



## Water scarcity footprint of cocoa irrigation in Bahia

ARTICLES doi:10.4136/ambi-agua.2840

Received: 08 Mar. 2022; Accepted: 13 Jul. 2022

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### ABSTRACT

This study simulated the water scarcity footprint (WSF) of cocoa irrigation in municipalities considered suitable for cocoa growing in the state of Bahia, according to agro climatic zoning. Irrigation demand was calculated using the model proposed by FAO (Food and Agriculture Organization of the United Nations). Subsequently, impact on water scarcity was calculated using the product of crop irrigation demand and water scarcity characterization factors of the regionalized AWARE method for Brazil. The WSF in Bahia ranged between 0.28 and 646.5 m<sup>3</sup> of water per kilo of cocoa produced. From the defined scale, of the 417 municipalities in Bahia suitable for growing cocoa, 59% have a 'low' footprint, 18% 'medium', 10% 'high', and 12% have a 'very high' footprint. Based on these results, it is suggested that areas with lower WSF are a priority in the expansion of cocoa to avoid a possible compromise of other essential demands of the municipalities. In addition, irrigation should avoid waste, especially in regions with high levels of water scarcity. The results show that the inclusion of the WSF in agroclimatic zoning can contribute to the process of identifying potential and critical regions for new crops and the expansion of others.

**Keywords:** agriculture, agroclimatic zoning, AWARE, environmental indicator.

### Pegada de escassez hídrica do cacau irrigado na Bahia

### RESUMO

Este estudo teve como objetivo simular a pegada de escassez hídrica (PEH) da irrigação do cacau a ser produzido nos municípios considerados aptos para o cultivo de cacau no estado da Bahia, de acordo com o zoneamento agroclimático. O modelo proposto pela FAO (Organização das Nações Unidas para a Alimentação e a Agricultura), foi utilizado para calcular



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a demanda de irrigação. Posteriormente, o impacto na escassez hídrica foi calculado através do produto entre a demanda de irrigação da cultura e os fatores de caracterização da escassez hídrica do método AWARE regionalizado para o Brasil. A PEH na Bahia variou entre 0,28 e 646,5 m<sup>3</sup>-eq de água por quilo de cacau produzido. A partir da escala definida, dos 417 municípios baianos aptos para o cultivo de cacau, 59% possui uma PEH ‘baixa’, 18% ‘média’, 10% ‘alta’ e 12% possui uma pegada ‘muito alta’. Com base nestes resultados, sugere-se que as áreas com menor PEH sejam prioritárias na expansão do cacau para evitar um possível comprometimento de outras demandas essenciais dos municípios. Além disso, a irrigação deve evitar desperdícios, principalmente, em regiões com altos índices de escassez de água. Os resultados mostram que a inclusão da PEH em zoneamentos agroclimáticos pode contribuir no processo de identificação de regiões potenciais e críticas para novos cultivos e expansão de outros.

**Palavras-chave:** agricultura, AWARE, indicador ambiental, zoneamento agroclimático.

## 1. INTRODUCTION

Cocoa (*Theobroma cacao* L.) is grown in the humid tropical regions of Africa, Central and South America, and Asia. It is considered one of the most important perennial crops globally, as it is the raw material for chocolate. Brazil has been among the largest cocoa producers in the world for decades, currently occupying the sixth position in the world ranking, with almost 280 thousand tons produced per year (IBGE, 2021).

Production in southern Bahia, which has also been among the largest cocoa producers in the world (AIPC, 2021), is historic for Brazil. The region is considered a traditional cocoa growing area due to soil fertility and favorable climate conditions, contributing strongly to socioeconomic development in the region (Piasentin and Saito, 2014). The challenge for cocoa production lies in the expansion of cocoa farming to other regions, promoting irrigation systems and full-sun farming (Almeida *et al.*, 2014; Babadele, 2018; Begiato *et al.*, 2009; Sodré *et al.*, 2017; SENAR, 2018).

The critical factor in cocoa's productivity is water availability, as the cocoa tree consumes large amounts of water, and is very sensitive to water deficit in the soil (Carr and Lockwood, 2011). Precipitation for the cocoa tree must be greater than 1200 mm per year to be considered fair for production, and ideal rainfall must vary between 1800 to 2500 mm per year. In regions with precipitation below 1200 mm per year, additional irrigation is required (Carr and Lockwood, 2011; SENAR, 2018; Souza *et al.*, 2016).

Despite its importance in guaranteeing production and increasing productivity, irrigation can reduce available water resources, since irrigated agriculture is responsible for the withdrawal of 70% of the world's freshwater (FAO, 2020). In addition to competing with other environmental uses and services, irrigated agriculture is the sector that wastes the most water in Brazil. According to Olivo and Ishiki (2015), 60% of water intended for irrigation is lost due to failures in irrigation channels, application of excess water, and evapotranspiration.

In this context of global water scarcity, tools and methods are required to quantify and adequately address adverse environmental impacts (Boulay *et al.*, 2018). In 2014, the Water Scarcity Footprint (WSF) of products and organizations was recognized as an important environmental management tool, based on the ISO 14046 standard, to assess the potential impacts of products and processes throughout the life cycle in the intensification of water scarcity of a region (ISO, 2014). The assessment of the WSF provides information that can contribute to the identification of critical processes in the life cycle of a product, supporting decision-making on the performance of its processes, combining the efficient use of water, and improving water availability locally (Aldaya *et al.*, 2008).

This study therefore assesses potential water scarcity impact arising from cocoa irrigation in the Bahia region.

## 2. MATERIALS AND METHODS

### 2.1. Definition of the study area

The studied area comprises the 417 municipalities considered suitable for cocoa cultivation, according to the Agro Climatic Zoning of cocoa for the state of Bahia (Brasil, 2011).

### 2.2. Cocoa Irrigation Demand Calculation

Water irrigation demand (WID) for cocoa was estimated based on the FAO methodology (Allen *et al.*, 1998) and expressed considering the actual crop evapotranspiration (ET<sub>c</sub>), the effective precipitation (P<sub>ef</sub>) and the irrigation system efficiency (Equation 1). ET<sub>c</sub> parameter indicates the amount of water (mm) needed by the plant in a given period to develop correctly. It was assumed that the irrigation requirement is equal to the crop evapotranspiration (ET<sub>c</sub>) when the P<sub>ef</sub> is zero and equal to the difference between the ET<sub>c</sub> and the P<sub>ef</sub> when the P<sub>ef</sub> is different from zero. The WID was divided by the efficiency of the drip irrigation system, assumed to be 95% according to the National Water Agency (ANA) manual (ANA, 2019). Drip irrigation is the main irrigation system used in Bahia for cocoa irrigation (Brasil, 2011).

$$WID = \frac{(ET_c - P_{ef})}{Efficiency} \quad (1)$$

ET<sub>c</sub> is obtained by the product between the reference evapotranspiration (ET<sub>o</sub>) and the crop coefficient (k<sub>c</sub>) (Equation 2). ET<sub>o</sub> indicates the water requirement (mm) for a reference crop. ET<sub>o</sub> data were obtained by the Penman-Monteith equation (Allen *et al.*, 1998), collected in the WorldClim 2 database (Fick and Hijmans, 2017). The factor k<sub>c</sub> is related to crop characteristics and varies over the growing period (Allen *et al.*, 1998). Given the need for this coefficient and its difficult calculation, FAO provides a table of coefficients for each stage of different crops (Allen *et al.*, 1998).

$$ET_c = ET_o \times k_c \quad (2)$$

According to FAO (Allen *et al.*, 1998), the k<sub>c</sub> coefficient for cocoa is 1 for the vegetative growth phase, formation of new shoots and leaves on the plants, and 1.05 in the second year, when the plant's vegetative development takes place. From the third year onwards, during flowering and fruit development, the value of k<sub>c</sub> is also 1.05. To calculate the WID, the stage of total cocoa production was considered for all municipalities; therefore, k<sub>c</sub> was equal to 1.05.

Finally, to calculate the effective precipitation for each region, the method of the United States Department of Agriculture's Soil Conservation Service (USDA, 1970), based on total precipitation (P<sub>total</sub>) was used, as suggested by the FAO (Equations 3 and 4).

$$P_{ef} = \frac{(P_{total} \times (125 - 0.2))}{125}, \text{ when } P_{total} < 250 \text{ mm} \quad (3)$$

$$P_{ef} = 125 + (0.1 \times P_{total}), \text{ when } P_{total} \geq 250 \text{ mm} \quad (4)$$

### 2.3. Calculation of the WSF of cocoa irrigation in Bahia

An average life cycle of 25 years and average productivity of 2,500 kg ha<sup>-1</sup> was assumed to calculate the WSF. The WDI per kilogram of cocoa per month was multiplied by the monthly characterization factors (CFs, expressed in m<sup>3</sup>-eq) from Andrade *et al.* (2019). Andrade *et al.* (2019) regionalized the AWARE method (Boulay *et al.*, 2018) for Brazilian state hydrographic units (SHU) using national data from ANA. FSM results were expressed in m<sup>3</sup>-eq kg<sup>-1</sup> of cocoa.

The AWARE method was recommended by the United Nations Environment Program (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC) to assess impacts related to water scarcity in Life Cycle Assessment (LCA) studies of products and processes (UNEP/SETAC, 2016). AWARE assesses the potential for water deprivation for humans and aquatic ecosystems, considering that the lower the availability of water in a given region, the greater the likelihood of water scarcity (Boulay *et al.*, 2018).

AWARE provides characterization factors (CFs) - a ratio applied to translate water consumption to a potential impact on water scarcity - from 0.1 (assumed as very low water scarcity potential) to 100 (very high water scarcity potential). A qualitative assessment of CFs was proposed by Andrade *et al.* (2019) to better guide users from recommendations (Table 1).

**Table 1.** Definition of ranges for qualitative assessment of water scarcity characterization factors.

Range	Definition	Qualitative potential impact on the watershed's water scarcity
= 0.1	Minimum CF value defined by the method	Very low
0.02 – 33.3	Linear distribution of CFs between minimum and maximum values of the method.	Low
33.4 – 66.6		Medium
66.7 – 99.9		High
= 100	Maximum CF value defined by the method	Very high

There is currently no scale to qualitatively define the calculated WSF. However, it is important to consider presenting the results at this scale to facilitate the identification of less and more critical regions in Bahia when installing a new cocoa orchard. In the present work, a scale from 'Low WSF' to 'Very high WSF' was adopted, considering a linear division of the WSF values of the municipalities. Thus, the scale between 0 (minimum WSF found in the present study) and 700 (maximum value found in the present study) for WSF was considered (Table 2).

**Table 2.** Definition of ranges for qualitative assessment of water scarcity footprint (WSF).

WSF ( $\text{m}^3\text{-eq kg}^{-1}$ of cacao)	WSF qualitative classification
0 – 165	Low WSF
165.1 – 330	Medium WSF
330.1 – 495	High WSF
495.1 – 700	Very High WSF

### 3. RESULTS AND DISCUSSION

#### 3.1. Water demand for cocoa irrigation in Bahia

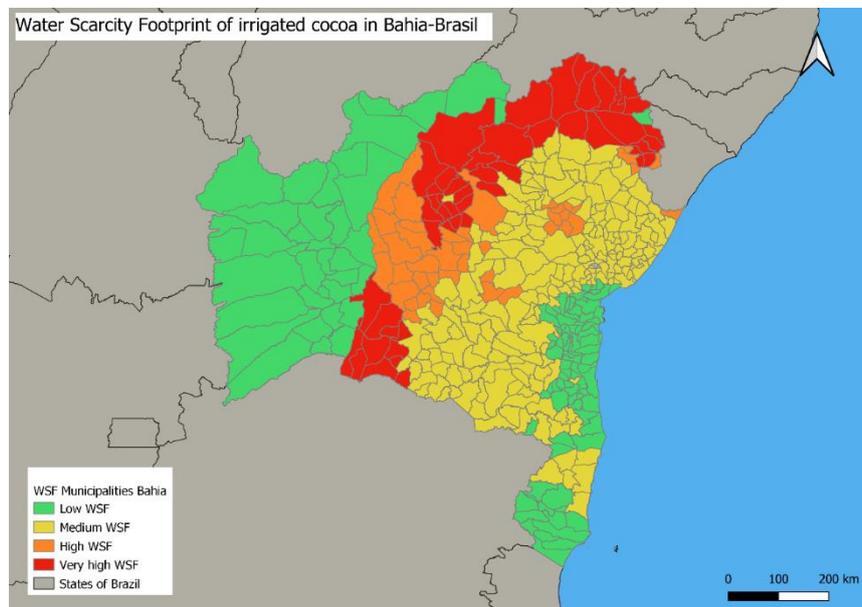
The precipitation in Bahia municipalities varies from 299.5 mm (in Sobradinho) to 1707.3 mm (in Cairu on the coast). A total of 50 municipalities in the state have precipitation equal to or greater than 1200 mm. The average annual reference evapotranspiration of the municipalities ranges from 1356.6 to 1980.3 mm. The west, south, and southwest regions of Bahia are the most favorable for cultivation, as they have the best precipitation values, potential lower irrigation demands, and SHUs with low scarcity impact.

The demand for irrigation in the state ranged from 1.26 to 7.1  $\text{m}^3 \text{kg}^{-1}$ . Naranjo-Merino *et al.* (2018) accounted for the irrigation water consumption of cocoa production in Colombia and

presented an average of  $18.876 \text{ m}^3 \text{ kg}^{-1}$ . The demand for irrigation in the municipalities was below the average (up to 93.3%) found by the authors mentioned above due to the favorable weather conditions in Bahia.

### 3.2. Water scarcity footprint of irrigated cocoa in Bahia

The annual WSF for irrigation of cocoa produced in Bahia ranged from 0.28 to  $646.5 \text{ m}^3\text{-eq kg}^{-1}$  of cocoa (Figure 1).



**Figure 1.** Water Scarcity Footprint of cocoa irrigation in the municipalities of Bahia.

According to the range established, of the 417 municipalities in the state, 28% have a 'Low WSF'; 50%, 'Medium WSF'; 10%, 'High WSF'; and 12%, 'Very high WSF'.

Irrigation of cacao in six SHUs would have the greatest impact on water scarcity: Macururé and Curaçá, Carnaíba de Dentro, Salitre, Vaza-Barris, Verde and Jacaré and Verde Grande. These SHUs have characterization factors (CFs) equivalent to  $100 \text{ m}^3\text{-eq}$  for at least seven months of the year and have the potential to compromise essential local demands.

A total of 40 (9.6%) municipalities in Bahia have CF equal to  $100 \text{ m}^3\text{-eq}$  in at least one month of the year. On the other hand, 42 municipalities (10%) have CF equivalent to  $100 \text{ m}^3\text{-eq}$  in the whole year, meaning they have a very high water scarcity potential throughout the year.

The largest WSF is cocoa production in the municipality of Juazeiro ( $646.5 \text{ m}^3\text{-eq kg}^{-1}$ ), located in the SHU of Macururé and Curaçá. In Juazeiro, the average annual demand for irrigation was estimated to be  $6.74 \text{ m}^3 \text{ kg}^{-1}$ . However, this municipality has 11 months with CFs of  $100 \text{ m}^3\text{-eq}$ , except in March, when the CF is  $39.5 \text{ m}^3\text{-eq}$ .

The monthly demand for irrigation in SHU of Macururé and Curaçá ranged from  $1.26$  to  $7.10 \text{ m}^3 \text{ kg}^{-1}$ . Although the highest WSF was in the municipality of Juazeiro, the highest demand for irrigation was in the municipality of Sobradinho ( $7.10 \text{ m}^3 \text{ kg}^{-1}$ ).

The municipality of Sobradinho is part of the SHU Lago de Sobradinho whose CFs vary from 0.2 to 0.7, provoking a very low impact on water scarcity. Thus, the WSF of cocoa produced in Sobradinho was only  $3.13 \text{ m}^3\text{-eq kg}^{-1}$ , 99.5% smaller than Juazeiro's WSF. This fact highlights that a larger footprint does not indicate a greater water demand. Otherwise, the WSF is more affected by the water stress, and related CF, attributed to the SHU in which the municipality is located.

The municipalities with the smallest WSF (between 0 and  $165 \text{ m}^3\text{-eq kg}^{-1}$ ) were inserted in the west, south coast, and extreme south of Bahia. However, according to Oliveira *et al.* (2019), the west region of Bahia is the largest agribusiness area in the state and has faced pressure on water resources, mainly due to irrigation, causing conflicts between water users.

The ten leading cocoa-producing municipalities are in southern Bahia, and they have low WSFs, ranging from 9.73 to  $24.13 \text{ m}^3\text{-eq kg}^{-1}$ . These municipalities are located in the SHUs Leste, Recôncavo Sul and De Contas. The municipalities located in these SHUs demand between 0 to  $0.44 \text{ m}^3 \text{ kg}\cdot\text{month}^{-1}$ .

### 3.3. Comparison with other studies for agricultural products

Few previous studies assessed the WSF of tropical irrigated fruits applying the AWARE method (Boulay *et al.*, 2018). Those studies considered the WSF of irrigation as well as the production of inputs used in the cropping systems in the study of Brazilian mango (Carneiro *et al.*, 2019), Peruvian and Italian grapes (Vázquez-Rowe *et al.*, 2017; Borsato *et al.*, 2019), Brazilian green coconut (Sampaio *et al.*, 2021) and Argentine lemon (Ferrero *et al.*, 2022). Although only the WSF of the cocoa irrigation process was accounted for in this study, comparing results with the WSF of these other fruits is essential to understand their magnitude.

Irrigation was the process that most contributed to crop WSF, although different irrigation systems were applied (micro sprinkler and drip), each with different efficiencies. Furthermore, the applied irrigation water in these studies was often higher (Carneiro *et al.*, 2019) or lower (Sampaio *et al.*, 2021) than the crop irrigation water demand. Carneiro *et al.* (2019) found an average footprint of  $0.93 \text{ m}^3\text{-eq kg}^{-1}$ . Sampaio *et al.* (2021) evaluated the WSF of green coconut in the main regions of Northeast Brazil, in the states of Alagoas, Bahia, Ceará, and Sergipe. Coconut WSF ranged from 0.332 to  $0.758 \text{ m}^3\text{-eq kg}^{-1}$ . As in the present study, the state of Ceará had the worst performance compared to the other regions analyzed, consuming a greater volume of water for irrigation and presenting the largest footprints.

Vázquez-Rowe *et al.* (2017) obtained an average irrigation WSF of  $210 \text{ m}^3\text{-eq kg}^{-1}$ . This value was due to the region's high CFs values, ranging from 61 to 100. In comparison, Borsato *et al.* (2019) found an irrigation WSF of  $0.243 \text{ m}^3\text{-eq kg}^{-1}$ , and Ferrero *et al.* (2022) obtained  $0.102 \text{ m}^3\text{-eq kg}^{-1}$  for fresh lemon.

### 3.4. Uncertainties in the study

The uncertainties of the study are related mainly to the uncertainties of the CFs. Alves *et al.* (2020) have shown that the greater the temporal variation, the greater the uncertainty of CFs, such as in the Brazilian semiarid region. Another point of uncertainty is regarding kc; applying specific kcs to the different stages and locations can provoke different irrigation demands, contributing to reducing uncertainties in footprint calculation.

## 4. CONCLUSIONS

The coastal region of Bahia is the most favorable for cacao cultivation (or expansion) considering potential WSFs for the municipalities, as it has the smallest WSF (from 0.28 to  $159.62 \text{ m}^3\text{-eq kg}^{-1}$ ). In the interior of the state, where cocoa irrigation is still a prospective activity, the WSF increases up to  $646.5 \text{ m}^3\text{-eq kg}^{-1}$ , indicating that irrigated cocoa cultivation could conflict with other essential local demands. Furthermore, this study showed that increased demand for cocoa irrigation does not necessarily correspond with an increase in the water scarcity footprint, as the impact is related to the water stress of the local water source. Thus, it is possible to infer that including WSF and CFs could improve agroclimatic zoning studies by adding new parameters to assess the potential water scarcity of the locals. Finally, the results of this study could be used as a baseline in the future for more specific WSFs for cocoa in Bahia.

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