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Water footprint of biofuels in Brazil: assessing regional differences

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Abstract: The expected expansion of bioenergy in Brazil has raised concerns about the implications for its current comfortable situation of water resources availability. As water availability within the Brazilian territory is uneven, the bioenergy expansion might represent different impacts on the water resources of different regions. This work assessed, at the municipal and state levels, (i) the green and blue water footprint (WF) of the main liquid biofuels produced in Brazil (sugarcane ethanol and biodiesel); (ii) the impacts of full and salvage irrigation strategies on sugarcane WF; and (iii) the water demand for different agricultural land use scenarios. For the states of São Paulo, Minas Gerais, and Goiás, the WF of sugarcane ethanol was evaluated around 71 L MJ^{-1}, while in the state of Paraná it reaches 100 L MJ^{-1}. For biodiesel, values were between 40 and 50 L MJ^{-1}. The blue WF was negligible for both biofuels, as the use of irrigation is still limited in Brazil today. Additionally, the analysis showed that full and salvage irrigation strategies would lead to lower WFs in all states considered, though in the expense of larger volumes of blue WF. Regarding land use change, the results suggested that additional evapotranspiration is occurring due to sugarcane expansion. Nevertheless, given the current situation of the Brazilian water basins, there is no evidence that sugarcane expansion over these areas will lead to critical pressure on water resources. © 2013 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: *Saccharum officinarum*; *Glycine max*; sustainability; water resources; irrigation; bioenergy.

Introduction

Bioenergy has been globally promoted as a way to reduce the dependence on fossil fuels and mitigate the emissions of greenhouse gases (GHGs). Nevertheless, criticisms have been raised about the potential environmental impacts of biofuels production, including those on water quality and availability.[1] About 70% of the global water withdrawals are due to the agricultural activity,[2] and it is argued that an increase in demand for food in combination with a shift from fossil energy toward bioenergy would put additional pressure on freshwater resources.[3]

It is usually acknowledged that the world's single biggest water problem is scarcity,[4,5] which is not equally distributed around the globe. The distribution of global freshwater (or river) runoff among the continents is highly uneven and corresponds poorly to the distribution of

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world population. South America, for instance, with less than 6% of world population, contains almost 30% of the global internal renewable freshwater resources.[2] As a consequence, in some countries the increase in evapotranspiration appropriation for human uses could lead to further enhancement of an already stressed water resources situation, while there are also countries where such impacts are less likely to occur.[6]

Brazil is already marked today by the strong participation of modern biomass in the country's energy supply system, and a substantial expansion of bioenergy is expected in the future. In terms of water availability, Berndes[6] indicates that apparently no constraints would be imposed on the assumed level of bioenergy production in the country. However, as water availability within the Brazilian territory is also uneven, the bioenergy expansion might represent different impacts on the regional water resources availability, requiring regional analyses.

The water footprint (WF) concept is an indicator of the amount of freshwater used, directly and indirectly, to produce a product along its supply chains.[7,8] In general, the WF of fossil energy carriers and derived fuels are much lower than for biofuels, mostly due to the nature of plants to consume water to grow. This water is fulfilled by rain or irrigation water, defined in the WF methodology as green and blue WF, respectively.[3,9,10] Among the bioenergy crops, sugarcane is one of the most favorable options with respect to WF, more particularly in Brazil. According to Mekonnen and Hoekstra,[11] the weighted global average WF of sugarcane is 196 $m^3\ t^{-1}$, accounting only for the green and blue components. Soybeans, on the other hand, feature a much higher WF (2107 $m^3\ t^{-1}$). Such difference is reflected on the derived biofuels, so the weighted global average WFs for sugarcane ethanol and soybean biodiesel, with reference only to the green and blue components, were respectively evaluated as 85 and 337 L MJ^{-1}.[3]

Irrigation does not play a significant role in Brazilian agriculture – in 2006, the irrigated areas accounted for only 7.4% of the agriculture area (i.e. 4.45 million hectares).[12] In the sugarcane areas, however, the participation of irrigation (in addition to fertirrigation with vinasse) is more relevant. A survey based on 103 mills indicated that more than 12% of the sugarcane area in Brazil was irrigated in the 2011/2012 season, compared to less than 10% verified in the previous season.[13] Most of that area receives the so-called salvage irrigation (i.e. one or two water application of 40 to 60 mm applied right after harvesting to guarantee sugarcane sprouting). Such upward trend observed in important sugarcane producing states encourages the assessment of the impacts of irrigation on the water footprint of sugarcane in Brazil. The increase of water withdrawals for sugarcane irrigation may lead to greater blue WF. However, in locations where water resources are available, sustainable sugarcane irrigation might lead to greater water productivity and, consequently, reduces sugarcane and sugarcane ethanol WF.

Given the wide range of values and implications for the water resources availability and management, the objective of this study was to assess, at the municipal and state levels, the green and blue WF of the main liquid biofuels produced in Brazil. Especial emphasis was given to sugarcane ethanol and the impacts of different irrigation strategies on the WF of sugarcane. Analyses were made for the traditional sugarcane producing states in the Brazilian Center-South region as well as for those states where the sugarcane area has shown a significant increase in the last decade. Additionally, the water requirements of the main crops cultivated in Brazil (sugarcane, soybean, corn and pasture) were evaluated in order to have an indication whether the expansion of bioenergy crops could lead to additional pressure on the water resources in Brazil.

Biofuels and land use in Brazil

In 2010, more than 45% of the domestic energy supply in Brazil was provided by renewable energy sources, with sugarcane products representing a remarkable share of 17.8% of the domestic supply.[14] Further, in 2010 the biodiesel blend mandate was set at 5% and the production reached 2.4 billion liters, while ethanol amounted almost 28 billion liters.[14]

The production of sugarcane ethanol in Brazil started back in 1930s, but only during the 1970s, the national ethanol program (Pro-álcool) was launched and the production boosted. With respect to biodiesel, a national program (PNPB) was launched in December 2004, starting in 2005 the ramp up blend mandate. Today, Brazil is among the largest producers and consumers of biodiesel in the world, using soybean as the main feedstock (about 80% of the total), and the second largest producer of ethanol.[14]

Over the last decade, the production of biofuels in Brazil experienced an impressive increase due to the implementation of the biodiesel program and the surge of flex fuel cars, which can run with any blend of the Brazilian gasoline C (E18-E25) and ethanol. Such rapid expansion, in combination with the expansion that is projected for the future, has brought the international attention about the potential environmental impacts from land-use change in Brazil, more particularly related to sugarcane ethanol. In fact, the total crop area in Brazil almost doubled (from

41.8 to 76.7 Mha) in the 1995–2006 period, but with a minor contribution from sugarcane.[15]

Brazil's total surface area is about 850 million hectares, composed of 65% forests and natural vegetation, 23% pasture lands, 7% perennial and annual croplands, and 4% urban settlements.[16] Soybean is currently the main crop, with a crop area of approximately 23 Mha, followed by corn (13 Mha) and sugarcane (9 Mha).[17] From 1996 to 2010, annual crops expanded 17.8 Mha, mostly due to the expansion of the soybean area (13 Mha). The corn area practically did not change, while sugarcane increased about 4 Mha. At the same time, the production of soybean and corn increased, respectively, 103% and 58%, while the planted area increased only 28%,[18] which highlights significant gains in production efficiency.

Pasture lands decreased 19 Mha from 1995 to 2006, but featuring a marked intensification of the cattle stocking rates, from 0.86 to 1.08 heads per hectare.[17] Actually, different strategies have been employed to increase pasture productivity (for example, through higher carcass weight per slaughtered cattle, lower slaughter age and improved reproduction parameters), which has released enough area for the expansion of other crops in Brazil without effects on the total beef production.

In the Brazilian Center-South region, where 99% of the recent sugarcane expansion has occurred, sugarcane expanded primarily onto pasturelands and annual croplands, being irrelevant the expansion on forest areas. However, Fig. 1 indicates that in many cases annual crops have first expanded over pastures and then converted to sugarcane. Such practice has been commonly adopted in order to improve soil quality in degraded pasture areas before establishing the sugarcane crop.[19,20] In the sugarcane production system, around 15% of the fields are renewed (terminated and replanted) every year. Commonly, an annual crop cycle is cultivated before replanting the sugarcane field.

Methods and data

This study assessed the water requirements of crops and WF of biofuels at municipal and state levels, for the traditional sugarcane producing states in the Brazilian Center-South region (São Paulo, Paraná, and Minas Gerais) and for those states where the sugarcane area has shown a significant increase in the last decade (Mato Grosso, Mato Grosso do Sul, and Goiás). The values for each state were calculated as the weighted average (with respect to crop production) calculated at the municipal level for the top ten producers within the state. Figure 2 shows the municipalities selected for the simulations, as well as the sugarcane areas in Brazilian Center-South and the major Brazilian hydrographic regions.

The climate data used in the calculations are from Embrapa Cerrados' database[21] and refer to a time series of at least 30 years. This is a reliable database as the primary climate data are treated to eliminate possible measurement and/or recording errors. Furthermore, it covers a more extensive list of municipalities in comparison to the CLIMWAT database,[22] which allows more accurate calcu-

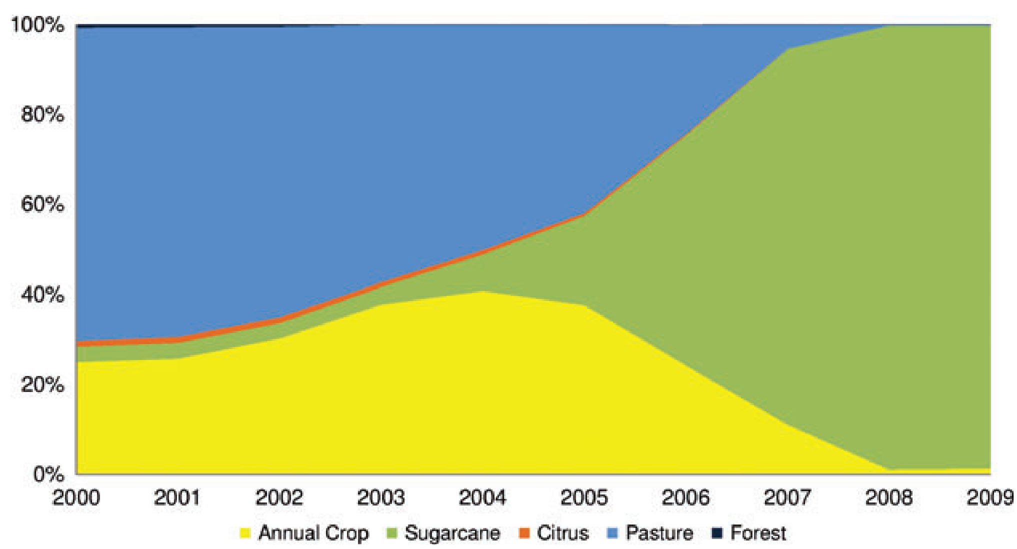


Figure 1. Land use change dynamics for sugarcane expansion in the Brazilian Center-South region. (Adapted from Adami *et al.*[20])

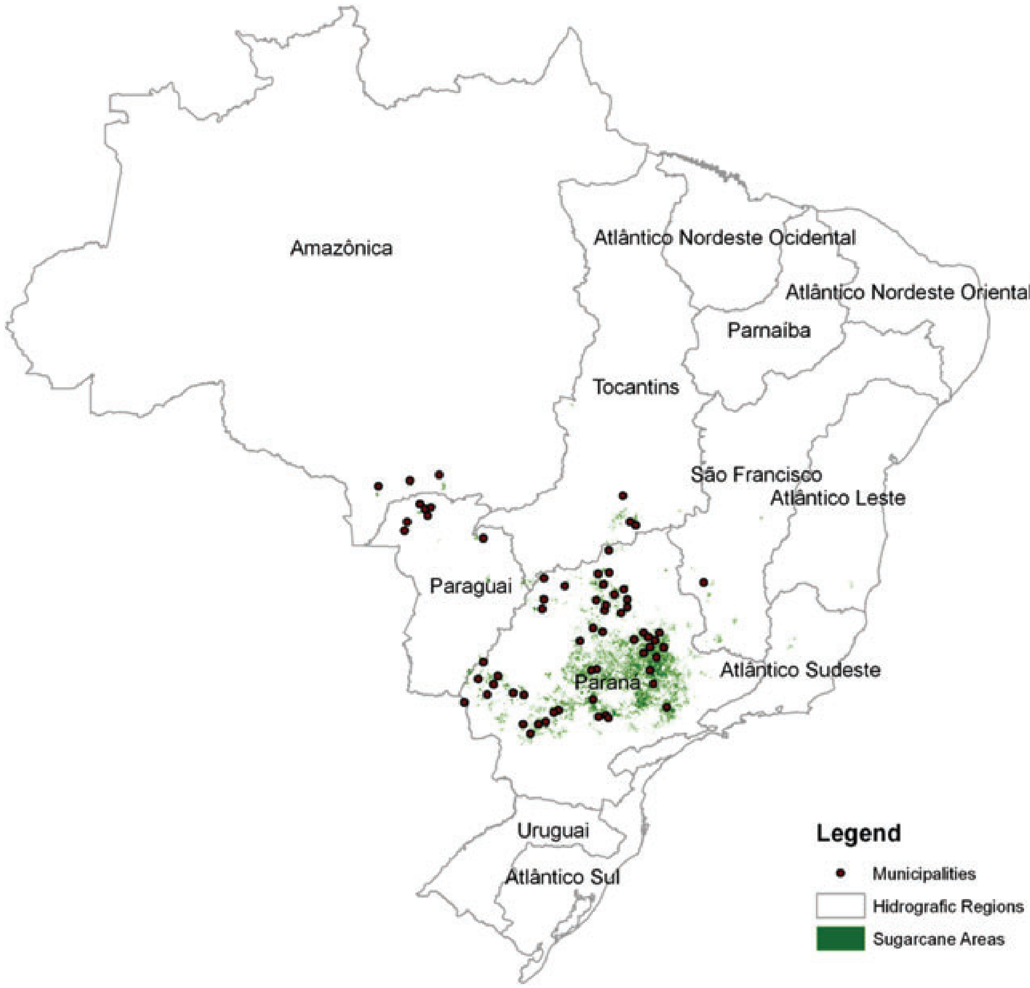


Figure 2. Selected municipalities for WF evaluation with respect to the major Brazilian hydrographic regions and the sugarcane areas[41] in the Brazilian Center-South.

lations. As for soil parameters, the simulations were made for a medium texture oxisol, which is an ordinary soil class in the Center-South region of Brazil. Table 1 presents the soil parameters adopted in this work.

The crop planting dates were set considering the Brazilian Agroecological Zoning[23] and the soybean sanitary break, adopting consistent planting and harvesting schedules especially for those cases involving crop rotation. For sugarcane, the ratoon cycle was simulated so that the planting and harvesting dates coincide. Tables 2 and 3 present the crop parameters used in the simulations. Table 2 brings the crop coefficients and the stage duration, and Table 3 presents the rooting depth and the planting dates. The remaining parameters are based on CROPWAT's default values.[24]

Table 1. Physical characteristics for a medium texture oxisol in Brazil.[a]

Parameter	Units	Value
Total available soil moisture	mm m^{-1}	100
Maximum rain infiltration rate	mm day^{-1}	100
Maximum rooting depth	cm	50
Initial soil moisture depletion	%	0

[a]From Embrapa Cerrados.[21]

Water footprint of biofuels

For the assessment of biofuels' WF, only the green water component was considered in the agricultural phase, hence the blue water (surface or groundwater), in this case, corresponds exclusively to the water used in the industrial phase. For biodiesel, a mass-based allocation was adopted to split the footprint between soy oil and soy meal, assuming the yields given in Mourad[25] (Table 4).

Table 2. Crop coefficients and stage durations.

Crop	Parameter[a]	Stage				Total (days)
		Initial	Development	Mid-Season	Late Season	
Corn	Kc	0.65	1.1	1.1	0.6	
	Duration	20	35	40	30	125
Soybean	Kc	0.6	1.05	1.05	0.6	
	Duration	10	40	50	20	120
Pasture	Kc	0.4	1.1	1.1	0.6	
	Duration	140	60	120	45	365
Sugarcane	Kc	0.5	1.25	1.25	0.8	
	Duration	30	60	180	95	365

[a]The crop coefficient (Kc) and the stage duration (in days) are from references.[21,36,42,43,44]

Table 3. Rooting depths and planting dates considered in the study.

Crop	Rooting Depth (m)[d]		Planting
	Minimum	Maximum	Date
Corn	0.15	0.3	Oct, 1st[a]
Winter corn	0.15	0.3	Feb, 20th[a]
Soybean	0.15	0.25	Oct, 5th[a]
Pasture	0.15	0.4	Mar, 3rd[b]
Sugarcane	0.25	0.45	Jul, 1st[c]

[a]Brazilian Agroecological Zoning.[23]
[b]Embrapa Gado de Corte.[33]
[c]UNICA.[39]
[d]From references.[21,36,42,43,44]

Table 4. Main parameters related to the conversion plants.

Parameter	Units	Biodiesel	Ethanol
LHV[a]	MJ L^{-1}	33.2	21.3
Fuel Yield[b]	L t^{-1}	189.2	80.4–84.9
Water withdrawal[c]	m^3 t^{-1}	24.2	1.85

[a]Lower heating value, from EPE.[14]
[b]Yields in L t^{-1} of feedstock.[25,40]
[c]Water withdrawal in m^3 t^{-1} of feedstock.[37,28] For biodiesel, it includes the water input for oil extraction (8.8 L t^{-1} of soybean) and conversion to biodiesel (92.7 L t^{-1} of biodiesel).

The glycerin co-produced in the transesterification process was disregarded in this assessment. For sugarcane ethanol, the analysis assumes an autonomous distillery and no co-products were accounted for, even though electricity has been progressively consolidated as an additional product of the sugarcane mill. Currently, the electricity surplus represents, on average, only 3% of the energy output from the mills.[26]

Filter cake and vinasse are important residues of the cane industry that are recycled to the field as organic fertilizers. Vinasse is the main liquid effluent, produced in a ratio of 10-15 L L^{-1} of ethanol, which is completely employed in cane fertirrigation. But such water input is relatively small, and its impact on the water footprint was neglected. Table 4 summarizes the main parameters considered for the industrial phase, which were assumed to be the same for all municipalities and states (except for ethanol yield).

It is worth mentioning the substantial reduction of the water withdrawal in the sugarcane mills as a result of the environmental legislation and progressive water reuse.[27] The water withdrawal used to be 15–20 m^3 t^{-1} of cane three decades ago, and today it has been reduced to about 1.85 m^3 t^{-1} of cane through water recycling, among other actions to improve the water use efficiency.[28] Actually, in many regions the water withdrawal permit was set at 1 m^3 t^{-1} of cane, and there are already mills operating around 0.7 m^3 t^{-1} of cane.

The method employed for the calculation of the WF was based on Hoekstra *et al.*,[29] using the CROPWAT 8.0 model as auxiliary tool.[30] The model was set with the 'Irrigation Schedule' mode in order to achieve better estimations of the actual crop water use. The reference crop evapotranspiration was calculated by the Penman Montheit equation, while the effective rainfall was estimated using the USDA Soil Conservation Service Method.[31]

The calculation of the WF considered the crop yields given by the Instituto Brasileiro de Geografia e Estatística (IBGE),[32] except for pasture, for which data were based on field measurements for Brachiaria.[33] IBGE's database contains the yields for all crops in each municipality under study, and in all cases the most recent data available for each crop were used in the analysis.

Impact of irrigation on the WF of sugarcane

Both salvage and full irrigation strategies were considered in the analysis, as the former is the most frequent irrigation management adopted in many regions in Brazil, while the later – despite not being common – provides estimations for an extreme scenario. A single application of 60 mm just after the initial stage (day 31) was adopted for the sugarcane salvage irrigation simulations, which ensure germination in dry periods.[34,35] For full irrigation, the conditions adopted according to the CROPWAT's default option, i.e. it was chosen the 'irrigate at critical depletion' mode and 'refill soil to field capacity' option, assuming optimal irrigation where the irrigation intervals are at a maximum while avoiding any crop stress.[29]

For those cases involving irrigation, the sugarcane yields were estimated according to Eqn (1), which relates the yield losses (%) due to the hydric stress[36] to the actual yield from IBGE.

$$Y_{IRR} = \frac{Y_{RF} \times (100\% - YL_{IRR})}{(100\% - YL_{RF})} \quad (1)$$

where Y_{IRR} is the irrigated yield; Y_{RF}, the rain-fed yield (from IBGE);[32] YL_{RF} and YL_{IRR}, the yield losses respectively for rain-fed and irrigated conditions (salvage or full irrigation), estimated using the CROPWAT model.

Water demand for different land use scenarios

In addition to the evaluation of the WF of biofuels, the water requirements of the main crops cultivated in Brazil (sugarcane, soybean, corn, and pasture) were also estimated. The annual water demand (evapotranspiration) per hectare was assessed considering five land use scenarios: sugarcane; cultivated pasture; soybean; soybean + winter corn and corn + winter corn. No estimations were made on blue water consumption for soybean, pasture and corn, since these crops are practically not irrigated in Brazil. The parameters used in the evaluation of the crop water requirement are given in Tables 1, 2 and 3.

Results

WF of biofuels

The WFs of the biofuel crops feature a significant variation among the states. Sugarcane values were between 124 m^3 t^{-1} (São Paulo) and 170 m^3 t^{-1} (Paraná) and the weighted average for the Center-South was 137 m^3 t^{-1}. For soybean, the WF was 1360 m^3 t^{-1} in the best case (Goiás) and 1781 m^3 t^{-1} in the worst case (São Paulo), reaching a weighted average of 1408 m^3 t^{-1}.

Such spatial variation is reflected in the WFs of biofuels, as shown in Fig. 3. As the industrial parameters are almost the same in all cases, virtually no differences exist among the states in terms of the blue WF of biodiesel and ethanol. Except for the state of São Paulo (SP), the total WF of ethanol is remarkably higher than for biodiesel. The most significant differences are verified in Mato Grosso do Sul (MS), Mato Grosso (MT), and Paraná (PR), where the WF of ethanol is approximately twice than biodiesel's. Further, much less blue water is required for biodiesel production than for ethanol, though the blue water content

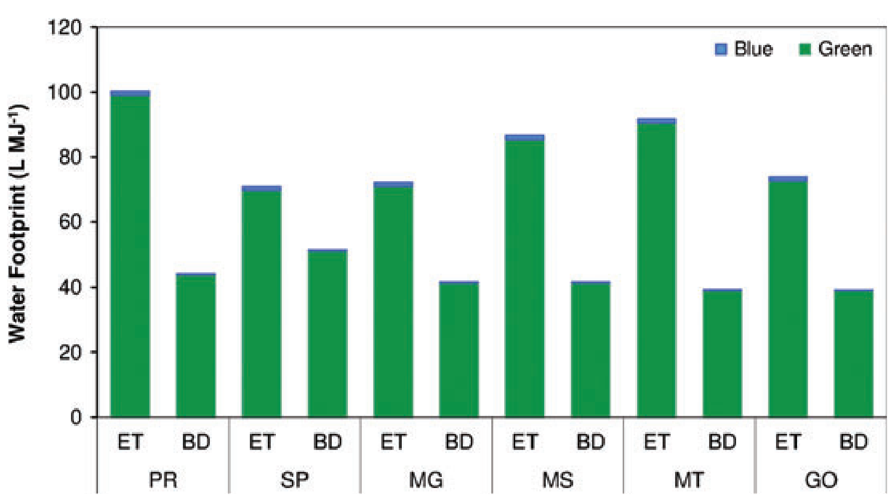


Figure 3. Water footprint of ethanol (ET) and biodiesel (BD). PR: Paraná; SP: São Paulo; MG: Minas Gerais; MS: Mato Grosso do Sul; MT: Mato Grosso; GO: Goiás.

is negligible for both fuels: less than 1.5% for ethanol and 0.01% for biodiesel.

Among the states, São Paulo (SP), Minas Gerais (MG), and Goiás (GO) show almost the same pattern regarding ethanol's WF (around 71 L MJ^{-1}). Mato Groso do Sul (MS) and Mato Grosso (MT) present somewhat higher values, whereas Paraná features a substantially higher WF, reaching almost 100 L MJ^{-1}. With respect to biodiesel, São Paulo shows the largest WF (51 L MJ^{-1}), while all other states present very similar results. The weighted average for soybean biodiesel in the Brazilian Center-South was around 40 L MJ^{-1}, and for sugarcane ethanol, about 78 L MJ^{-1}.

The crop and biofuel WF values found for each state, basically reflects their production water use efficiency, that depends on the differences of two variables: the crop evapotranspiration, that encompass the climatic conditions, including rainfall availability, and the yield potential, which encompass the soil conditions and the efficiency of production practices.

On one hand, if the magnitude of yield differences among regions is not significantly large, it is expected that regions that naturally have larger potential evapotranspiration would also present larger WF. This effect could be seen for the WF values found for biodiesel in São Paulo and Goiás. Both states present similar yield potentials (around 2.9 t ha^{-1}), but São Paulo's higher crop evapotranspiration resulted in higher biodiesel WF compared to Goiás. On the other hand, if the magnitude of crop evapotranspiration differences among regions is not significantly large, it is expected that regions with better soil conditions and/or more efficient production practices, would have higher yield potentials and lower WF values. This impact of the yield potential was clearly reflected in the WF values for sugarcane ethanol in São Paulo, Minas Gerais and Goiás. The evapotranspiration found for these states are similar, but the higher yield potential of São Paulo promoted a slightly lower WF values for the state.

As far as WF is concerned, and considering the rain-fed condition, the results indicate that Paraná is the least recommended state for ethanol production, while São Paulo presents the most suitable condition. For biodiesel, on the other hand, the largest WF occurs in the state of São Paulo, whereas the best performance is found in Goiás. For both fuels a relatively high discrepancy exists between the best and worst cases.

However, the WF methodology alone would not be appropriate to compare the sustainability nor to recommend the production of biofuel crops in one region or another. The sustainability of water use of a region is more related to the balance between water use and water availability. It means that producing biofuel crops in a region with larger WF, but with enough water supplies to fulfill that production, might be more sustainable than producing biofuel crops in regions with lower WF but without water supplies to support its production.

Comparing results from other works, the WFs found in this study are lower than those given in Resende Neto[37] (95 L MJ^{-1} for ethanol and 176 L MJ^{-1} for biodiesel), which represent the average of the locations of the top ten producers of bioethanol and biodiesel, respectively, in Brazil. Compared to the global averages provided in Mekonnen and Hoekstra[11] (85 L MJ^{-1} for ethanol and 337 L MJ^{-1} for biodiesel), the results were also lower, although with very different contributions from the blue water. The discrepancies among the estimates are essentially due to the differences related to evapotranspiration, crop yield values, length of crop development stages and climate data, which were less site-specific than those used in the present study. Further, Mekonnen and Hoekstra[11] used the higher heating values of biofuels, while this study presents the results with respect to the lower heating values. For biodiesel, however, substantial differences exist possibly due to the adoption of different allocation procedures to deal with the co-products from soybean, i.e. only 18% of the total evapotranspired water was attributed to biodiesel in the WF calculation.

Impact of sugarcane irrigation on WF

The impact of irrigation on the WF of sugarcane was estimated considering three water regimes: rain-fed (RF), salvage irrigation (SI) and full irrigation (FI). In all states (Fig. 4), the blue WF component increases with the use of irrigation, as expected. However, the total water footprint was reduced in about 1% and 7%, from the rain-fed to salvage and full irrigation regimes, respectively.

Among other variables, the WF of a crop depends largely on the crop water use efficiency – or crop water productivity – which is defined as the amount of harvestable biomass produced per unit of water evapotranspired by the crop. Under water stress conditions, actual crop evapotranspiration is reduced by a fraction of the crop potential evapotranspiration.[36] Consequently, productivity and water use efficiency are also reduced, increasing WF.[36] The greater the water stress a crop is submitted, the greater is the reduction of potential evapotranspiration, and the larger is the WF.[36] This is especially verified in the states of São Paulo and Minas Gerais, where the WF was reduced in about 1 and 9%, from the rain-fed regime to the salvage and full irrigation regimes, respectively.

Figure 4. Sugarcane water footprint considering three different irrigation regimes. RF: rain-fed; SI: salvage irrigation; FI: full irrigation.

These numbers suggest that São Paulo and Minas Gerais show the best performance in terms of converting irrigation water into higher yields, as the reductions of total water footprint with full irrigation are more significant and the blue WF components are the smallest among the states. However, it must be noted that those estimations did not take into account the differences in crop management between the locations, so experiments covering thorough irrigation regimes with a uniform crop management (soil, fertilizers, etc.) are necessary in order to draw more consistent conclusions about the water use efficiency.

Setting apart any dilemma regarding sugarcane and soybean as food or fuel, as it might be used either way, its worldwide demand as a feedstock is likely to continuously increase driven by consumption. In order to promote a rational and sustainable use of land and water resources, sustainable irrigation technologies and practices should be considered in regions where water resources are available in order to reduce land expansion pressure in other regions where land and water resources are limited. Increasing yield with sustainability might support the reduction of land and water resources to supply world's food and fuel demand.

Water demand for different land use scenarios

Figure 5 shows the water demand per hectare for five land-use scenarios. As sugarcane presents by far the highest above ground productivity among those crops, its water demand per hectare is also the largest (more than 11 000 m^3 ha^{-1} yr^{-1}). Cultivated pasture appears in the second position, followed by corn + winter corn, soybean + winter corn and finally soybean. Besides the low productivity, the relatively low water demand of soybean is explained by the fact that the crop area is occupied for only few months (4–5) throughout the year. However, it is known that during the remaining months evapotranspiration also occurs, either due to bare soil evaporation, some vegetation spontaneously emerged, or ground cover plants associated with no-tillage (although none of these aspects were considered here).

Since sugarcane expansion in Brazil has occurred essentially over areas covered with pasture and annual crops,[19,20] Fig. 5 suggests that such expansion has led to additional evapotranspiration. According to the simulations, the impact on the water demand is smaller when the expansion takes place over pasture lands, followed by areas with two corn crops. It must be noted, however, that most of the expansion has occurred over degraded pastures,[19,20] which possibly feature different water demands. Additionally, it shall be considered that when sugarcane or annual crops take place over degraded pastures, rainfall interception and infiltration patterns (rainfall harvest) also change, usually increasing rainfall harvest.[36] Regardless, it is not possible to conclude whether the additional evapotranspiration or rainfall harvest promoted by sugarcane expansion (or of any other crop) will lead to improved or critical water availability situations without further analyses on the water availability in each region. Water quality aspects are relevant as well, and in terms of overall sustainability and water resource management,

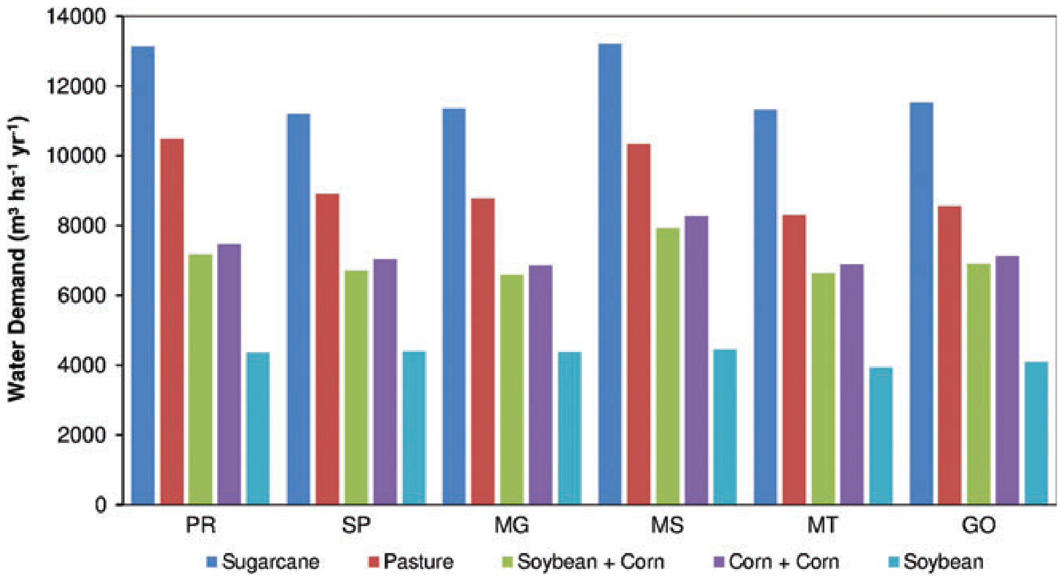


Figure 5. Water demand for different land use scenarios.

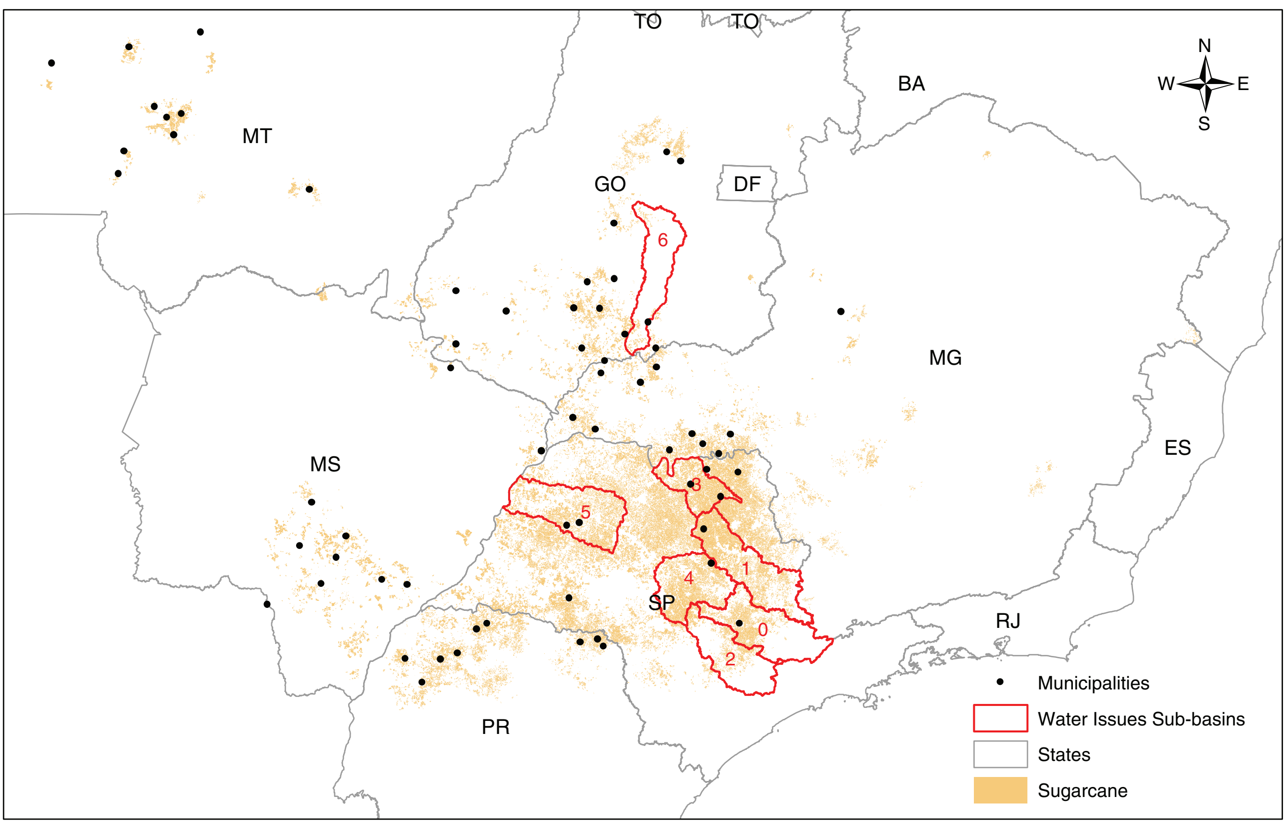


Figure 6. Sub-basins featuring water issues in terms of quality or/and quantity. Sugarcane areas according to Canasat.[41]

other factors should also be considered, such as soil cover, rain interception, infiltration and soil sediments erosion, which are quite different for those land use scenarios.[36]

The analysis on these matters should therefore initially include the assessment of the current situation in terms of water availability and quality issues in the basins where

Table 5. Sub-basins featuring water issues in terms of quality or/and quantity.

Sub-basin[a]	State	Municipalities	Water Issues[b] (%)	
			Quantity[c]	Quality[d]
Tietê/Jacaré (4)	São Paulo	Araraquara	> 40	0.5–1
Baixo Pardo/Grande (3)	São Paulo	Barretos, Morro Agudo, Guaíra	20–40	1–5
Baixo Tietê (5)	São Paulo	Araçatuba, Guararapes	> 40	0.5–1
Mogi-Guaçu (1)	São Paulo	Jaboticabal	10–20	1–5
Tietê/Sorocaba (2)	São Paulo	Piracicaba	> 40	5–20
Meia Ponte (6)	Goiás	Bom Jesus de Goiás, Goiatuba, Itumbiara	> 40	5–20
Piracicaba/Capivari/Jundiaí (0)	São Paulo	Piracicaba	> 40	> 20

[a]Refer to Fig. 6.
[b]According to ANA.[38]
[c]Ratio between the withdrawal and water availability.
[d]Ratio between the pollutants discharge and the assimilation capacity of the water bodies.

sugarcane has been expanding. Some of these aspects are discussed below, based on the data provided by ANA.[38] Figure 6 and Table 5 present the sub-basins that feature water issues in terms of quality or/and quantity[38] and the municipalities (among those investigated here) which are in their influence areas. As described in ANA's annual report,[38] the analysis of water quality refer to the assimilation capacity of the water bodies, and the water availability was determined by the ratio between the withdrawal and the water availability.

The vast majority of the municipalities considered in this study is located in the Paraná basin (Fig. 2), while those sites in Mato Grosso are either in the Amazônica or Paraguai basins. As 99% of the watercourses in the Amazônica basin show excellent or comfortable situations in terms of water availability,[38] water issues should not be critical in the region. In the Paraguai basin, on the other hand, 35% of the watercourses are currently categorized under critical or very critical situations[38] – despite the vast extension of wetlands – but none of the selected sites are located in areas with water issues today.

In the Paraná basin, some sites are already under critical water conditions. This region hosts the most developed area of the country and concentrates 32% of the Brazil's population, with an extremely high urbanization level. In 2010, the total water demand in the region amounted to 6.4% of its average flow, corresponding to 31% of the total water demand of the country.[38]

In the state of Goiás, regarding the Meia-Ponte basin , the ratio between water withdraw and water availability is higher than 40% and the pollutants discharge is between 5 and 20% of the maximum water bodies assimilation capacity. This critical state, both in terms of water quality and quantity, affects the selected municipalities of Bom Jesus de Goiás, Goiatuba, and Itumbiara. In the remaining cities in Goiás state, no water concerns exist today.

Water issues are especially concerning in the state of São Paulo, where three sub-basins present quantitative problems, and two sub-basins show both qualitative and quantitative issues. Piracicaba is the municipality featured with the major water problems, presenting in 2010 a pollutant discharge higher than 20% of the water bodies' assimilation capacity and water withdraw/water availability higher than 40%. In despite of the large crop area in the state (especially sugarcane, with approximately 5 Mha),[15] the water problems in the region are highly related to population pressure in metropolitan areas, with large water demand for urban supply and industrial activities. Still, 77% of the watercourses in this basin are classified under excellent or comfortable situations, while 75% and 5% show respectively excellent and good water quality standards.[38]

The Paraná basin is characterized by a high consumptive demand (in good part due to the São Paulo and Curitiba metropolitan areas), and not by coincidence is also one of the Brazilian basins where water management is most structured. At present, there are forty state committees installed and most of the states in the basin have already elaborated their master plan on water resources.[38]

All these aspects suggest that, despite the additional evapotranspiration imposed by sugarcane, no severe impacts should be expected from sugarcane expansion in Brazil. Regarding blue water, irrigation has become more common in the Center-South region, but it is still essentially linked to supplementary irrigation (either to restore soil moisture at field capacity or provide water needs during water stress periods), or salvage irrigation (to promote a better ratoon sprouting and extend the sugarcane fields lifespan, i.e. number of harvests).[27] As irrigation volumes are usually small, critical water stress situations would hardly be reached, especially in the water-consuming state of São Paulo, where the rain-fed conditions are appropriate for sugarcane cultivation.

At the industry phase, water withdrawal has been substantially reduced. Over the last two decades, the sugarcane industry in the state of São Paulo has increased the production while reducing the relative water use – it now accounts for 25% of industrial sector use and 8% of total water use in the state, but projected to decline to less than 1% of the state's total water use by 2015.[27]

Conclusion

Bioenergy has been seen as one of the main options to enhance energy security and mitigate climate change. On the other hand, criticisms have been raised about the potential environmental impacts of biofuels production, including those on water quality and availability. Brazil is already marked today by the strong participation of modern biomass in the country's energy supply system, and a substantial expansion of bioenergy is expected for the future, which has raised concerns about the implications for the current comfortable situation in terms of water resources availability.

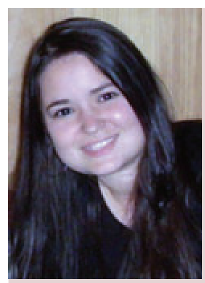
This study assessed the water footprint of the main liquid biofuels produced in Brazil, capturing the differences between the main producing states in the Brazilian Center-South region. The analysis showed that the blue water component is negligible for both soybean biodiesel and sugarcane ethanol, as the use of irrigation is still limited today. However, important regional differences exist regarding the total water footprint of ethanol. Significant lower values were found for the states of São Paulo, Minas Gerais, and Goiás, while for biodiesel the differences among the states are minor. It is interesting to note that São Paulo is the most efficient state in terms of WF of ethanol, but presents the largest WF for biodiesel.

The impacts of different irrigation strategies on the WF of sugarcane were also estimated, showing that full irrigation practices would lead to lower WFs in all states, though in the expense of larger volumes of blue water. Regarding land use change, the results suggest that additional evapotranspiration has been verified due to sugarcane expansion over pastures and croplands. Nevertheless, given the current situation of the Brazilian water basins, there is no evidence that sugarcane expansion over these areas will lead to critical pressure on water resources. Still, local analyses are necessary to properly investigate the implications of changes in land use and crop management for the water balance of specific sites.

References

1. Walter A, Dolzan P, Quilodran O, de Oliveira JG, da Silva C, Piacente F *et al.,* Sustainability assessment of bio-ethanol production in Brazil considering land use change, GHG emissions and socio-economic aspects. *Energ Policy* **39**(10):5703–5716 (2011).
2. FAO, *Aquastat.* [Online]. (2013). Available at: http://www.fao.org/nr/water/aquastat/main/index.stm Accessed on [19 September 2013].
3. Gerbens-Leenes W, Hoekstra AY and van der Meer TH, The water footprint of bioenergy. *P Natl Acad Sci USA* **106**(25):10219–10223 (2009).
4. Jury WA and Vaux H, The role of science in solving the world's emerging water problems. *P Natl Acad Sci USA* **102**(44):15715–15720 (2005).
5. Ward FA and Pulido-Velazquez M, Water conservation in irrigation can increase water use. *P Natl Acad Sci USA* **105**(47):18215–18220 (2008).
6. Berndes G, Bioenergy and water - the implications of large-scale bioenergy production for water use and supply. *Global Environ Chang* **12**(4):253–271 (2002).
7. Gerbens-Leenes PW, Hoekstra AY and van der Meer T, The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bio-energy in energy supply. *Ecol Econ* **68**(4):1052–1060 (2009).
8. Gerbens-Leenes W and Hoekstra AY, The water footprint of sweeteners and bio-ethanol. *Environ Int* **40:**202–211 (2012).
9. Wu M, Mintz M, Wang M and Arora S, Water consumption in the production of ethanol and petroleum gasoline. *Environ Manage* **44**(5):981–997 (2009).
10. Gerbens-Leenes W and Hoekstra AY, The water footprint of biofuel-based transport. *Energ Environ Sci* **4**(8):2658–2668 (2011).
11. Mekonnen M and Hoekstra A, The green, blue and grey water footprint of crops and derived crop products. *Hydrol Earth Syst Sc* **15**(5):1577–1600 (2011).
12. IBGE, *Censo agropecuário 2006: Brasil, Grandes Regiões e Unidades da Federação.* Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro, Brasil (2009).
13. Pinto R, Afférri A, Díaz P, Elias A and Trento E, Resultados preliminares da pesquisa sobre a cana irrigada no Brasil. Projeto Cana Pede Água (2011).
14. EPE, *Brazilian Energy Balance 2011 Year 2010*. Empresa de Pesquisa Energética, Rio de Janeiro (2011).
15. Hernandes T, Walter A, Galdos M and Cunha M, A review of recent land use change driven by sugarcane expansion in Brazil. *20th European Biomass Conference and Exhibition*, Milan, Italy, 18–22 June 2012 (2012).
16. RedeAgro, *Rede de Conhecimento do Agro Brasileiro* [Online]. (2012). Available at: http://www.redeagro.org.br [16 January 2012].
17. IBGE, *Sistema de Recuperação Automática. Base de Dados Agregados: Instituto Brasileiro de Geografia e Estatística.* [Online]. (2012). Available at: http://www.sidra.ibge.gov.br [16 January 2012].

18. CONAB. *Séries históricas*. [Online]. Available at: www.conab.gov.br [21 January 2013].
19. Nassar AM, Rudorff BFT, Antoniazzi LB, Aguiar DA, Bacchi MRP and Adami M, Prospects of the sugarcane expansion in Brazil: Impacts on direct and indirect land use changes, in *Sugarcane Ethanol: Contributions to Climate Change Mitigation and the Environment*, ed by Zuurbier P and van den Vooren J. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 63–93 (2008).
20. Adami M, Rudorff BFT, Freitas RM, Aguiar DA, Sugawara LM and Mello MP, Remote sensing time series to evaluate direct land use change of recent expanded sugarcane crop in Brazil. *Sustainability* **4**(4):574–585 (2012).
21. Embrapa, Collection of internal reports. Embrapa Cerrados. Brasília, DF, Brazil (2012).
22. FAO, *CLIMWAT for CROPWAT: A climatic database for irrigation planning and management. Irrigation and Drainage,* paper No. 49. Food and Agriculture Organization, Rome, Italy (1993).
23. MAPA, Zoneamento Agrícola – Portarias segmentadas por UF [Online]. Ministério da Agricultura, Pecuária e Abastecimento (2012). Available at: http://www.agricultura.gov.br [06 February 2012].
24. FAO, *CROPWAT: A computer program for irrigation planning and management. Irrigation and Drainage,* paper No. 46. Food and Agriculture Organization, Rome, Italy (1992).
25. Mourad AL, Avaliação da produção de Biodiesel a partir da Soja em sua Cadeia Produtiva. Unicamp, Campinas, Brazil (2008).
26. Seabra J, Macedo I, Chum H, Faroni C, Sarto C. Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use. *Biofuel Bioprod Bioref* **5**(5):519–532 (2011).
27. Yeh S, Berndes G, Mishra G, Wani S, Neto A, Suh S *et al.,* Evaluation of water use for bioenergy at different scales. *Biofuel Bioprod Bioref* **5**(4):361–374 (2011).
28. ANA, FIESP, UNICA and CTC, *Manual de conservação e reúso de água na agroindústria sucroenergética*. ANA, Brasília, pp. 288 (2009).
29. Hoekstra AY, *The Water Footprint Assessment Manual: Setting the global standard*. Earthscan, London (2011).
30. FAO, *CROPWAT 8.0.* FAO, Rome (2013).
31. Dastane NG, *Effective rainfall in irrigated agriculture.* Food and Agriculture Organization, Rome, Italy (1978).
32. IBGE, IBGE Cidades, *Instituto Brasileiro de Geografia e Estatística.* Available at: www.ibge.gov.br [May 2012].
33. Embrapa, *Pastagem: Tecnologias*. Embrapa Gado de Corte (2010).
34. ANP, *Anuário Estatístico Brasileiro do Petróleo e do Gás Natural 2013*. ANP, Rio de Janeiro (2013).
35. REN21. *Renewables 2013 Global Status Report.* REN, Paris (2013).
36. Allen RG, Pereira LS, Raes D and Smith M, *Crop evapotranspiration: Guidelines for computing crop water requirements. Irrigation and Drainage,* paper 56. FAO, Rome, Italy (1998).
37. Resende Neto A, *Sustentabilidade, água virtual e pegada hídrica: Um estudo exploratório no setor bioenergético*. Universidade Federal do Rio Grande do Sul, Porto Alegre (2011).
38. ANA, *Conjuntura dos recursos hídricos no Brasil: Informe 2012.* Agência Nacional de Águas, Brasília, DF, pp. 215 (2012).
39. UNICA, *União da Indústria da Cana-de-Açúcar 2012* [Online]. Available at: www.unica.com.br [06 February 2012].
40. CONAB, *Acompanhamento de safra brasileira: Cana-de-açúcar, segundo levantamento, agosto/2011*. Companhia Nacional de Abastecimento, Brasília (2011).
41. Canasat, Sugarcane crop monitoring in Brazil [Online]. (2013). Available at: http://www.dsr.inpe.br/laf/canasat/en [21 January 2013].
42. Doorenbos J, Pruitt WO, Guidelines for predicting crop water requirements. Irrigation and Drainage, paper 24. FAO, Rome, Italy (1977).
43. Silva TGF, Moura MSB, Zolnier S, Soares JM, Vieira VJS, Gomes Júnior WF. Requerimento hídrico e coeficiente de cultura da cana-de-açúcar irrigada no semiárido brasileiro. *Revista Brasileira de Engenharia Agrícola e Ambiental* **16**(1):64-71 (2012).
44. Inman-Bamber NG, McGlinchey MG. Crop coefficients and water-use estimates for sugarcane based on long-term Bowen ratio energy balance measurements. *Field Crop Res* **83**(2):125-138.



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