Australian Journal of Crop Science AJCS

AJCS 13(07):1203-1210 (2019) ISSN:1835-2707
doi: 10.21475/ajcs.19.13.07.p1832

The water footprint of the sugarcane agro-industry in the Northeast region of Brazil

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Abstract

The water footprint (WF) is an important indicator for water management, as it identifies the amount of water used directly and indirectly by a consumer or a product. The objective of this study is to analyze the sugarcane industry's WF in Brazil's Northeast region for the 2016/17 and 2017/18 harvest seasons. The blue, green and grey WFs of sugarcane were quantified, as well as the blue WFs of the production processes of ethanol and sugar, the main subproducts of sugarcane for both harvests. The work was carried out in an area with 18.42 hectares of sugarcane crops under sprinkler irrigation. The process of sugarcane production and use of pesticides was surveyed and meteorological data for the production period was collected. Right after, mathematical models were used to estimate the blue, green and grey WFs. The WF of the sugarcane was found to be 2,364.87 $m^3\ t^{-1}$ and 1,043.92 $m^3\ t^{-1}$ for the first and second harvest, respectively. The grey WF made up the largest part of this value, mostly due to use of the pesticides Diuron 800 and Imazapic. The processes of ethanol and sugar production, meanwhile, were found to have a blue WF of approximately 10 $m^3\ t^{-1}$ and 5 $m^3\ t^{-1}$, respectively. From these results, we can conclude that the WF is an effective indicator for monitoring water use in the production cycle of sugarcane and its subproducts, and that the use of fewer polluting pesticides would aid in reducing the WF of this cycle.

Keywords: agricultural product; ethanol; pesticides; sugar; water resources.

Abbreviations: AR_application rate per hectare of pesticides in the field (t ha^{-1}); ARCP_Application rate of the commercial product per area; cdp_crop development period; C_{max}_maximum allowable concentration (t m^{-3}); C_{nat}_natural concentration of the pollutant (t m^{-3}); CWU_{blue}_the blue component in crop water use($m^3\ ha^{-1}$); CWU_{green}_the green component in crop water use ($m^3\ ha^{-1}$); ET_{blue}_blue water evapotranspiration (mm day^{-1}); ET_{green}_green water evapotranspiration (mm day^{-1}); ET_0_reference evapotranspiration; e_s_saturation vapor pressure; e_a_actual vapor pressure; G_heat flow in the soil; K_c _crop coefficient; L_pollutant load (t); NA_number of applications; PC_product concentration; P_{eff} _Effective precipitation; Rn_net radiation on crop surface; T_daily average air temperature; TAR _total application rate of the substance for 1 hectare; WF_water footprint; WF_{blue} _blue water footprint; WF_{green}_green water footprint; WF_{grey}_grey water footprint; Y_ crop yield (t/ha); β_10 = conversion factor from mm of water to ($m^3\ ha^{-1}$); α_leaching/runoff fraction; u_2 _wind speed (daily average) at 2 m height; Δ_ slope of the saturation vapor pressure curve; γ_psychrometric factor.

Introduction

Sugarcane (*Saccharum officinarum* L) plays a major role in the agribusiness of Brazil, which is the largest sugarcane producer in the world. The country's Northeast region, and the states of Alagoas and Pernambuco in particular, has the potential to develop a sugar-ethanol industry given the availability of areas for expansion and the favorable solar radiation found in the region (Andrade Junior et al., 2017). Pernambuco produced 10.82 million tons of sugarcane in the 2017/18 season, making the state the second largest producer in Brazil's Northeast (Conab, 2018). Due to the low amount of cumulative rainfall this region receives, irrigation management is required in sugarcane crop development to compensate for the hydric deficit, which, according to Doorenbos and Kassam (1994), may demand up to 2,500 mm of water uniformly distributed throughout the growing season.

The high demand for agricultural products, coupled with economic and population growth, motivates an increased overall use of water that can cause scarcity of local water resources (Gerbens-Leenes and Hoekstra, 2009; Fraiture and Wichelns, 2010). To improve the overall efficiency of agricultural operations, it is therefore highly important that the flow of this natural resource's consumption be understood and monitored using indicators of water resource consumption.

Developed by Arjen Hoekstra in 2002, the concept of the water footprint (WF) is a multidimensional indicator of water use that was introduced to measure the extent of human appropriation of freshwater throughout the world (Hoekstra and Hung, 2002). Conceived of as the total volume of water used along a production chain, WF measurements of crops are used as a basis for further estimates of the WFs of agricultural products and other products derived from them

(Chenoweth et al., 2014). To differentiate between volumes of water appropriated from different water sources, the WF is divided into three components: blue, green and grey. Hoekstra et al. (2011) define the blue WF of a product as the volume of water (surface or subsurface) consumed in its production; in agriculture, this measurement corresponds to the water used in irrigation. The green component of WF, meanwhile, is defined as the volume of rainwater consumed, and the grey component as the volume of water required to dilute chemical products to acceptable concentrations according to existing water quality standards.

Determining the amount of water consumed in the production of sugarcane, as well as in the production of its main subproducts, ethanol and cane sugar, is highly relevant to the elaboration of formal policies that ensure sustainablity. Taking into account the the importance of the sugarcane crop for agribusiness in the Brazilian Northeast and of WF measures for proper water management, the main objective of this study is to calculate the WF of the sugarcane agro-industry in the Brazilian state of Pernambuco based on measurements of the WF of sugarcane and its subproducts.

Results and discussion

Water footprint of sugarcane

In the first growing season (2016/17), 2,664.94 mm of evapotranspiration and 889.80 mm of total precipitation were measured, with 2,032.07 mm of evapotranspiration and 884.20 mm of total precipitation being measured in the second season (2017/18). The measured values of each component of the WF for sugarcane are presented in m³ t^{-1} in Fig. 1. It is worth noting that the total WF of the sugarcane grown in the first season, (2,364.87 m³ t^{-1}) is higher than that of the sugarcane grown in the second season (1,043.92 m³ t^{-1}). This difference is due to fact that different pesticides were used from one season to another, causing the grey WF of the crop to be significantly higher in the first season than in the second.

A product's green WF increases as its blue WF decreases, a tendency observed between the first and second seasons. With precipitation being almost equal from one season to next, the longer period of cultivation and higher amount of evapotranspiration observed in the first season resulted in a greater consumption of blue water and higher blue WF. Hoekstra et al. (2011) note that the loss of water through evaporation, the return of water to another basin or to the sea, or simply the use of water in the product can all contribute to blue water consumption.

The total WF of the sugarcane crop decreased by 55.86% from the first to the second season. In both seasons, the grey WF was the largest component of the total WF and the green WF the smallest (Fig. 2).

Water footprints vary according to the crop, season and region in which the crop is grown (Gobin et al., 2017), as well as other conditions of production such as water use efficiency, the production site and the duration of the production process. Studies of a single product will therefore generate different WF results when the product is cultivated in a different region or under different conditions of production.

Kongboon and Sampattagul (2012) measured the WF of sugarcane cultivated in multiple provinces in Thailand, and found that in each location the WF values were different. Overall, the average blue, green and grey WFs of each crop were 87, 90 and 25 m³ t^{-1}, respectively. In a study of the WF for water basins located in São Paulo, Scarpare et al. (2015) found the blue, green and grey WFs of sugarcane to be 38, 145 and 18 m³ t^{-1}, respectively. Silva et al. (2015), meanwhile, yielded results of 107.39, 119.56 and 9.00 m³ t^{-1}, respectively, for the blue, green and grey WFs of sugarcane grown in the state of Paraíba using the CropWat model. These latter authors also found that in treatment with irrigation at 100% evapotranspiration, the blue WF (measured at 97.71 m³ t^{-1}) was higher than the green WF (50.24 m³ t^{-1}). In the present study, the blue WF was also observed to be higher than the green WF, as water requirements were met in the field by irrigation.

Mekonnen and Hoekstra (2011) calculated the global average values for the blue, green, grey and total water footprints of sugarcane to be 57, 139, 13 and 210 m³ t^{-1}, respectively. The total WF calculated by these authors is lower than that found in the present study, mainly because these authors considered only the use of nitrogen in their calculations, a less critical pollutant than pesticides, the use of which in the present study led to relatively high grey WF and total WF values.

Most studies concerning the WF of sugarcane yield a lower value of grey WF than that found in the present study, because the former tend to consider only the effects of pollutants already present in the environment and not the effects of pesticide use. Matos et al. (2017), in a study of the WF of onion crops, found onion's grey WF to be 75,078.8 m³ t^{-1} in the semi-arid region of Brazil where the pesticide Dicarzol 500PS was used. Boff (2016) found that the grey WF of soybean cultivation 7651 m³ t^{-1} when the herbicide 2,4-D was introduced.

The main pesticides used in the cultivation of sugarcane in the present study, and their application rates per hectare, are presented in Tables 1 and 2.

Among these substances, the herbicide Glyphosate had the highest application rate in both growing seasons. This pesticide is classified as highly toxic (Class II) and harmful to the environment (Class III). According to Orgeron et al. (2017), it is commonly applied before a sugarcane harvest to improve the sucrose levels of the crop.

Calculations for the grey water footprint of each pesticide in m³ can be seen in Tables 3 and 4. These values are calculated based on the leaching/runoff fraction (α), the total application rate of the substance for 1 hectare (TAR), the pollutant load (L) and the maximum allowable concentration of the pesticide(C_{max}).

In the first season, as Table 3 indicates, Diuron 800 was the pesticide with the highest WF. Thus, with the average yield being 97.79 t ha^{-1} of the sugarcane for the studied area, the WF of 1 ha of sugarcane was therefore 2,039.48 m³ t^{-1}. In the second season, meanwhile, Table 4 shows Imazapic to have had the highest WF; with an average yield of 91.03 t ha^{-1} of the sugarcane, the WF for the exploitation of 1 ha was found to be 785.53 m³ t^{-1}. These WF values correspond to the most critical pollutants in each season, which, according to Hoekstra et al. (2011), are those that generate the greatest volume of polluted water.

Table 1. Application rate of the pesticides used in the sugarcane crop in the 2016/17 season.

Pesticides	ARCP	Unit	PC	Unit	NA	Application rate of the substance (t ha^{-1})
1	2	3	4	5	6	7=(2x4x6) x10^{-6}
2,4 D	0.66	(L ha^{-1})	806	(g L^{-1})	1	0.00053
Ametryn	1.97		500		1	0.00099
Diuron 500	1.8		500		1	0.0009
Ethiprole	1		200		1	0.0002
Glyphosate	2.64		648		1	0.00171
Metribuzin 480	1.68		480		1	0.00081
MSMA	1.48		790		1	0.00117
Paraquat dichloride	0.87		200		1	0.00017
Tebuthiuron	1.51		500		1	0.00076
Diuron 468	1.5	(kg ha^{-1})	468	(g kg^{-1})	1	0.0007
Diuron 800	1.15		800		1	0.00092
Hexazinone	1.5		132		1	0.0002
Isoxaflutole	0.13		750		1	0.0001

ARCP = Application rate of the commercial product per area; PC = product concentration; NA= number of applications.

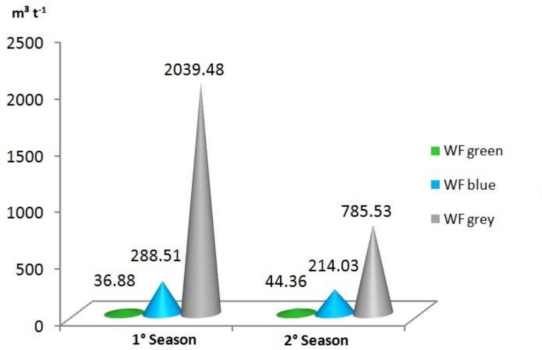

Fig 1. Blue, green and grey water footprint for sugarcane, in m^3 t^{-1}, in the first and second seasons.

Table 2. Application rate of the pesticides used in the sugarcane crop in the 2017/2018 season.

Pesticides	ARCP	Unit	PC	Unit	NA	Application rate of the substance (t ha^{-1})
1	2	3	4	5	6	7=(2x4x6) x10^{-6}
2,4 D	0.79	(L ha^{-1})	806	(g L^{-1})	1	0.00064
Ametryn	2.02		500		1	0.00101
Glyphosate	2.62		648		1	0.0017
Metribuzin 480	1.97		480		1	0.00095
Paraquat dichloride	0.97		200		1	0.00019
Picloram	0.37		388		1	0.00014
Imazapic	0.17	(kg ha^{-1})	700	(g kg^{-1})	1	0.00012
Isoxaflutole	0.13		750		1	0.0001
Metribuzin 700	1.5		700		1	0.00105

ARCP = Application rate of the commercial product per area; PC = product concentration; NA= number of applications.

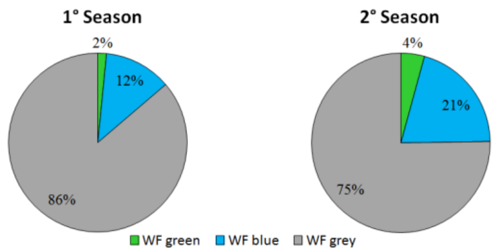

Fig 2. Percentage contribution of blue, green and grey components to the total water footprint in sugarcane cultivation for the 2016/17 and 2017/18 seasons

Table 3. Grey water footprint of the pesticides used in the sugarcane crop in the 2016/2017 season.

Pesticides	α	TAR (t)	L (t)	Cmax (t m^{-3})	WFGrey (m^3)
1	2	3	(4=2x3)	5	(6=4/5)
2,4 D	0.0467	0.00053	2.50E-05	4.00E-09	6211.08
Ametryn	0.0484	0.00099	4.80E-05	6.00E-08	793.77
Diuron 468	0.0434	0.0007	3.00E-05	2.00E-10	152182.02
Diuron 500	0.0434	0.0009	3.90E-05	2.00E-10	195105.15
Diuron 800	0.0434	0.00092	4.00E-05	2.00E-10	199440.82
Ethiprole	0.0517	0.0002	1.00E-05	1.00E-10	103496.6
Glyphosate	0.0317	0.00171	5.40E-05	6.50E-08	833.47
Hexazinone	0.0601	0.0002	1.20E-05	6.00E-07	19.83
Isoxaflutole	0.0401	0.0001	3.90E-06	1.00E-10	39107.2
Metribuzin 480	0.0517	0.00081	4.20E-05	1.00E-09	41729.83
MSMA	0.0467	0.00117	5.50E-05	1.00E-08	5460.56
Paraquat dichloride	0.0467	0.00017	8.10E-06	4.00E-08	203.16
Tebuthiuron	0.0601	0.00076	4.50E-05	1.60E-09	28354.95

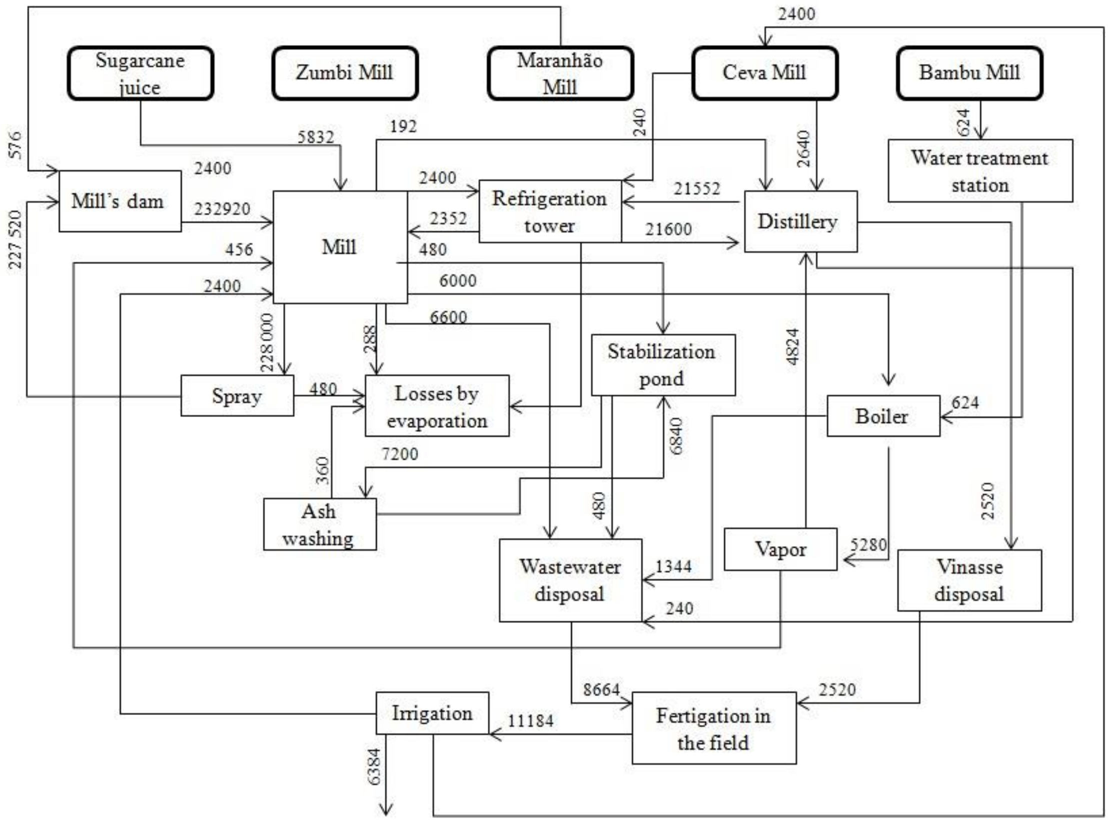

Fig 3. Flowchart of water use in the sugarcane mill, with values in m³ day^{-1}.

Table 4. Grey water footprint of the pesticides used in the sugarcane crop in the 2017/2018 season.

Pesticides	α	TAR (t)	L (t)	Cmax (t m^{-3})	WFGrey (m^3)
1	2	3	(4=2x3)	5	(6=4/5)
2,4 D	0.0467	0.00064	3.00E-05	4.00E-09	7434.47
Ametryn	0.0484	0.00101	4.90E-05	6.00E-08	813.92
Paraquat dichloride	0.0467	0.00019	9.10E-06	4.00E-08	226.51
Glyphosate	0.0317	0.0017	5.40E-05	8.00E-07	67.21
Imazapic	0.0601	0.00012	7.20E-06	1.00E-10	71507.04
Isoxaflutole	0.0401	0.0001	3.90E-06	1.00E-10	39107.2
Metribuzin 480	0.0517	0.00095	4.90E-05	1.00E-09	48933.19
Metribuzin 700	0.0517	0.00105	5.40E-05	1.00E-09	54335.72
Picloram	0.0634	0.00014	9.10E-06	2.90E-08	314.03

Despite having relatively high grey WF values, the Diurom 800 and Imazapic were not the ones with the highest application rates, as might be expected. Rather, the high grey WF values of Diuron 800 and Imazapic resulted mainly from the pesticides having low C_{max} values and high leaching/runoff fractions.

Water footprint for ethanol production

In the 2016/17 season, the average ethanol yield of 1 ton of sugarcane was 86.82 L. As 10,000 tons of sugarcane were crushed each day by the mill, the daily production of ethanol was thus 868,200 L. Since the daily water consumption of the mill is 6,480 m³, as described in item "water footprint of the ethanol and sugar production process", the WF of ethanol production, is 7.46 L of water/L of ethanol, expressed as the volume of water consumed divided by the volume of the ethanol produced.
The WF for ethanol production can also be calculated in $m^3\ t^{-1}$. With the density of ethanol being 0.789 kg L^{-1} and 868,200 L of ethanol being produced per day, the mass of ethanol that was being produced daily was 685 t. The WF for ethanol production in $m^3\ t^{-1}$, calculated as the volume of water consumed divided by the mass of ethanol produced over the corresponding time period, is therefore equal to 9.46 $m^3\ t^{-1}$.
In the 2017/18 season, the average yield of 1 ton of sugarcane was 79.45 L of ethanol. The daily production of ethanol was therefore equal to 794,500 L, with the WF for ethanol production totaling 8.16 L of water/L of ethanol, or 10.34 $m^3\ t^{-1}$.

Water footprint of sugar production

The yield of sugar from 1 ton of sugarcane was 141.53 kg in the first growing season. With 10,000 tons of sugarcane crushed per day, the daily production of sugar equaled 1,415.3 t. Calculated as the 6,480 m³ of water consumed daily by the mill each day divided by the daily mass of sugar produced, the WF of the first season's sugar production is determined to have been 4.58 $m^3\ t^{-1}$. With a yield of 132.44 kg of sugar per ton of sugarcane in the second season, the daily mass of sugar produced was 1324.4 t, making the WF for sugar production 4.89 $m^3\ t^{-1}$.
After calculating the WF of the products derived from the sugarcane, the WF of ethanol production is thus demonstrated to have been higher than that of sugar production.

Total water footprint of ethanol and sugar

The total WF of ethanol in the first season is calculated as the sum of the 9.46 $m^3\ t^{-1}$ consumed simply in its production and the 2,364.87 $m^3\ t^{-1}$ consumed in the production of the sugarcane; this results in a total WF of 2,374.33 $m^3\ t^{-1}$, or, expressed in terms of volumes, 1,873.35 L of water/L of ethanol (comprised of 235.10 L of blue water, 29.10 L of green water and 1,609.15 L of grey water per L of ethanol).
In the second season, the total WF of ethanol was found to be 1,054.26 $m^3\ t^{-1}$ calculated as the sum of the WF of the ethanol's production, 10.34 $m^3\ t^{-1}$, and the WF of the sugarcane's production, 1,043.92 $m^3\ t^{-1}$, or, in terms of volumes, 831.81 L of water/L of ethanol (comprised of 177.03 L of blue water, 35.00 L of green water and 619.78 L of grey water per L of ethanol).
The total WF of sugar in the first season was 2,369.45 $m^3\ t^{-1}$, calculated as the sum of the WF of the sugar's production, 4.58 $m^3\ t^{-1}$, and that of the production of the sugarcane, 2,364.87 $m^3\ t^{-1}$. In the second season, the WF of the sugar was 1,048.81 $m^3\ t^{-1}$,or the sum of the WF of its production, 4.89 $m^3\ t^{-1}$, and the WF of the sugarcane, 1,043.92 $m^3\ t^{-1}$.
The values of 1,873.35 L L^{-1} and 831.81 L L^{-1} calculated for the WF of ethanol were lower than the global average found by Mekonnen and Hoekstra (2011), which was 2,107 L L^{-1} (comprised of a blue WF of 575 L L^{-1}, green WF of 1,400 L L^{-1} and grey WF of 132 L L^{-1}). These values were also lower than the global average value and the average value for Brazil determined by Gerbens-Leens and Hoekstra (2009), which were 2,855 L L^{-1} and 2,450 L L^{-1}, respectively.
In a study by Santiago et al. (2017) of the state of Alagoas in Northeast Brazil, the WF of ethanol was found to be approximately 2,002 L L^{-1} (with a blue WF of 63 L L^{-1}, a green WF of 1,154 L.L^{-1} and a grey WF of 785 L L^{-1}), with the same irrigation system (sprinkler) being used as in the present study. Meanwhile, Chico et al. (2015), also researching in Alagoas, found the WF of ethanol to be 1,229 L L^{-1}; their study did not measure the grey components, however.
It is notable that most of the studies presented above calculated the total WF of ethanol to be higher than the value calculated in the present study. Meanwhile, the grey WFs established by Mekonnen and Hoekstra (2011) and Santiago et al. (2017) were lower than those in the present study because these authors considered only the leaching of nitrogen as contributing to the grey WF, disregarding pesticides, which are the more critical pollutants.
The average of the values derived for the total WF of sugar in the two seasons adheres closely to the global average of 1,782 $m^3\ t^{-1}$ found by Mekonnen and Hoekstra (2011). In the state of Piauí in Northeast Brazil, meanwhile, Andrade Junior et al. (2012) found the WF of sugar to be 1,493 $m^3\ t^{-1}$.

Materials and methods

Characterization of study area

The study was carried out at the *Usina Central Olho D'Água S/A*, located in the Goiana River basin in the county of Camutanga in Pernambuco. Its specific location is lat. 7°25'7"S, long. 35°16'35"W, and its elevation is 109 m. 18.42 hectares were devoted to the cultivation of the RB867515 variety of sugarcane using sprinkling irrigation.
The regional climate is classified under the Köppen system as the type *As*, featuring warm and wet weather and rains from autumn to winter. The mean relative humidity fluctuated between 75% and 89% during the first growing season and 76% to 91% in the second. As for rainfall, 889.8 mm total fell during the first season and 884.2 mm during the second. Finally, the reference evapotranspiration (denoted by ET_0), was 2,664.94 mm in the first season and 2,032.07 mm in the second.

Execution of the study

Blue, green and grey WFs of sugarcane were calculated for the 2016/17 season (8th cut), on the one hand, which lasted from September 2015 to October 2016 and saw the production of 1801.21 tons of sugarcane, and the 2017/18 season (9th cut) on the other, which lasted from October 2016 to September 2017 and produced 1676.72 tons of sugarcane. In addition, blue WFs were calculated for the main products of the sugarcane agro-industry, ethanol and sugar.

Data concerning sugarcane production and cultivation, including regarding the pesticides used, the ethanol and sugar yields of the crop and the volumes of water consumed by the mill during the production of ethanol and sugar were provided by *Usina Centra Olho D'Água*.

Calculation of the blue and green water footprints of the sugarcane

The green and blue WFs of the sugarcane were quantified using the methodology proposed in the water footprint evaluation manual elaborated by Hoekstra et al. (2011), in which the blue water footprint (denoted below as WF_{blue}), measured in $m^3\ t^{-1}$, is calculated using Eq. 1 below and the green water footprint (denoted below as WF_{green}), measured in $m^3\ t^{-1}$, is calculated using Eq. 2:

$$WF_{blue} = \frac{CWU_{blue}}{Y} = \frac{\beta \sum_{d=1}^{cdp} ET_{blue}}{Y} \quad (1)$$

$$WF_{green} = \frac{CWU_{green}}{Y} = \frac{\beta \sum_{d=1}^{cdp} ET_{green}}{Y} \quad (2)$$

In these equations, CWU_{blue} denotes the blue component of crop water used measured in $m^3\ ha^{-1}$, while CWU_{green} denotes the green component of crop water used in $m^3\ ha^{-1}$; Y denotes the yield of the sugarcane in $t\ ha^{-1}$; ET_{blue} is the measure of blue water evapotranspiration in mm day^{-1} and ET_{green} the measure of green water evapotranspiration in mm day^{-1}; β is a conversion factor set equal to 10 in order to convert mm of water to $m^3\ ha^{-1}$; and cdp denotes the crop development period measured in days.

The measure of blue water evapotranspiration (ET_{blue}) was calculated using Eq. 3 and the measure of green water evapotranspiration (ET_{green}) using Eq. 4, shown below. Effective precipitation (denoted by P_{eff}) was determined following the method of the Soil Conservation Service of the United States Department of Agriculture.

$$ET_{blue} = \max(0, ET_c - P_{eff}) \quad (3)$$

$$ET_{green} = \min(ET_c, P_{eff}) \quad (4)$$

Overall crop evapotranspiration (ET_C) was defined as the product of the reference evapotranspiration (ET_0) measured in mm day^{-1} and the crop coefficient (K_c). The value of ET_0 was established using the Penman-Monteith equation, which is employed by the Food and Agriculture Organization of the United Nations (Allen et al., 1994), and is reproduced below as Eq. 5:

$$ET_0 = \frac{0.408\Delta(Rn-G) + \gamma\frac{900}{T+273}u_2(e_s-e_a)}{\Delta + \gamma(1+0.34u_2)} \quad (5)$$

Here, Rn denotes the measure of net radiation on the crop surface in MJ $m^{-2}\ day^{-1}$; G denotes the measure of heat flow in the soil in MJ $m^2\ day^{-1}$; T is the daily average air temperature in ºC; u_2 is the daily average wind speed at the height of 2 m in m s^{-1}; e_s denotes the saturation vapor pressure and e_a the actual vapor pressure, both in kPa, with $e_s - e_a$ denoting the vapor pressure deficit in kPa; Δ is the slope of the saturation vapor pressure curve in KPa $ºC^{-1}$; and γ is the psychrometric factor given in MJ kg^{-1}.

Data for determining the reference evapotranspiration was obtained from the data collection platform located at the mill of the *Usina Central Olho D'Água S/A*. For the crop coefficient, the average values obtained by Silva et al. (2014) were used, as the conditions of the area treated in their study are similar to those of the area treated in the present study.

Calculation of grey water footprint of the sugarcane

The grey water footprint of the sugarcane (denoted below by WFgrey), measured in m³ t-1, was calculated based on the WFs of the pesticides used in each season as shown in Eq. 6. The WF of sugarcane crop is ultimately equal to the highest WFgrey found among the pesticides used on that crop.

$$WF_{grey} = \frac{\left(\frac{L}{C_{max} - C_{nat}}\right)}{Y} = \frac{\left(\frac{\alpha\ x\ AR}{C_{max} - C_{nat}}\right)}{Y} \quad (6)$$

In this equation, L denotes the pollutant load in t; C_{max} is the maximum allowable concentration of the pesticide in t m^{-3}; C_{nat} is the natural concentration of the pollutant in t m^{-3}; α is the leaching/runoff fraction; AR denotes the application rate of pesticides in the field in t ha^{-1}; and Y denotes the crop yield, measured in t ha^{-1}.

The leaching/runoff fraction (α) was determined for each pesticide following the methodology outlined by Franke et al. (2013). The data used to calculate this fraction was obtained from the Pesticides Properties Database (2018).

The application rate (AR) of each pesticide is calculated by multiplying the amount of the pesticide used in each application by the concentration of pollutants in the pesticide and the number of times the pesticide was used. The maximum allowable concentration for each pesticide was determined according to the Conama Resolution n°357/2005 and other international legislations established by the European Union (Eu, 2013) and the governments of the United States (Epa, 1989) and Canada (Ccme, 2013). The natural concentration of the pollutant was set at zero, as the pollutants found in pesticides do not occur naturally.

Water footprint of the ethanol and sugar production process

The mill at which the sugarcane in this study was processed for the production of ethanol and sugar is powered by water supplied by four dams, namely the Zumbi, the Maranhão, the Ceva and the Bambu. These dams remove 2,400, 576, 2,880 and 624 m³ of water each day, respectively, for use in the mill, totaling 6,480 m³ of water per day, a quantity which permits the mill to crush 10,000 tons of sugarcane. The distribution of this water is depicted in the flowchart presented in Fig. 3.

The WF of the production of the ethanol and sugar was calculated by dividing the total volume of blue water used in the daily production process, or 6480 $m^3\ day^{-1}$, by the volume of ethanol and the mass of sugar, respectively, produced per day. The WF for ethanol production was then converted to m^3 t^{-1} using 0.789 kg L^{-1} as the density of ethanol.

The average yields of ethanol and sugar in the first and second seasons, respectively, were 86.82 L and 79.45 L of ethanol per ton of sugarcane, and 141.53 kg and 132.44 kg of sugar per ton of sugarcane.

The WFs of the ethanol and sugar production process are comprised entirely of the process's blue WF. There was no green WF in this process, given that the green WF corresponds to the consumption of rainwater, which does not occur in the production process in the mill. The grey WF was not analyzed either, as wastewater and vinasse are used in sugarcane fertigation, and since only the most critical pollutant should be taken into account when measuring WF, pesticides were the only pollutants evaluated in the present study, and these had no role in the production of ethanol and sugar.

Total water footprint of ethanol and sugar

The calculation of the total WF of ethanol and sugar took into account the blue, green and grey WFs of the sugarcane's production in m^3 t^{-1} and the blue WF of the production process of ethanol and sugar in m^3 t^{-1}. The WF of ethanol is therefore calculated as the WF of the sugarcane added to the WF of the ethanol production process, with the WF of sugar calculated as the WF of the sugarcane added to the WF of the sugar production process.

The overall sugarcane agro-industry consists of the cultivation of sugarcane crops and the subsequent production of ethanol and sugar from those crops. Its overall WF can therefore be calculated as the sum of the total WF of ethanol and the total WF of sugar.

Conclusion

The concept of a water footprint (WF) serves as a sound basis for decision-making in the management of water resources because it quantifies the direct and indirect water consumption associated with a product along its entire production chain. In this study, the WF of sugarcane cultivated in the state of Pernambuco was found to be 2361.87 m^3 t^{-1} and 1043.92 m^3 t^{-1} for the 2016/17 and 2017/18 growing seasons, respectively. The grey component comprised the largest part of the crops' WFs, representing 86% and 75% of the WF of the sugarcane grown in each respective season, as a result of the use of the pesticides Diuron 800 and Imazapic. The WFs of the processes of ethanol and sugar production, the other main activities of the sugarcane agro-industry, were also calculated, and ethanol production was found to entail higher water consumption than the production of sugar. These results ultimately demonstrate how measuring the water footprint of the operations of the sugarcane agro-industry can allow us to identify where in the production chain the largest amounts of water are being consumed and which conditions are most favourable to the industry's sustainability.

Acknowledgements

Thank CAPES and Usina Central Olho D'Água by aid for the research

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