall rate in the area was observed.
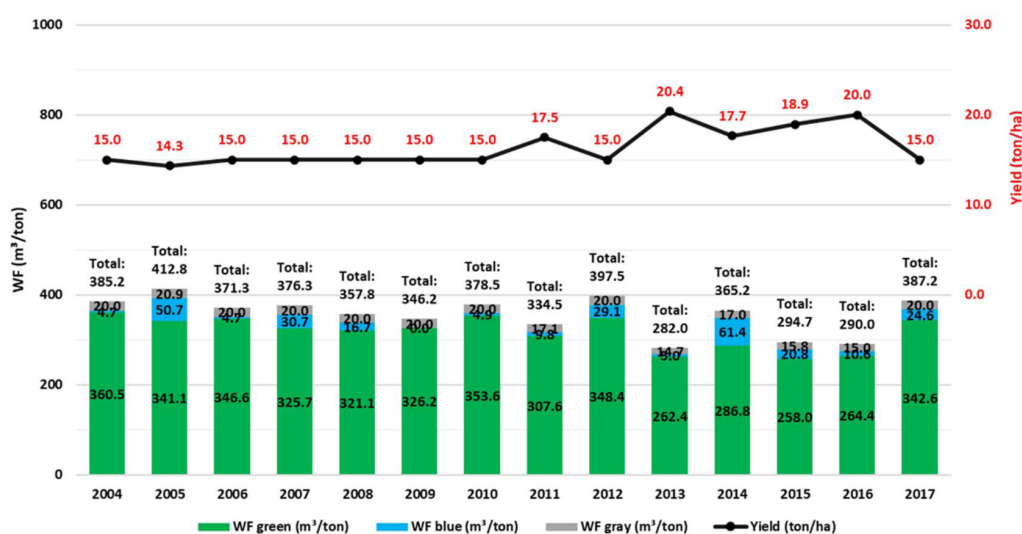

Figure 6. Cassava water footprint, in São Carlos/SP, between 2004 and 2017. The green part of the graph represents the green water footprint (WF$_{green}$), the blue part represents the blue water footprint (WF$_{blue}$) and the gray part represents the gray water footprint (WF$_{gray}$). The sum of the three plots is the total water footprint (WF$_{total}$). The graph also shows the crop yield over the years.

The rice crop presented a low yield in the study area, 2 ton ha⁻¹, close to the national average in the 1980s and 1990s (Empresa Brasileira de Pesquisa Agropecuária, 2019b). Currently, the national average yield approaches 5 to 6 ton ha⁻¹ (Empresa Brasileira de Pesquisa Agropecuária, 2019b). This low productivity can indicate a delay in the use of new methods and technologies in this crop growing, leading to high water footprint values in São Carlos (SP). The green (average of 2546.7 m³ ton⁻¹) and gray (average of 447.9 m³ ton⁻¹) plots were 2 times greater than the global mean values (Mekonnen & Hoekstra, 2011), 1146 m³ ton⁻¹ for WF_{green} and 187 m³ ton⁻¹ for WF_{gray}. Even with high water consumption in the national and regional context, the rice WF values of São Carlos are well below the maximum results observed in the globe (8822, 7405, 2145 and 18372 for WF_{green}, WF_{blue}, WF_{gray} and WF_{total})

Considering Brazilian context, Mekonnen & Hoekstra (2011) found 1943, 356 and 104 m³ ton⁻¹ as averages for WF_{green}, WF_{blue} and WF_{gray}. Chapagain & Hoekstra (2011) conducted a study of the water footprint in the 13 major rice-producing countries, including Brazil. They found 791, 670 and 61 m³ ton⁻¹ as average values for green, blue, and gray water footprints, respectively, in Brazilian plantations. The green and blue components are close to each other, as observed in our study, indicating high crop water demand. According to these results, we can conclude that rice cultivation in São Carlos uses a high amount of water, and is not the most appropriate crop for the region, concerning WF evaluation.

Beans

Figure 8 presents the results for the water footprint for beans. Beans presented an average of 8360.1 m³ ton⁻¹ for the total water footprint, higher than the global mean value, 5053 m³ ton⁻¹, but still below the greatest total values in the globe,
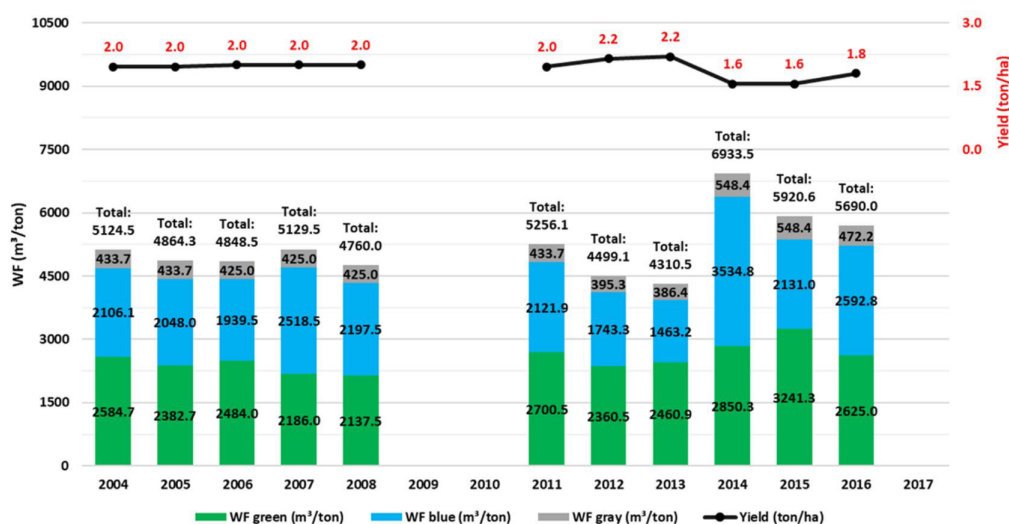

Figure 7. Rice water footprint, in São Carlos/SP, between 2004 and 2017. The green part of the graph represents the green water footprint (WF_{green}), the blue part represents the blue water footprint (WF_{blue}) and the gray part represents the gray water footprint (WF_{gray}). The sum of the three plots is the total water footprint (WF_{total}). The graph also shows the crop yield over the years.
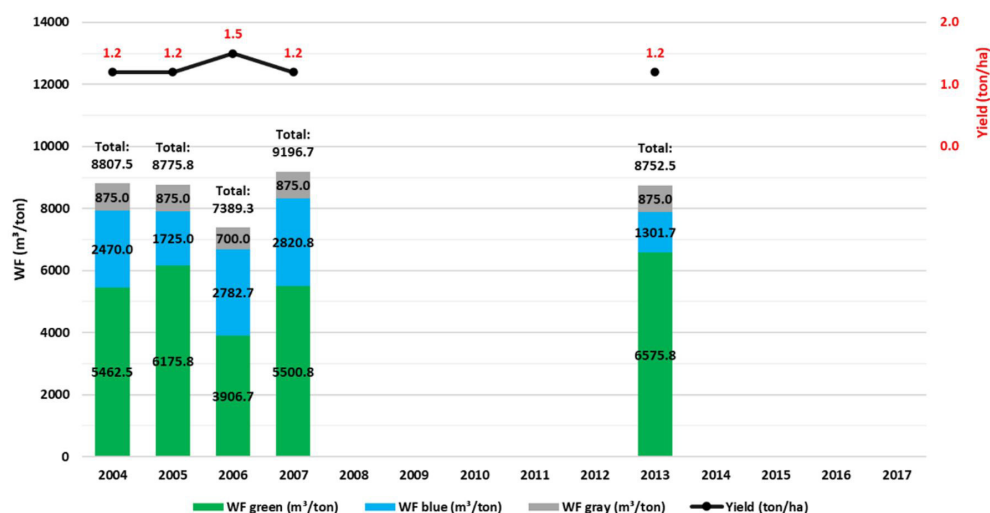

Figure 8. Bean water footprint in São Carlos/SP, between 2004 and 2017. The green part of the graph represents the green water footprint (WF_{green}), the blue part represents the blue water footprint (WF_{blue}) and the gray part represents the gray water footprint (WF_{gray}). The sum of the three plots is the total water footprint (WF_{total}). The graph also shows the crop yield over the years.

36392 m³ ton⁻¹ (Mekonnen & Hoekstra, 2011). This crop can be planted and harvested three times in sequence, according to the calendar proposed by Companhia Nacional de Abastecimento (2019a). This fact raises the blue and green water footprint components, because of the water demand during the rainy and dry seasons. The crop yields in São Carlos did not vary significantly, and are close to the national average, according to Companhia Nacional de Abastecimento (2019b), indicating good management and crop adaptation to the local conditions. The most discrepant plot is the blue water footprint, with values above 2000 m³ ton⁻¹, while the world average is only 125 m³ ton⁻¹ and the Brazilian average is approximately 62 m³ ton⁻¹. The green component values present a small difference. The gray water footprint values, an average of 840 m³ ton⁻¹, were lower than the global mean (983 m³ ton⁻¹) in all years.

Lopez & Bautista-Capetillo (2015) determined WF values for beans planted in Mexico. They simulated scenarios with different planting dates and irrigation conditions. Considering an irrigated crop, they obtained values between 2000 and 3500 m³ ton⁻¹ for the sum of green and blue components, varying according to the region where beans are cultivated. Considering global averages as a basis of comparison, Lopez and Bautista-Capetillo (2015) found a similarity in the green WF and a great variation in blue WF, once this component for Mexican beans was 14 times higher than the global averages. The same facts were detected in our study, for these two WF components.

Groundnut

Groundnut water footprint results are shown in Figure 9. It was difficult to find effective conclusions due to the small planting period (2014 and 2015) and the crop productivity variation. This crop is commonly harvested in rotation with other crops, specially sugarcane, with an important role in soil nitrogen fixation (Santos et al., 2009). Despite this, groundnut cultivation was estimated considering two harvests, considering both situations proposed by Companhia Nacional de Abastecimento (2019a). The crop yield values of São Carlos (1.9 ton ha⁻¹ for 2014 and 2.5 ton ha⁻¹ for 2015) are lower than the national average, which is approximately 3.8 ton ha⁻¹ (Companhia Nacional de Abastecimento, 2019b). These two aspects are the main reasons for high water footprint levels. The total water footprint (average of 4147.2 m³ ton⁻¹) was higher than the global mean value, 2728 m³ ton⁻¹, and also higher than the national (2793 m³ ton⁻¹) and subnational (2828 m³ ton⁻¹) results, informed in the global study (Mekonnen & Hoekstra, 2011). Even with high values, São Carlos results are far from the maximum values found in the globe (27154 m³ ton⁻¹)

Bulsink et al. (2010) calculated WF components for primary crops in Indonesia, using data from 2000 to 2004. These authors found, for groundnut, average values of 2962, 162 and 0 m³ ton⁻¹ for the green, blue and gray components, respectively. Green WF was very close to the values calculated in our study, probably because of the climate similarity of both regions. However, blue and gray components presented larger discrepancies, possibly caused by the assumptions of two harvests in the same year and thelow yields observed in São Carlos.

Statistical tests

The results of the Mann-Kendall, Shapiro-Wilk and t-student tests are presented in Table 6. Each row shows a water footprint component (green, blue, gray and total), which are grouped by crop. The results are divided by color: white cells indicate null hypothesis confirmed by the test, and gray cells indicate rejection. In each cell, the correspondent p-value result is also shown.
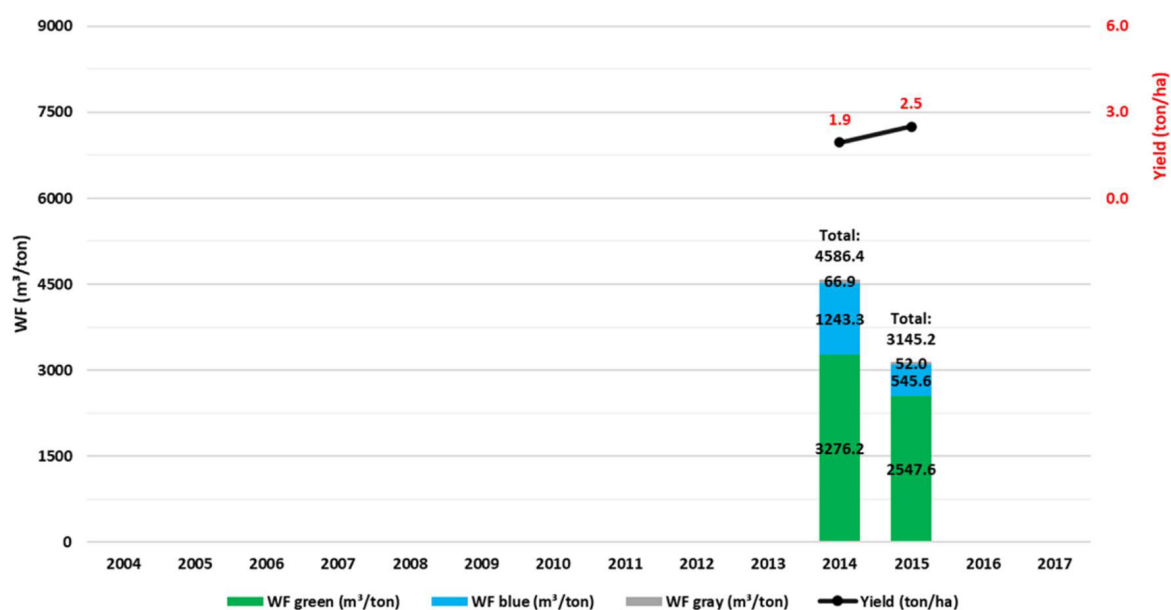

Figure 9. Groundnut water footprint, in São Carlos/SP, between 2004 and 2017. The green part of the graph represents the green water footprint (WF$_{green}$), the blue part represents the blue water footprint (WF$_{blue}$) and the gray part represents the gray water footprint (WF$_{gray}$). The sum of the three plots is the total water footprint (WF$_{total}$). The graph also shows the crop yield over the years.

Table 6. Statistical test results. White cells indicate the null hypothesis confirmed while gray cells indicate the null hypothesis rejected. The p-value results are shown for each WF component.

Crop	WF component	Statistical tests			
		Shapiro-Wilk	Mann-Kendall		T-Student
			Upward trend	Downward trend	
1	Green	> 0.1000	0.1622	0.8377	0.0000
	Blue	> 0.1000	0.4564	0.5436	0.0007
	Gray	> 0.1000	0.3920	0.6080	0.0000
	Total	> 0.1000	0.3712	0.6287	0.0000
2	Green	0.0270	0.7079	0.2920	Not applied
	Blue	> 0.1000	0.9227	0.0773	0.0000
	Gray	> 0.1000	0.8632	0.1368	0.0010
	Total	> 0.1000	0.8632	0.1368	0.0003
3	Green	0.0230	0.6692	0.3307	Not applied
	Blue	> 0.1000	0.4564	0.5436	0.0526
	Gray	< 0.0100	0.6291	0.3709	0.0000
	Total	0.0130	0.6692	0.3307	Not applied
4	Green	> 0.1000	0.7444	0.2556	0.0000
	Blue	> 0.1000	0.9601	0.0399	0.0000
	Gray	0.0270	0.9859	0.0140	Not applied
	Total	0.0340	0.8858	0.1142	Not applied
5	Green	> 0.1000	0.9813	0.0187	0.0000
	Blue	0.0440	0.1622	0.8378	Not applied
	Gray	> 0.1000	0.9910	0.0090	0.0000
	Total	> 0.1000	0.9601	0.0399	0.0000
6	Green	> 0.1000			0.0000
	Blue	0.0550	Not applied		0.0000
	Gray	> 0.1000			0.0000
	Total	> 0.1000			0.0000
7	Green	> 0.1000			0.0260
	Blue	> 0.1000	Not applied		0.0020
	Gray	> 0.1000			0.0000
	Total	0.0420			Not applied

Crops: 1 = Sugarcane; 2 = Maize; 3 = Soybean; 4 = Tomato; 5 = Cassava; 6 = Rice; 7 = Beans.

For the Shapiro-Wilk, with a significance level of 5%, we observe the null hypothesis dominating the statistical test evaluation. From 28 water footprint components verified, 20 were confirmed as a sample of a normal population, with high p-values. We see different behavior in some WF components in maize (green), soybeans (green, gray and total), tomato (gray and total), cassava (blue) and beans (total), probably caused by local conditions. Considering this prevalence in the samples analyzed, we can accept a normality assumption for water footprint components. In this sense, this distribution can be used to predict the water footprint values of different cultures. A longer WF data series, considering local and global levels, could ensure this conclusion to all temporary crops.

Using the t-student test, applied in 21 WF components, with a significance level of 5%, we observe that the null hypothesis was rejected in 19. This indicates that most of the average results of our study are significantly different from global mean values defined by Mekonnen & Hoekstra (2011). It makes clear how the water footprint can vary from a regional scale (sample) to a global mean value (population) (Brauman et al., 2013; Mekonnen & Hoekstra, 2014). The difference between the study periods should also be considered in these results.

The results of the ANOVA and Tukey test were resumed in Table 5. In the same column, identical lower-case letters indicate no significant difference between the mean values of WF components, according to these tests. We note that the sugarcane, cassava and tomato crops showed a similarity in all WF components. These crops formed a group of low water use in this region, according to our results. Isolated similarities were found in each WF component, but we cannot make further conclusions on these results.

Considering the Mann-Kendall test results (Table 6), we observe the null hypothesis confirmation predominance.

From 20 WF components verified by the test, 15 presented no monotonic trend, with a significance level of 5%. The exceptions were the blue and gray WF component of tomato; and blue, green and gray for cassava, all of them with a downward trend.

These results show how this indicator varies over time, in general, with no monotonic trend. This can be explained by the number of variables involved in calculating the water footprint and how they may change over time. Examples are human decisions linked to agricultural management and crop implementation, or climate variations, whose data are inserted into the CROPWAT model (Zhuo et al., 2014). All these variables input a high uncertainty in the WF calculation, which can reach values above 20% (Zhuo et al., 2014; Elliott et al., 2014). Thus, it is difficult to expect a monotonic trend in this water use indicator.

Correlation coefficients

Table 7 summarizes the linear correlation coefficients, calculated between each WF component and the yields of each crop analyzed. As expected, the majority of the values are negative, as the yields are inversely proportional to WF components (Equations 1, 2, and 3). An exception was the relation of WF blue and beans yields. However, this result is not representative, once this crop yields changed only one time over the years (1.2 ton ha^{-1} in four of the five years analyzed), while WF_{blue} varied in a range of 1307.1 to 2820.8 m^3 ton^{-1}. This outlier in yield data causes an interpretation problem in this result. Also, for this crop, we have few results that not allow many conclusions of this behavior. The same is valid for groundnut, where all coefficients were -1, because of the low amount of data (only 2 years).

Considering the coefficients between crop yields, WF_{green} and, WF_{gray}, we can see how elevated yields are important to reduce these components. In both cases, six out of eight crops presented correlation coefficients from -0.75 to -1, which indicate a strong negative relationship between the two variables correlated. In general lines, for WF_{green}, this correlation result can indicate that the crop is well adapted to the local rainfall regime. For WF_{gray}, this strong negative correlation can indicate that yield is not of additional fertilizer use. Thus, natural conditions are favorable for these temporary crops in São Carlos. Nevertheless, it is important to compare WF results with other regions to confirm these evidences and to completely observe how good is the use of water in a region.

For the correlation coefficients between yields and WF_{blue}, six out of eight crops have correlation coefficients less than -0.5, resulting in a weak negative relationship between the variables. Possibly, more irrigation can be a favorable factor to raise yield rates for some temporary crops, once the coefficients values tend to be close or bigger than to zero. Also, using optimal development conditions, with no water restriction, the blue components values were overestimated, what approximated the coefficients values to zero, far from the tendency expected.

CONCLUSIONS

Here, we presented water footprint values of the temporary crops, produced in São Carlos, Brazil, between 2004 and 2017. This study was developed considering two aspects: a lack of water footprint studies in Brazil at a municipal level; and the absence of WF temporal evaluation, regarding data behavior and disparity causes.

Considering the crops evaluated in this study, sugarcane, a predominant crop in São Paulo state, presented low water footprint total average values (166.2 m^3 ton^{-1}) when compared to the literature, because of the high local yield, and good adaptation in the region. Tomatoes showed good results compared to the global values in all the years evaluated. This indicates that sugarcane and tomatoes are favorable for cultivation in the São Carlos region. On the other hand, rice and groundnut crops demonstrate high water footprint variations, compared to world averages. This may indicate the inadequacy of these crops in the region.

In general terms, the statistical tests show that WF components do not follow a monotonic trend, either upward or downward. The tests also indicated that data can follow a normal distribution, and the results from local studies can be significantly different from global values. Correlation coefficients between yields and each water footprint components were strongly negative for WF_{green} and WF_{gray}, indicating that the crop productivity is important to reduce the water use in these components and also that the natural conditions are favorable to the reduction of these components. The behavior for WF_{blue} was not the same, probably because of the less important influence of irrigation in crop yield and also because of modeling assumptions (no water restriction).

These conclusions can be useful for future studies. First, they emphasize the importance of WF evaluation at the municipality, using local data, when available, as global values cannot be effective to represent all regions. Also, stochastic simulations and future

Table 7. Correlation coefficients between water footprint components and crop yield.

Crop	$\rho\left(\mathbf{WF_{green}}\, x\gamma\right)$	$\rho\left(\mathbf{WF_{blue}}\, x\gamma\right)$	$\rho\left(\mathbf{WF_{gray}}\, x\gamma\right)$	$\rho\left(\mathbf{WF_{total}}\, x\gamma\right)$
1. Sugarcane	-0.1791	-0.3779	-0.9998	-0.6924
2. Maize	-0.9260	-0.6762	-0.9445	-0.9250
3. Soybeans	-0.9202	-0.4496	-0.9592	-0.9409
4. Tomato	-0.5618	-0.2873	-0.4544	-0.4938
5. Cassava	-0.9328	-0.1027	-0.9974	-0.9091
6. Rice	-0.7767	-0.7372	-0.9947	-0.9360
7. Beans	-0.8877	+0.4652	-1.0000	-0.9648
8. Groundnut	-1.0000	-1.0000	-1.0000	-1.0000

WF_{green}: green water footprint; WF_{blue}: blue water footprint; WF_{gray}: gray water footprint; γ: crop yield.

previsions can be made, considering the statistical distribution we confirmed in this study.

The WF values may contain uncertainties because of the assumptions that are made. So, it is important to analyze the results carefully. In our study, we noted that the use of CROPWAT model, with an optimal development condition, can overestimate WF_{blue}, being a source of bias for this component. But this approach can be useful for a first approximation in areas with no detailed information about irrigation schedule. We also point out uncertainties linked to crop variables, which can change according to the geographic, economic and cultural aspects. Some examples are the choices made by farmers, which are linked to agricultural crop management, new methods and technology applications and possible market opportunities (i.e. good prices). All these factors can influence the type of crop that will be planted in a region, and consequently, the water use.

Water footprint estimation can be important to evaluate the water used by agriculture, considering water and food security aspects. These values can be used as indicators for the conservation and conscious use of water resources. We expect to encourage another WF studies in Brazil, at local scale, as this concept is not properly explored in our country. Finally, the results from this study could be used as a first reference for other studies in regions with similar characteristics, in terms of climate and crops produced.

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