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Increasing efficiency in ethanol production: Water footprint and economic productivity of sugarcane ethanol under nine different water regimes in north-eastern Brazil

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Abstract

Ethanol production in Brazil has grown by 219% between 2001 and 2012, increasing the use of land and water resources. In the semi-arid north-eastern Brazil, irrigation is the main way for improving sugarcane production. This study aimed at quantifying water consumed in ethanol production from sugarcane in this region using the water footprint (WF) indicator and complementing it with an evaluation of the water apparent productivity (WAP). This way we were able to provide a measure of the crop's physical and economic water productivity using, respectively, the WF and WAP concepts. We studied sugarcane cultivation under nine different water regimes, including rainfed and full irrigation. Data from a mill of the state of Alagoas for three production seasons were used. Irrigation influenced sugarcane yield increasing total profit per hectare and economic water productivity. Full irrigation showed the lowest WF, 1229 litres of water per litre of ethanol (L/L), whereas rainfed production showed the highest WF, 1646 L/L. However, the lower WF in full irrigation as compared to the rest of the water regimes implied the use of higher volumes of blue water per cultivated hectare. Lower water regimes yielded the lowest economic productivity, 0.72 US\$/m³ for rainfed production as compared to 1.11 US\$/m³ for full irrigation. Since economic revenues are increased with higher water regimes, there are incentives for the development of these higher water regimes. This will lead to higher general crop water and economic productivity at field level, as green water is replaced by blue water consumption.

Additional key words: biofuel; water productivity; blue water; green water.

Abbreviations used: ETc (crop evapotranspiration); ETp (potential evapotranspiration); *pf* (product fraction); *vf* (value fraction); WAP (water apparent productivity); WF (water footprint)

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Introduction

The use of sugarcane ethanol in Brazil is one of the greatest examples of partial or total substitution of oil in the world. Liquid biofuels are the fastest growing sector of bioenergy. Besides reducing oil consumption, the production and use of sugarcane ethanol has competitive advantages in terms of economic returns and greenhouse gas emissions, compared both to non-renewable fuels and to renewable fuels from other crops. Their development has been the result of an interaction of policies, public and private institutions and partnerships

that have created one of the most dynamic and competitive innovation systems in the world (Furtado *et al.*, 2011). Brazilian ethanol production grew by 260% from 2001 to 2009, achieving 27,512 hL in 2009 (Unica, 2013). The United States has set objectives of biofuel usage for 136,274 ML in 2022 (EPA, 2007). Both US and European targets are above their domestic production capacity, so they rely on internationally traded ethanol to meet them (FAO, 2013). Since Brazil is the world's second largest producer and first largest exporter, the country is in position to fill this gap and so global demand for Brazilian biofuel is expected to grow.

Nevertheless, there are concerns over the possible negative effects of biofuel production. Bioethanol production from corn (*Zea mays* L.) and sugarcane (*Saccharum officinarum* L.) may impact commodity prices and negatively affect food security¹ (FAO, 2008, 2013). Direct or indirect land use change from increased ethanol production may contribute to these negative effects (Martinelli & Filoso, 2008; Meloni *et al.*, 2008). Another major concern is the possible influence that large-scale biofuel development may have over the use of water (Gerbens-Leenes *et al.*, 2009). To develop the potential of bioenergy, its development must be adapted to economic, environmental and social conditions, this last one being closely related to food security (FAO, 2008). From a global point of view, Hoekstra & Chapagain (2007) estimated that the volume of water used in agricultural production worldwide is about 6,390 Gm³/yr. The cultivation of sugarcane consumes 4% of the total water used in the world. Brazil leads the world's sugarcane production being also India, China, Thailand and Mexico important producers (FAO, 2013). Brazil produced 734 million tonnes in 2011, intended for the production of both sugar and ethanol. Commonly, mills are able to obtain both products and companies decide

the amount of cane allocated to sugar or ethanol production based on the international sugar prices.

To meet the growing demand of ethanol and sugar, the area cultivated with sugarcane in Brazil increased from 4.82·10⁶ ha in 2000 to 9.6·10⁶ ha in 2011 (FAO, 2013). This increase was made possible by the incorporation of new areas that were previously dedicated to other agricultural activities, mainly pastures and crops like citrus, corn and beans (Meloni *et al.*, 2008). The adoption of new technologies of production and processing has also played a relevant role on this expansion of sugarcane (Mello Ivo *et al.*, 2008; Vasconcelos *et al.*, 2008). The largest sugarcane producing region (shared among the states of Sao Paulo, Minas Gerais, MatoGrosso, and Paraná, Fig. 1), traditionally produces sugarcane under rainfed conditions. In these regions, productivities average 80 t/ha. Sugarcane is also rapidly expanding from these central areas west into Mato Grosso do Sul, and north further into Bahia, Goiás, and Maranhao states (Meloni *et al.*, 2008). These areas have lower annual precipitation than Sao Paulo.

Sugar and ethanol sector is one of the leading economic sectors in the Alagoas state, and has important implications at the social level, in the number of jobs

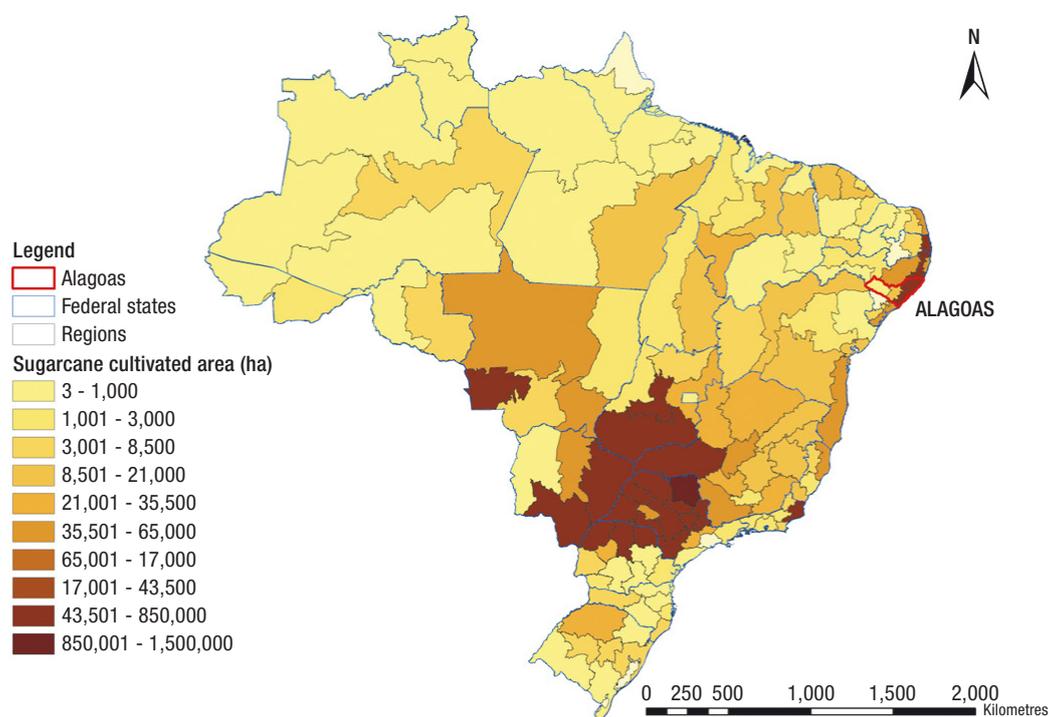


Figure 1. Sugarcane cultivated area per micro-region. In red, Alagoas State. *Source:* IBGE (2013).

¹ G20's declaration (2011), point 41, stated: *We will continue to address the challenges and opportunities posed by biofuels, in view of the world's food security, energy and sustainable development needs. We recognize the need to further analyse all factors that influence the relationship between biofuels production and (i) food availability, (ii) response of agriculture to price increase and volatility, (iii) sustainability of agriculture production, and further analyse potential policy responses, while recognizing the role biofuels can play in reduction of greenhouse gases, energy security and rural development.* Available in http://agriculture.gouv.fr/IMG/pdf/2011-06-23_-_Action_Plan_-_VFinale.pdf.

provided, but also on their quality. The modernization from a labour intensive sector with a high demand of low-skilled seasonal job to a more capital intensive sector demanding skilled technicians has very important implication for the local economy (Furtado *et al.*, 2011). The development of the industry is related to capital access and policy support. These are likely to continue in the near future, reinforced by continuing flows of foreign direct investment. These factors will likely stimulate, at national level, sugarcane expansion, mills modernization and the development and implementation of co-generation technologies (*ibid.*), but also applies to mills in Alagoas state. At a regional level, these factors may also promote the intensification of the crop through irrigation and harvest mechanization.

In Alagoas most of the sugarcane plots are rainfed, although irrigation is rapidly expanding. The most common irrigation practice is to apply only supplemental irrigation in one or two applications. Nevertheless, sugarcane farmers have been investing in technologies to increase production, notably through the adoption of new varieties and more frequent irrigation applications. This way plantations obtain higher productivities and the number of ratoons is increased. At present, most mills combine various irrigation levels according to several factors like water availability and expected yield at field level, or harvest organization and milling capacity of the industrial stage.

In the state of Alagoas, the irrigated area was 186,385 ha in 2007/2008 season and increased by 5.9% in the following year. From this area, only 3.6% was fully irrigated; 62.5% received just one application of 50-70 mm depth; and 33.9% received 2-3 irrigation applications of 70-100 mm depth. Vinasse was applied to 55,291 ha (SINDACUCAR-AL, 2015). In the state of Alagoas irrigation is the main water user and the fastest growing sector, currently representing 78% of water demand. Water demand exceeds availability by 40%, according to the Alagoas state water resources management plan (SEMARH, 2010).

In the industrial phase, the range of water consumption in this sector is wide. Buarque *et al.* (2003) studied the water consumption of 10 sugar-ethanol mills in the state of Alagoas and found that 0.7 to 12.2 m³/t of cane processed were needed. Several factors influence this consumption, among others, the age of the plant, proximity to water sources, and use of energy generation technologies. Nevertheless, water consumption by the industrial production of sugarcane has been declining rapidly during the last four decades (ANA, 2009), mainly because of environmental laws, as well as technological improvement in the machinery and the imminent implantation of a system to charge for water use. Water requirements ranging from 15 to 20 m³/t of cane in the 1970s decreased to 5.6 m³/t in the 1990s, and for new units in Sao Paulo being

implemented at present, consumption cannot be greater than 1 m³/t following state regulation (*ibid.*).

Another modernization that has improved overall water use efficiency in the sector has been the spread of water reuse from certain industrial process in the mill as irrigation water. In particular, the water used for washing the sugarcane stalks at the facility reception and the water effluents from the mill are now widely used in irrigation. Stalks washing is the most water intensive process of the industrial phase.

One of the tools available to quantify the amount of water used in the production of a particular product is the water footprint (WF). The WF is a methodology to account for the direct and indirect water consumption linked to a particular activity, spatially and temporally explicit (Hoekstra *et al.*, 2011). The WF tool is a useful way to evaluate empirically the overall chain of production stages that contributes to water consumption (Hughes *et al.*, 2007). Estimations can be used for decision-making regarding the amount of water consumed in the entire production chain of the product studied. When evaluated as litres consumed per unit produced, the WF is also a measure of water productivity. In some applications, WF accounting can also be a measure of the pressure that an activity makes over water resources. After this accounting of water use, an adequate contextualization of the area under study and water use within a basin helps to understand the consequences of such consumption.

The present article is intended for a detailed accounting of the WF of current irrigation practices in a sugarcane estate in Alagoas under nine water regimes, including rainfed and irrigated production, over three seasons (2009-2011). The methodology proposed by Hoekstra *et al.* (2011) was followed. An analysis of the economic productivity of water, estimated as the water apparent productivity (WAP) at farm level, was carried out to complete the analysis. It enabled us to evaluate the water consumption and productivity by an example of current practices in the region and support considerations over possible future developments of irrigation in the region.

Material and methods

Characterisation of the region

This study was based on field data from Seresta sugarcane mill, located in the city of Teotônio Vilela in the state of Alagoas, Brazil. The cultivated area is located in the region known as the Coastal Plains, which features flat terrain and low fertility soils.

The region has a tropical rainy climate with dry summers (CPRM, 2005) and an average precipitation of 1,634 mm, which is concentrated in the months from

May to July. Podzolic soil types dominate, with Fregipan, Podzols and Podzolic Plintic soils in small depressions. An important characteristic of these soils is the presence of cohesive layers located between 0.75 to 1.50 m depth (Jacomine, 2001). In Alagoas, average rainfed productivities are 60 t/ha, mainly limited because of a marked dry season in the months from September to February but also related to soil fertility.

Characterisation of the production systems

The production system of the sugarcane mill studied is the common form of the north-east region. In line with the general trend in this region, the studied company dedicates an important share of their cultivated area to different irrigation depths. Sugarcane is harvested between 10 and 14 months after transplanting. The period of grinding in the mill runs from the second half of August to March. This work considered a growing period of 365 days starting on November 1st and ending on October 31st of the following year.

In the 2009, 2010 and 2011 agricultural seasons, the company cultivated around 11,000 ha using nine water regimes, which ranged from no irrigation to 552 mm in plots that varied in area from 204 to 1,550 ha. Relevant data for the calculation of the WF were collected by the mill technicians and used for the calculation of sugarcane water consumption (Table 1). These data included planting and harvesting dates, irrigation depth and irrigation frequency, fertilizer rates and amounts of vinasse applied in the areas that received fertigation. Sugarcane productivity for each water regime was used for the quantification of crop WF.

Irrigation in eight of the nine different water regimes was applied using three irrigation systems: pivot, irrigation traveller and drip irrigation (Table 1). Full irrigation to satisfy crop water needs (552 mm) was carried out with a sub-surface drip. For all water regimes, approxi-

mately half of the area received only mineral fertilization while the other half received vinasse diluted in water and reduced fertilizer application. The seven water regimes with irrigation from 50 mm to 350 mm, applied, respectively, one to seven irrigation event of 50 mm, each spaced 30 days from the previous event starting from the harvest date of the previous year. Sprinkler irrigation was carried out with an irrigation traveller for lower water regimes, between 50 and 150 mm. Water regimes between 200 to 350 mm were applied with an auto-towable pivot. The complex logistics of irrigation in the mill prevents the application of smaller, more frequent irrigation events, which would reduce the risk of water losses from irrigation runoff and percolation. Sugar mills tend to use an irrigation pivot for higher water regimes because of its low labour requirements lower economic costs. Full irrigation by drippers provided 9 mm whenever the soil presented the need for water supplementation, which was estimated based on the experience of the technicians at the mill, approx. every 2 to 3 days.

Fertilization was applied in order to satisfy crop needs in terms of N, P, K and micronutrients with commercial formula. Fertilization rates also took into account the use of vinasse, which satisfies sugarcane's potassium needs. The area not irrigated with vinasse, which represented approximately half of the area irrigated in each water regime, received 77 kg/ha of nitrogen. When applied, vinasse was diluted with irrigation water to a level of 7% and applied to 23% of the total area of the mill. This area received only 65 kg/ha of nitrogen and no potassium fertilization. Fertilising was done in one event in topdressing immediately before planting the new sugarcane or after harvesting previous ratoon.

Water footprint calculation

The WF calculation was based on the methodology developed by Hoekstra *et al.* (2011). As an indicator,

Table 1. Description of treatments, irrigation method, cultivated area and average productivity

Water regime	No of irrigation events	Irrigation methods	Area (ha)			Productivity (t/ha)		
			2009	2010	2011	2009	2010	2011
Rainfed	—	—	2,213	2,550	2,513	52.43	49.56	56.37
50 mm	1	Irrigation traveller	2,508	2,509	2,319	57.25	52.27	61.86
100 mm	2	Irrigation traveller	1,244	1,538	1,700	64.61	57.25	63.51
150 mm	3	Irrigation traveller	1,050	1,019	1,278	67.28	60.09	64.31
200 mm	4	Pivot	829	849	892	70.25	65.19	68.17
250 mm	5	Pivot	548	514	437	73.17	67.30	71.14
300 mm	6	Pivot	280	204	209	76.46	69.74	76.55
350 mm	7	Pivot	467	381	274	76.77	73.03	78.32
552 mm (Full)	107-127	Drip	1,481	1,481	1,464	96.41	103.43	96.83

Source: Own elaboration based on information from the mill.

it includes three dimensions (colours) of water use (green, blue and grey). Green water is defined as the amount of precipitation that is stored in the soil and consumed during plant growth and evaporation. Blue water is extracted from the water surface and groundwater bodies and used for irrigation or in industrial processes. This distinction builds on the different implications that each water colour has on the water hydrological cycle. While green water is linked to land use and the opportunity cost of land, blue water is usually related to resource scarcity and allocation. In our case, the application of the methodology involved the estimation of the WF of sugarcane production under each water regime, vinasse use and studied year, and the WF of the industrial phase. This way, we could estimate the WF of ethanol production, in litres of water per litre of ethanol produced (L/L).

For the quantification of blue and green water for each water regime, we used the program Cropwat 8.0 (FAO, 2009). The program performs a soil water balance to calculate the crop evapotranspiration as a function of soil water availability. Local data on monthly potential evapotranspiration (ET_o), precipitation and soil type were provided by the mill. Irrigation data provided by the mill was fed into the program to estimate the fraction of evapotranspiration consumed from soil or irrigation water, thus obtaining the green and blue water consumption, respectively. In treatments that received irrigation, blue water consumption was calculated by subtracting the irrigation losses from the total net irrigation. Irrigation efficiency (including technical efficiency and scheduling efficiency) averaged 65% for all water regimes and years, and a standard deviation of 3.5%. Green water was estimated as the difference between crop evapotranspiration (ET_c) and blue water. Green and blue water consumption (m^3/ha) was divided by the agronomic productivity (t/ha) for each water regime to obtain the sugarcane green and blue WF (m^3/t of sugarcane) of each water regime and year. Ethanol green and blue WF was then calculated based on average ethanol production of 80 L ethanol per tonne of sugarcane (ANA, 2009).

In relation to water consumption in the industry for ethanol production, the ANA (2011) estimates that the reuse of water in the various circuits should be considered in the average use of water in processing ethanol, with or without treatment. In the state of Alagoas values are estimated in the range of $5.6 m^3/t$ cane. It is estimated that $1.8 m^3/t$ is lost from this amount by evaporation (*ibid.*). Therefore, the value considered in this work as blue water consumption in the industrial phase was $1.8 m^3/t$.

In this study, the use of wash water for irrigation was not considered as a consumption of the industrial phase but as part of the water used in irrigation.

Alongside ethanol, the main by-products of ethanol production (sugarcane bagasse and vinasse) were evaluated. Bagasse is the solid waste resulting from stalk grinding, which is burned for co-generation of heat and electricity. This is a way of allocating water consumption in the production of sugarcane into its different products, including ethanol. The concepts of product fraction (pf) and value fraction (vf) were used according to the WF methodology (Eq. [1], from Hoekstra *et al.*, 2011). Product fraction is defined as the quantity of (by-) product obtained, in mass, per unit of primary product, in mass. In this case, product fractions refer to the amount of ethanol, bagasse or vinasse obtained per tonne of sugarcane. The value fraction is defined as the ratio of the market value of (by-) product to the aggregated market value of all products and sub-products obtained.

$$WF_{by-product} = (WF_{primary product}) \times \frac{P_{primary product}}{P_{by-product}} \times \frac{v_{by-product} \times pf_{by-product}}{\sum_{all_by-products} (v_{by-products} \times pf_{by-products})}$$

In which, $WF_{by-product}$ = the WF of the by-product taken into consideration (vinasse or bagasse, L/L or L/kg); $WF_{primary product}$ = the WF of the primary product that derives in several by-products (sugarcane, L/kg); $P_{primary product}$ = weight of the primary product (kg); $P_{by-product}$ = weight of the specific by-product taken into consideration (kg); $v_{by-product}$ = economic value of the specific by-product taken into consideration (US\$); and $pf_{by-product}$ = product fraction of the specific by-product taken into consideration.

By using pf and vf , we acknowledge the relevance of by-products with an economic value in reducing the pressure over water resources of a particular production. Their use avoids the need of their safe disposal and prevents potential environmental harm (Silva *et al.*, 2007).

In the literature, several papers have reported the amount of vinasse generated in ethanol production, with values varying from 10 to 16 L of vinasse per litre of ethanol produced. In this work, we have used an average rate of 12 L of vinasse obtained per litre of ethanol produced (ANA, 2009). In order to assign an economic value to the vinasse, the price of the potassium chloride was used, which is no longer applied when the vinasse is used (Almeida *et al.*, 2007).

In Brazil, sugar and ethanol mills are self-sufficient in terms of energy, because the bagasse is used as a source of energy co-generation. An average distillery generates around 14 kWh per tonne of cane processed (Bajay & Ferreira, 2005). The excess electricity between the plant's energy generation and consumption is sold to utility companies for general use. On average, 85% of the generated energy is used in the industrial unit

itself and only the excess 15% may be negotiated with the power companies. These were the values used in this study for the estimation of the value of bagasse. Prices per MWh were obtained from the Electricity Chamber of Commerce (CCEE, 2013).

Economic evaluation of water footprint results

The study complemented bioethanol's WF quantification under different water regimes in economic terms by including an analysis of the profits and water economic productivity (WAP, in US\$/m³). For the calculation of the crop's economic benefits (US\$/t), an estimation of the revenues and costs of production (US\$/ha) was carried out. Economic benefit per ha was then divided by the corresponding yield (t/ha) to obtain the crop's economic benefits (US\$/t) for each of the nine water regimes. WAP was calculated as the quotient of the crop's economic benefit (US\$/t) and the WF (m³/t).

Total operational costs were calculated as the costs associated with irrigation, sowing, crop management and harvesting costs per hectare, including associated labour, energy and transport costs. The operational costs of irrigation and the capital investments costs of irrigation systems were obtained from the mill technicians. There is no water pricing in the state of Alagoas. However, each company is responsible for building, maintaining and managing the water infrastructure, including the river dam, water conveyance and distribution to the fields. In this case, separate data for operational costs were available for the analysis of irrigation with auto-pivot or sprinkler irrigation with an irrigation traveller as estimated by the mill, including electricity costs, transport, and labour and associated taxes (Table 2).

Drip irrigation has the lowest operational cost among the irrigation systems, whereas the irrigation traveller method has the highest cost. However, in drip irrigation, capital investment costs are significantly higher than the rest of the irrigation systems. Crop management and harvest costs are also higher in drip irrigation as a result of the significant increase in productivity.

The revenue included the valuation of the sub-products together with ethanol production. Ethanol production per hectare was multiplied by its average yearly price. The prices were based in the data collected by CEPEA/USP (2015), for the ethanol market in Alagoas. The average of the three years of this study was 0.55 US\$/L. Bagasse production and vinasse application were evaluated by the electricity generated and potassium chloride that they respectively substitute.

Results

Ethanol water footprint results

Rainfed production had the highest value of WF of all the water regimes evaluated, resulting in an ethanol's WF of 1,647 L/L (1,626 and 21 L/L for green and blue respectively, Fig. 2). Ethanol from sugarcane under full irrigation had an average green and blue WF of 1,229 L/L (774 and 455 L/L for green and blue, respectively). In areas that received intermediate and high water regimes, from 50 to 350 mm, the WF decreased constantly from 1,555 to 1,304 L/L. It was observed that the larger the water supply through irrigation, the lower the share of green WF and the greater share of blue WF (Fig. 2).

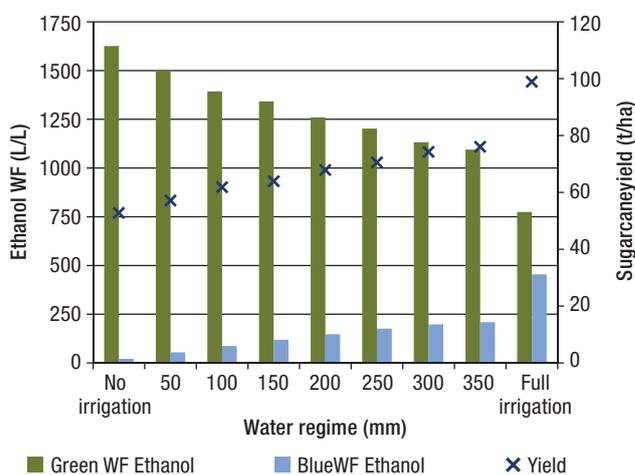


Figure 2. Green and blue water footprint (WF) of ethanol (L/L), as well as obtained yield (t/ha) per water regime.

Table 2. Irrigation costs per hectare and per millimetre associated to each irrigation system. Average of three years (2009, 2010 and 2011)

	Rainfed	Irrigation traveller	Pivot	Drip irrigation
Average capital investment costs (US\$/ha)	0	3,097	4,837	7,750
Average operational costs (US\$/ha)	1,232	1,488	1,629	2,182
Average operational costs (US\$/mm)	0	11.6	10.6	2.2

Source: Own elaboration based on information from the mill.

Comparing water consumption in the agricultural and industrial phases, it was found that the volume of water consumed in the operations of the industry is small in comparison to the total blue WF, 22.5 L/L, representing only 1.1% of the total. The use of water in the plant is estimated at 70 L/L, of which 22.5 L/L is consumed. The rest of the water is collected and mixed with vinasse and then diluted with irrigation water. This supports the idea that the concerns about the impacts of ethanol production on water resources should primarily be focused on the crop production phase. In past decades, important efforts and investments have succeeded in bringing down mills' water use and consumption, as well as effluent reuse and treatment (Martinelli & Filoso, 2008). However, this study suggests that the water lies more in the crop production phase than in the industrial one. In this respect, production in north-eastern Brazil differs from the rest of the country where sugarcane is still mostly rainfed.

Water economic productivity of ethanol production

An analysis of irrigation costs and revenues obtained from the sugarcane products provided estimates of the economic benefits and the WAP of sugarcane. The economic benefits of the different irrigation systems were estimated as the difference between the revenue per hectare, and the estimated total costs per hectare. In the case of revenue, since it is a direct function of yield, rainfed production provides the lowest returns, including those coming from sub-products use. Areas with drip irrigation showed the highest profit (1,363 US\$/ha) as an average of the three years, which run higher than 830 US\$/ha with irrigation traveller, 941 US\$/ha with auto-pivot and the 951 US\$/ha under rainfed conditions. Drip irrigation fully satisfied plant water needs and obtained significantly higher yields, while using larger amounts of water.

Mainly as a function of the increase in stalk productivity and consequently ethanol, vinasse and energy co-generation, the drip irrigation system provided the greatest economic benefits and WAP, followed by water regimes of 300 and 350 mm. High irrigation regimes, 200-350 mm, applied with pivot showed similar average WAP than rainfed production, 0.71 and 0.72 US\$/m³ (Fig. 3). The application of only 50 mm provided the lowest benefits when comparing the treatments that received supplemental irrigation (783 US\$/ha). It can be seen that drip irrigation (irrigation with 552 mm) shows the highest WAP, whereas 50, 100 and 150 mm water regimes, carried out with have in average similar

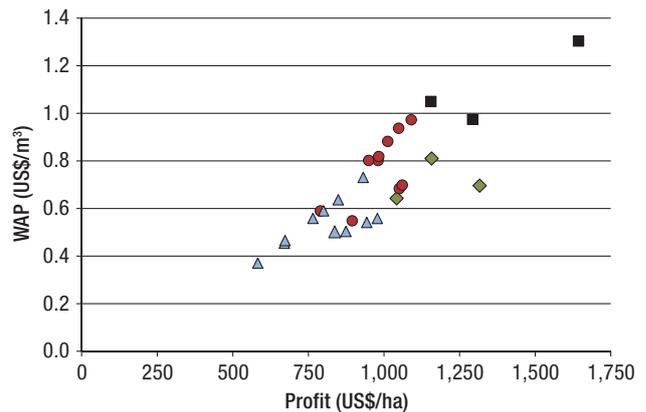


Figure 3. Total profit (US\$/ha) and water apparent productivity (US\$/m³) per water regime and year. Colours indicate water regime (rainfed in green diamonds, lower water regimes 50-150 mm in blue triangles, higher water regimes 200-350 mm in red circles, full irrigation in black squares).

productivities as rainfed irrigation (Fig. 3). An approximate evaluation of the gross margin was obtained with the methods and sources mentioned above.

Discussion

The results for the WF obtained in this work are in agreement with similar works by other researchers. In their work assessing the WF of sweeteners and biofuels, Gerbens-Leenes & Hoekstra (2012) found average WF values for ethanol production from sugarcane of 2,612 L/L when computing data from twenty major producers of sugarcane, beet and corn, from 1996 to 2005. This result could be taken as a gross global average of the WF of ethanol production, as it includes result from very different conditions. In the case of Brazilian ethanol the authors presented an average of 1,806 and 74 L/L for green and blue WF. The lower green WF and higher blue WF of their results compared to ours derive from the different assumptions made in using the Cropwat software.

The methodology used for the calculation of crop water consumption influences significantly the WF results obtained (Hess, 2010). When conducting studies aimed at quantifying the water consumption for the production of sugarcane and other raw materials for obtaining biofuel, Gerbens-Leenes *et al.* (2009) concluded that there is a wide variation of results, mainly due to two factors: the use of different production systems and climate, both of which condition the specific application of water to crops. In this regard, our study shows the variations in the results from different production techniques in a single location.

The works of Maschio (2011) and Veloso Leal (2012) studied the productivity of sugarcane under two

water regimes, 70% and 100% ET_c , under experimental conditions in Sao Paulo state. They achieved in sugarcane stalks water productivities of 40.8 and 43.2 m^3/t , for the 100% and 70% ET_c water regimes, respectively, compared to 122.3 m^3/t obtained in this work. Sugarcane stalks yield averaged 192 and 142 t/ha, which may be seen as potential yields for sugarcane.

As for WF studies centred in Brazil, Resende (2011) calculated the volume of water required to produce ethanol in the conditions of the state of Sao Paulo using the global databases of CLIMWAT 2.0 and FAOSTAT. Their estimation (2,021 L/L), is similar to ours. It is noteworthy that in the region of Sao Paulo irrigation is hardly used in the cultivation of sugarcane. Under cropping systems in subsurface drip fertigation, in north-eastern Piauí state, Brazil, Andrade Junior *et al.* (2012) obtained WF values that ranged from 1378 L/L (1,040 L/L for green water and 338 L/L for blue water) to 1865 L/L (1638 L/L for green water and 227 L/L for blue water). These results were similar to those obtained in our work, although the crop water productivity was significantly higher in their case, 101 t/ha for rainfed production. This study did not take into account the provision of sub products alongside ethanol.

The WF in relative terms, as presented here, is largely related to obtained yields. In terms of crop productivity, yield increases with evapotranspiration. In treatments without irrigation and those with 50 mm, productivity was below 60 t/ha, which is similar to the average for the state of Alagoas. In areas where 100, 150 and 200 mm were applied, yields averaged 65 t/ha, and the average was 74 t/ha in the areas that received 250, 300 and 350 mm of irrigation water. The highest productivity was obtained in the area that received full irrigation with values around 99 t/ha, which is well above the averages of Alagoas and Brazil (55 and 80 t/ha, respectively).

So in order to increase crop water productivity, irrigation applications must be augmented. Although there is little data about irrigated surface at state, regional or national level, the Sugar and Alcohol Industry Union from Alagoas reports that in the 2007/2008 and 2008/2009 crop seasons, 95% of the irrigated area received one irrigation event or supplemental irrigation (two to three events), representing 55% of the cultivated surface (SINDACUCAR-AL, 2015). Only 2-3% of the area received full irrigation. However, the trend in the region is to move to larger irrigation depths (300-400 mm) or full irrigation with drip systems. The great dynamism of the sector (Martinelli & Filoso, 2008) may imply that already irrigated area share is higher than 55%, especially the share of area irrigated with large applications. Up to now, there is no information in federal, state or sector databases that detail

irrigated sugarcane area aside from the limited data presented.

The results of the WAP point again to the fact that at the farm level improving towards large irrigation depths is a more economically productive way of using water as irrigation than the 50–150 mm regimes. These results are in agreement with Farias *et al.* (2008), who found that sugarcane water use efficiency increased at least until 50% ET_c was met. As a result, the tendency already observed in sugarcane plantations is to increase irrigation significantly in order to increase productivity and profitability. On the other hand, a limit to this high-irrigation development in real settings is the ethanol plant boiling capacity, which limits the amount of juice that may be fermented, and consequently the amount of sugarcane stalks that may be harvested in a short period.

In view of the limited reliable data on economic variables, the economic results should be taken with caution and be considered as merely indicative. First, the price of ethanol is volatile, as they are also the prices of some other inputs including fertilizers and outputs, such as electricity. Secondly, the opportunity cost of water is assumed null, but eventually there might be an application of water tariffs that may change the results of the study. Lastly, the production costs are always more variable than what are assumed in this study.

From a methodological point of view, some uncertainties in parameters used such as soil water storage capacity and infiltration rate, which strongly influence the results of the WF, suggest the need for more detailed studies. In a context where the national and international demand for biofuels is expected to increase, and considering the concerns over indirect land-use changes with negative environmental consequences (Martinelli & Filoso, 2008), productivity growth stands out as a feasible solution to avoid this negative environmental effect. In the semi-arid north-eastern Brazil gains are being achieved through irrigation, which may lead to higher overall water productivity and economic benefits. The water regimes studied in this work proved to have greater relevance than the amount of precipitation in the variation of the WF results. The industrial part of the WF is much smaller compared to that consumed in the production of sugarcane. This way, efforts for a more sustainable water use in the ethanol production should pay particular attention to the agricultural production phase. This may imply supporting alternative agricultural practices to minimize water consumption and impacts on water resources.

The results presented in the study show that under real operating conditions the highest water consumption efficiency in terms of crop productivity was achieved either through the application of higher water regimes. In economic terms, production under lower water re-

gimes, using irrigation traveller is less economically efficient than rainfed production and those obtained by applying larger depths with pivot. However, rainfed areas showed higher WF than irrigated areas, had the lowest yields and, therefore, provided the lowest economic profits. This suggests that area cultivated under rainfed systems will become increasingly residual. Among the water regimes, the lowest WF results were obtained in areas under full irrigation (550 mm), followed by those areas receiving 350 mm.

Still, significant differences in the division of the WF were found among the results for the different water regimes including rainfed production, increasing irrigation amounts and full irrigation. The share of green water diminished while the weight of blue WF in the total WF grew as irrigation increased. However, differences in ethanol WF between the lowest water regimes (50 to 150 mm) and the non-irrigated areas average 9%.

As a measure of crop water productivity, these WF results show the water physical and economic productivity gains from sugarcane irrigation. Full irrigation, although having the lowest values of WF, has the highest total water consumption of blue water with a higher opportunity cost than green water. Nevertheless, the opportunity cost of green water will be linked to the alternative land uses in the region, including natural Atlantic rainforest area, one important biodiversity hotspot.

The economic analysis shows the advantages of increasing the water regimes, and the increased efficiency (per product, but also economic) of switching from rainfed systems to water regimes in which higher irrigation layers are applied. This may contribute to understand the main driver of innovation and change in the production practices. It may also help, if related to other water uses in the region and evaluated at a state level, provide insights into the effectiveness of water allocation to sustain the regional economy. The increase in the irrigated area poses a potential threat to water resources, the result of which will depend on the relation of total water use to available water resources.

Particularly relevant is the efficiency of water use; that is, the relation of water consumption to water supplied, or the difference between gross and net irrigation. There may also be substantial room for improvement in this indicator, since at present-water application is only grossly adjusted between areas in the different fields. Each sugar mill, as the one studied in this work, cultivates vast areas, as so management units are also large. This limits the capability of field and irrigation managers to adapt fertilizing and irrigation to plant needs at a lower scale, which could be a way for improving irrigation efficiency. This also affects adapting irrigation amounts to each particular year's hydro-

logical condition. We have seen how irrigation layers applied were constant for several years.

Nevertheless, the aggregate impacts of generalized irrigation growth in the semi-arid north-eastern Brazil require further study. Regardless of the efficiency achieved, it is the overall water consumption the factor that may affect water availability in the region. Since sugarcane production covers such large areas in small watersheds, even a relatively small increase in the irrigation of sugarcane may greatly increase the pressure on water resources. Moreover, irrigation is carried out soon after harvesting, which is the end of the dry season, and the most fragile period for aquatic ecosystems.

Therefore, regional studies may complement field-level analyses. In this case, due to the importance of sugarcane in the area, the relative homogeneity of agricultural practices among the mills and their tendency to increase irrigated area, field level productivities may provide insights into regional water use efficiency and its future development, while drive regional total water use.

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