Estimation of the water footprint of sugarcane in Mexico: is ethanol production an environmentally feasible fuel option?

María Eugenia Haro, Ines Navarro, Ralph Thompson and Blanca Jimenez

ABSTRACT

Energy policies are taken throughout the world to reduce fossil fuel emissions from transportation sources. Agriculturally based biofuels are currently the only alternatives to liquid fossil fuels. However, as biofuel production spreads, so too do its cascading impacts on environment and food security. This paper analyzes the impact of Mexican ethanol-sugarcane policy on water resources. The water footprint of sugarcane (WFsc) was quantified for an agricultural region in Jalisco, Mexico, and used to estimate anthropologic water demand and stress index. This analysis was performed using historical climate data, and for projected changes under scenarios A2 and B1, using ECHAM and GFDL models. The average historical water footprint of sugarcane was estimated as 104.9 m³/ton, total average water demand as 152.3 Mm³/year and a historical water scarcity index as 59%. Under climate change, the footprint might increase 2% by 2020 and 3–4% by 2050. The available water is predicted to fall 4–7% by 2020, and 6–8% by 2050, with negative effects on water stress. Due to the strong influence of local factors on water footprint and stress, additional research is needed for all Mexican sugarcane regions, in order to evaluate the feasibility of the policy regarding the use of ethanol for transportation.

Key words | biofuel, climate change, ethanol, sugarcane, water footprint

INTRODUCTION

Increasing energy use, concerns about air quality, climate change resulting from greenhouse gas (GHG) emissions, and falling global oil reserves make switching to sustainable, low-emissions fuels a high priority. Some proposals to reduce fossil fuel dependence are the use of hydrogen fuel cells, hybrid electric vehicle technologies, and the use of alternative biofuels such as ethanol and biodiesel. Relative to the fossil fuels they displace, Hill et al. (2006) suggest that GHG emissions may be reduced 12% by the production and combustion of ethanol, and 41% by biodiesel.

Aggressive renewable energy policies have helped the biofuel industry grow at a rate few could have predicted. Global production of ethanol and biodiesel increased from around 18.2 billion liters in 2000 to 79.5 billion liters in 2008. In the United States alone, the production of corn ethanol was estimated at 34 billion liters in 2008 (Earley & McKeown 2009).

Agriculturally based biofuels from food crops, such as corn and sugarcane, used to produce ethanol, and soybeans, jatropha and palms, used for biodiesel production, are currently the only alternatives to liquid fossil fuels being produced profitably and in large volumes (Himmel et al. 2007), despite the potential of second-generation biofuels such as cellulosic-ethanol and algae-biodiesel.

Biofuel is potentially part of the solution to the world’s energy and climate change problems. But as biofuel production spreads around the world and the market for biofuels expands, so too do its cascading indirect impacts in the social, economic, and environmental spheres.

The growing demand for cleaner burning and more sustainable fuels, such as ethanol, is likely to generate changes in agricultural cropping patterns and land management practices. Many feedstocks require a large area, and their efficient
large-scale production generally involves monocultures (Sawyer 2008).

Depending on the location, previous land use and technology, the direct ecological effects of the expansion of cane monoculture may include depletion or loss of biodiversity, and soil erosion or loss of fertility, with the latter due to contamination, compaction, and loss of organic matter (Honty & Gudynas 2007). There is also an impact on water resources – for example, cane production and processing consumes huge quantities of water, as much as four liters per liter of ethanol. Furthermore, clear fields accelerate run-off, reducing infiltration of rainwater into the soil and aquifers, and potentially affecting water supplies in downstream reservoirs during the dry season (Lima & Silva 2002). Water may also become polluted with pesticides, and nitrogen and phosphorus from fertilizers (Hill et al. 2006). Impacts on the atmosphere include massive CO₂ emissions due to woodland clearing; greenhouse gas emissions (N₂O) from fertilizer use; and smoke and ash emissions from the widespread practice of burning sugarcane fields before manual cutting.

Water consumption for the production of biofuel feedstocks is a relevant impact of concern, recognizing that the global freshwater withdrawal has increased nearly seven-fold in the past century (Gleick 2000). With a growing population, coupled with changing dietary preferences, water withdrawals are expected to continue to increase in the coming decades (Rosengrant & Rinder 2000).

The recent major studies on global water consumption by agriculture were performed by Rost et al. (2008), Siebert & Döll (2008, 2010), Liu et al. (2009), Hanasaki et al. (2010), Liu & Yang (2010), Mekonnen & Hoekstra (2010), and Knox et al. (2012). These studies estimate the ‘blue’ virtual water content for several crops, based on coarse spatial resolutions that treat countries, continents, or even the entire world as a whole. The blue virtual water consumption for the production of a crop, also known as the crop’s water footprint, is defined as the total volume of freshwater that is used to produce the product (Hoekstra et al. 2009).

Mekonnen & Hoekstra (2010) found that the global average water footprint varies according to the type of crop, increasing from sugar crops (roughly 200 m³/ton), vegetables (300 m³/ton), roots and tubers (400 m³/ton), fruits (1,000 m³/ton), cereals (1,600 m³/ton), and oil crops (2,400 m³/ton), to pulses (4,000 m³/ton). They found that the water footprint varies within crop categories as well as by production region, and their estimation of the water footprint of sugarcane under irrigated agriculture (104 m³/ton) was almost half the global average (200 m³/ton).

Recent studies address local-regional blue, grey and/or water footprint of bioethanol production based on historical data analysis (Dalla et al. 2012), or sugarcane-ethanol production targets that implies competition for water resources (Kongboon & Sompattagul 2012). Another example is the Ghana study where sugarcane cultivation is planned and Black et al. (2012) found that it is possible to generate approximately 75% of the yield achieved in the Sao Paulo region, provided there is sufficient irrigation, and only explored an idealized temperature increase climate change scenario.

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In this context, and in keeping with international trends, Mexican energy policy has established mitigation goals to reduce GHG emissions. One of its strategies is the use of biofuels for transportation (SEMARNAT-INE 2009), with the short-term objective of producing ethanol from the 40 million tons of sugarcane that are on average produced nationally each year. However, there is no published research regarding the viability of producing sugarcane for ethanol production from the point of view of water availability.

Considering that Mexico is an arid and semi-arid country which consumes large volumes of water per capita (roughly 4,506 m³/capita/year) and taking into consideration that the agricultural sector accounts for around 77% of the total blue water resources (SEMARNAT 2011), the topic of water is relevant to the proposed mitigation plans for biofuel production.

For that reason, the aim of this research is to assess the water footprint of sugarcane by focusing on accounting the blue water footprint only as an indicator of consumptive use of water, fresh surface or groundwater, due to national water scarcity. In addition, three irrigation systems (flood, sprinkler, drip) are evaluated to analyze their impact on water saving with the purpose of contributing to the
exploration water strategies. It is done within a geographically delineated area on a daily-monthly temporal analysis with available data. And in order to get an idea of what the foot-print size means, a water balance model is applied as Hoekstra et al. (2011) suggest, to assess the available freshwater and the water scarcity index, with locally specific input data.

This study quantifies the blue water footprint of sugarcane (WFsc) production in the agricultural area of Tamazula, Jalisco State, Mexico, for a baseline scenario. A water balance model taking local climatic conditions into account was used to calculate, with a daily time step, crop water requirements over time, current crop water use, and finally the crop blue water footprint. This analysis was performed using historical climate data (baseline scenario), and also for projected changes under scenarios A2 and B1, using the models ECHAM and GFDL. The water availability and the demand on water services were also estimated for the region in order to evaluate the current impact of the WFsc on the local water resources.

**METHODOLOGY**

**Site description**

The Tamazula region is located at the western part of Mexico, in Jalisco state, in the municipality of Tamazula de Gordiano, and has a population of 126,246 (Comisión Estatal del Agua (CEA) 2011). The study region is located in a plain area with a mean altitude of 1,100 meters above sea level (MASL). The region has a tropical climate tempered by altitude, with mean annual temperature and precipitation of 20.9 °C and 897 mm, respectively (CEA 2011). The historical (1980–2007) temperature (minimum, maximum and average values) and precipitation daily recorded in the meteorological station 14141 (19°41’12.93”N, 105°13’53.17”W, 1152 MASL) and the relative humidity and wind speed data daily recorded in the agro-climatological station ITS-Tamazula (19°40’N, 105°15’W, 1140 MASL) during 2010, were the available data for this study.

The main surface water resource in the region is the Coahuayana River with an average annual flow rate of 10.6 m³/s. In the river basin a low per capita water availability level of 3,902 m³/person/yr (2005) has been estimated with a high water stress index of about 44% (CONAGUA 2009).

Tamazula is considered as an agricultural region; the main crops are sugarcane, beans and chickpeas. There is a sugar mill for sugar production, which during the 75 days of sugar harvesting in 2010 processed almost two million liters of ethylic alcohol as a secondary product (Unión Nacional de Cañeros (UNC) 2011). The major productive activities are focused in those of the sugar mill and the alcohol production; other minor activities are livestock, forestry to supply paper mill, and mining extraction (iron, barite and gypsum).

In the Tamazula region, sugarcane is grown in more than 15,500 ha, and has an average annual yield of 110 ton/ha – the second highest in Mexico (UNC 2011), where the average national yields are 92.4 ton/ha in irrigated land and 64.1 ton/ha in non-irrigated land (SAGARPA 2009). Moreover, the land used to grow sugarcane has complex irrigation systems, which have been progressively updated to improve efficiency. In around half of the land, water is supplied by traditional flood irrigation systems, with the remaining half evenly split between sprinklers and drip irrigation systems. These irrigation systems are not common practice spread over the five sugarcane regions of the country, where only 40% of the national sugarcane surface uses irrigation systems, mainly through flood irrigation channels, and supply 49% of the national sugar production.

**Estimation of the water footprint**

The approach proposed by Hoekstra et al. (2009) for the water footprint of crops was used for the specific conditions of sugarcane grown in the Tamazula region. This technique provides a framework to analyze the link between human consumption and appropriation of local freshwater. Therefore, the water footprint of sugarcane (WFsc, m³/ton) was calculated by dividing the total volume of crop water requirement (CWU, m³/ha), by the crop yield (Y, ton/ha) (Equation (1)). The crop water requirement is the water needed for ideal growing conditions, measured from planting to harvest, and allowing for evapotranspiration. ‘Ideal conditions’ means that adequate soil water is maintained by rainfall and/or irrigation so that it does not limit plant growth and crop yield. CWU is calculated using the sum
of the daily crop evapotranspiration \((ET_{sc}, \text{mm/day})\) over the length of the sugarcane growing period, from the day of planting \((d = 1)\) to the day of harvest \((d = N)\). A constant factor of 10 is used in Equation (2) to convert from water depths (mm) to water volumes per unit area \((\text{m}^3/\text{ha})\).

\[
WF_{sc} = \frac{CWU}{Y}
\]

\[
CWU = 10 \sum_{d=1}^{N} ET_{sc,d}
\]

The daily evapotranspiration for sugarcane, \(ET_{sc}\), was calculated from the reference crop evapotranspiration \(ETo\), and the crop factor for sugarcane \(K_{sc}\) at the different stages in its growing cycle, as described by Brouwer & Heibloem (1986). \(ETo\) expresses the evaporating power of the atmosphere at a specific location and time of the year, and does not consider the crop characteristics or soil factors. For this research, \(ETo\) was estimated with the Penman-Monteith method suggested by the Food and Agriculture Organization (FAO)-56 (Allen et al. 2006) (Equation (3)) for local radiation (sunshine), air temperature, relative humidity, and wind speed conditions, based on measurements recorded by a climatic station in Tamazula.

\[
ET_0 = \frac{1}{\lambda} \left[ \frac{\Delta(Rn - G) + \rho_a c_p((e_s - e_a)/r_a)}{\Delta + \gamma(1 + (r_s/r_a))} \right]
\]

where \(\lambda\) is latent heat of vaporization; \(\Delta\) represents slope of saturation vapor pressure temperature relationship, \(Rn\) is net radiation, \(G\) is soil heat flux, \((e_s-e_a)\) represents vapor pressure deficit of the air, \(\rho_a\) is mean air density at constant pressure, \(c_p\) is specific heat of the air, \(\gamma\) is psychometric constant, and \(r_s\) and \(r_a\) are (bulk) surface and aerodynamic resistances.

**Estimation of water scarcity**

The blue water scarcity index \((WS_{blue})\), also known as water intensity use index, was calculated over the municipal area of Tamazula, using the approach proposed by Hoekstra et al. (2009). The blue water scarcity in a defined area \((WS_{blue})\) is defined as the ratio of the areas total anthropogenic blue water demand \((WD_{blue})\) (which includes the blue biofuel demand) to the total available blue water resources \((WA_{blue})\), as follows:

\[
WS_{blue} = \frac{WD_{blue}}{WA_{blue}}
\]

A blue water scarcity index of one hundred percent means that all the available blue water is being consumed. Water stress conditions are considered to have occurred for values over 20%, and any value above this indicates excess demand and probable environmental stress.

Total blue water availability \((WA_{blue}, \text{m}^3/\text{yr})\) was estimated as natural renewable water, which is the amount of water that is replaced by precipitation each season minus the amount lost due to evapotranspiration, as described by Equation (5):

\[
WA_{blue} = [P - E] \times A \times f
\]

where \(P\) is the cumulative precipitation (mm/yr); \(A\) is the area of the zone under consideration, in this case the Tamazula municipality \((\text{km}^2)\); \(f\) is a unit conversion constant; and \(E\) is the cumulative evapotranspiration (mm/yr) estimated using the cumulative precipitation and the average temperature \((T_C)\) in Equations (6) and (7), following Turc (1954):

\[
E = \frac{P}{\left[0.9 + (P/L)^{0.5}\right]^{0.5}}
\]

\[
L = 300 + 25T + 0.05T^3
\]

Total anthropogenic blue water demand \((WD_{blue})\) was estimated using Equation (8):

\[
WD_{blue} = D_{muni} + D_{agri}
\]

where \(D_{muni}\) is the municipal demand, estimated by multiplying the total population by the usage per person (given as 150 L/person/day by Aparicio et al. 2006); and \(D_{agri}\) is the agricultural demand, estimated using Equation (9):

\[
D_{agri} = (WF_{sc} \cdot Y) \sum_{i=1}^{5} A_{fi}
\]
where: WF_{sc} and Y are the calculated water footprint of sugarcane (m$^3$/ton) and the local sugarcane yield (ton/ha) respectively, and the areas ($A_i$) and inefficiencies ($f_i$) take their values from the types of irrigation used in the region, as shown in Table 1. Note that this calculation only considers demand for the irrigation of sugarcane, and due to a lack of available data, demand for other crops and from industry is not included.

**Baseline scenario**

The WF_{sc} baseline scenario was calculated with precipitation and temperature historical data (station 14141, 1980–2007) based on daily evapotranspiration estimation, considering the daily mean for the climatic parameters. It was assumed that is possible to transfer data, without losing characteristic in climate patterns description, between meteorological station 14141 and ITS-Tamazula data; since both are located at a similar elevation ($\pm 12$ m) and within the same area of influence, according to results of the Thiessen method analysis applied to the region. Therefore, the daily local climatic data of relative humidity and wind speed recorded in ITS-Tamazula station were used; these values for the year 2010 were the only data available, and were taken as a constant value for the 27 years estimation. Another assumption, due to the absence of historical data, was the use of data from 2010 sugarcane production as constant values, for yield, total irrigation area and the percentage area irrigated with different irrigation systems. This assumption agrees with the Hoekstra et al. (2011) approach proposed when different periods are combined in one analysis: for example, taking production and yield data for a recent period but data on climate (temperature and precipitation) as an average for the past 30 years.

It should be emphasized that the assumptions mentioned were also applied for the climate change scenarios.

<table>
<thead>
<tr>
<th>Type of irrigation</th>
<th>$I$</th>
<th>Area (ha) $A_i$</th>
<th>Inefficiency factor* $f_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood</td>
<td>1</td>
<td>7,750</td>
<td>1.00</td>
</tr>
<tr>
<td>Sprinkler</td>
<td>2</td>
<td>3,875</td>
<td>0.70</td>
</tr>
<tr>
<td>Drip</td>
<td>3</td>
<td>3,875</td>
<td>0.56</td>
</tr>
</tbody>
</table>


In addition, the WF_{sc} calculated refers to the evapotranspiration of irrigation water from the crop field only. It excludes the evaporation of water from artificial surface water reservoirs built for storing irrigation water and also the evaporation of water from transport canals that bring the irrigation water from the place of abstraction to the field.

**Climate change scenarios**

Precipitation and temperature projections were used in this research to develop a future sugarcane production scenario. For this study two global climate models (GCMs) – ECHAM5 and GFDL – were selected to obtain the projections for the A2 and B1 scenarios, which are among those which are recommended for climate impact studies for Mexico (Conde et al. 2011). Conde et al. (2011) analyzed the results of bias estimation for Mexican projections generated from 20 general circulation models. They showed the root mean square error and the bias and root mean square error corrected by bias. Their main conclusion was that three models were chosen to reasonably represent the uncertainty range (ECHAM, HADGEM, and GFDL models under A2 and B1 scenarios). These models provide a broad range of possible temperature increases and, more importantly, they provide increases as well as reductions in precipitation for the impact studies in Mexico. In fact, those results of the bias analysis, revealed that the ECHAM model had a better performance at a global level and for the region of Mexico than all other models (Conde et al. 2011); meanwhile, the GFDL model showed the worst performance.

The projected monthly precipitation and temperature data for 2020 and 2050 were obtained from the Pacific Climate Impacts Consortium (PCIC) Regional Analysis Tool (PCIC 2012), as recommended for Mexican studies (Conde et al. 2008), which provides downscaling of future climate projections to regions and local sites.

PCIC is an interface to derive estimates of future climate projections from individual GCMs and ensembles from a 0.5 grid resolution. The (minimum, mean, maximum) temperature and (accumulated) precipitation projections are available as anomalies data in $^\circ$C and %, respectively. For this study, the monthly mean temperature and accumulated precipitation anomalies were downloaded (Table 2) from
the grid corresponding to the Tamazula region; the data columns recorded in Table 2 correspond to the mean temperature and precipitation anomalies projected over 2011–2040 time period for 2020 data columns, and 2041–2070 time period for 2050 data columns. The development done for the 2020 and 2050 data horizon, agrees with the time periods recognized for the projections downloaded from the Pacific Climate Impacts Consortium’s Regional Analysis Tool used for this research (Murdock & Spittlehouse 2014).

For estimating the future monthly sugarcane water footprint and water availability in the region as well, the historical daily precipitation and temperature data (1980–2007) from the meteorological station 14141, were corrected with the projected anomalies from the PCIC; this procedure is in agreement with the Murdock & Spittlehouse (2011) study that recommends to application of the anomalies to the baseline climate of the location of interest. Figure 1 illustrates the mean monthly precipitation behavior between the historical data and the 1961–1990 baseline data, which was used in the PCIC process to generate the future estimations; it shows that the highest difference between the mean values occurred for August and April months, but it is less than one standard deviation (0.6 and 0.8 respectively).

Thus, the WFsc estimated for historical data represent the baseline for comparison purposes with climate change scenarios. In addition, changed values for yield and the agricultural land area devoted to sugarcane production were considered, and a regional balance was also analyzed with the future water availability calculation, using the methodology previously described.

Data used

For crop evapotranspiration estimation, relative humidity and wind speed daily data recorded in the ITS-Tamazula station during 2010 were used, as well as local data such as the altitude in Tamazula. The values used for the other parameters were the average quantities founded in the FAO database (2006); Tables 3 and 4 summarize the values used in this study.

RESULTS AND DISCUSSION

The analysis was performed with historical data from meteorological station 14141 for the period 1980–2007 between February and September, during which irrigation

<table>
<thead>
<tr>
<th>Mean temperature anomalies [°C]</th>
<th>Precipitation anomalies [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2020</strong></td>
<td><strong>2050</strong></td>
</tr>
<tr>
<td>GFDL</td>
<td>ECHAM 5</td>
</tr>
<tr>
<td>A2</td>
<td>B1</td>
</tr>
<tr>
<td>Jan</td>
<td>0.7</td>
</tr>
<tr>
<td>Feb</td>
<td>1.1</td>
</tr>
<tr>
<td>Mar</td>
<td>1.6</td>
</tr>
<tr>
<td>Apr</td>
<td>1.6</td>
</tr>
<tr>
<td>May</td>
<td>1.4</td>
</tr>
<tr>
<td>Jun</td>
<td>1.3</td>
</tr>
<tr>
<td>Jul</td>
<td>1.3</td>
</tr>
<tr>
<td>Aug</td>
<td>1.1</td>
</tr>
<tr>
<td>Sept</td>
<td>1</td>
</tr>
<tr>
<td>Oct</td>
<td>1</td>
</tr>
<tr>
<td>Nov</td>
<td>0.7</td>
</tr>
<tr>
<td>Dec</td>
<td>0.7</td>
</tr>
</tbody>
</table>
is practiced on the 15,500 ha of Tamazula sugarcane land. The historical precipitation behavior observed in the region varied from 0 to 95 mm/d. Daily temperature recorded by the meteorological station varied from 3 to 45 °C, with an average of 22 °C. With this information and for the parameters data listed in Tables 3 and 4, the daily reference evapotranspiration ET₀ was estimated for historical data. It showed a variation from 1.9 to 7.1 mm/day, with the highest values observed between April and September.

Applying the collected data as described in the methodology, the total historical average available (renewable) water resource in the Tamazula region was calculated to be 255 Mm³/year. According to the climate models considered, this value is predicted to fall in the future (Table 5) under the ECHAM model (4–8%) with the ECHAM B1 being the worst scenario for both horizon, 2020 and 2050. In contrast, the GFDL climate model is predicting markedly higher available water (11–38%) than the historical average availability. However, both models in general are consistent with predicting less water by 2050 than 2020.

Using the historical weather data to calculate the crop water demand, and the current value of the yield (110 tons/ha), the historical sugarcane water footprint for the irrigation period (Figure 2) was calculated to vary between 100 to 107 m³/ton with annual average of 104.9 m³/ton; a value which is comparable to the estimated range between 120 and 410 m³/ton (Gerbens-Leenes & Hoekstra 2012) and which leads to an estimate of historical average of 152.3 Mm³/year for the total anthropologic water demand (of which, 145.7 Mm³/year is related to the average irrigation of sugarcane, and the remaining 6.6 Mm³/year is the estimated average municipal demand).

**Figure 1** | Mean precipitation behavior between baselines of observed data 1980–2007 and PCIC 1961–1990 data.

**Table 3** | Parameters used to calculate the sugarcane water footprint in the Tamazula region

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Units</th>
<th>Min</th>
<th>Mean</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latent heat of vaporization</td>
<td>( \lambda )</td>
<td>MJ/kg</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Rate of change of saturation vapor pressure with temperature</td>
<td>( \Delta )</td>
<td>Kpa/°C</td>
<td>0.009</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>Net radiation</td>
<td>( R_n )</td>
<td>MJ/m²d</td>
<td>15</td>
<td>20</td>
<td>23</td>
</tr>
<tr>
<td>Soil heat flux</td>
<td>( G )</td>
<td>MJ/m²d</td>
<td>–2</td>
<td>–0.0014</td>
<td>2</td>
</tr>
<tr>
<td>Mean air density</td>
<td>( \rho_a )</td>
<td>Kg/m³</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Specific heat capacity of air</td>
<td>( \varepsilon_p )</td>
<td>MJ/kg °C</td>
<td>0.0009</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Aerodynamic resistance</td>
<td>( r_a )</td>
<td>KPa/°C</td>
<td>58</td>
<td>210</td>
<td>1228</td>
</tr>
<tr>
<td>Wind speed</td>
<td>( u_2 )</td>
<td>m/s</td>
<td>0</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Temperature</td>
<td>( T )</td>
<td>°C/d</td>
<td>13</td>
<td>19</td>
<td>25</td>
</tr>
</tbody>
</table>
The 145.7 Mm³/yr estimation of agricultural water demand considers three irrigation systems in Tamazula (see Table 1); so the local water footprint varies between 58.7 m³/ton for drip irrigation, 73.4 m³/ton for sprinkler irrigation and 104.9 m³/ton under a flood irrigation system. Thus, there is net water saving of 18.5% which represents around 33 million m³ due to installed water irrigation systems, and it is equivalent to providing drinking water for more than 604,000 people for a year.

Under climate change, the evapotranspiration, and hence crop water demand, is expected to be affected by changes in temperature and precipitation, among other factors, so the crop water demand was recalculated for each scenario and climate model taking these changes into account. The results are shown in Table 6, and under inspection it can be seen that there is no great difference predicted between scenarios or models, with all models predicting an increase of approximately 2% in water footprint by 2020, and a 3 to 4% increase by 2050, when compared to the value for historical annual average water footprint (104.9 m³/ton). The table also shows the predicted total water demand, based on the average predicted water footprint of sugarcane, which shows a similarly modest increment over time when compared to the historical average of 152.3 Mm³/year for the total anthropologic water demand.

It should be noted that due to limited available data, the demand had to be estimated using a crude multiplication of the population and typical personal usage, in the case of municipal demand; and of the irrigated area with the crop water demand per hectare, using an ‘inefficiency factor’ to allow for different irrigation infrastructure, in the case of agricultural demand; ignoring other crops and industrial users. Due to this, the estimate of demand presented here is only a rough approximation of the true demand. Even if more detailed data were available, an annual variability in the total water demand is expected in the region, due to the continuous expansion of agricultural land in the Tamazula region for sugarcane production. This development is not seen in any other sugarcane region in the country.

Other factors that may influence the irrigated area, and therefore total water demand, are national variations in the price of sugar and its indirect sub-products, as well as

![Figure 2](https://iwaponline.com/jwcc/article-pdf/5/1/70/374978/70.pdf)
fluctuations in the price of other crops. For example, some years ago, an increase in the price of avocado encouraged its production, and reduced the land area devoted to sugarcane within a year. Thus, it is recognized that an important obstacle in the support of sugarcane production for biofuel use is the lack of a governmental policy that guarantees a competitive price of ethanol vs. sugar price, in order to encourage investments in technology to improve agricultural production, and upgrade refinery plants for the production of ethanol. Finally, it should be highlighted that the Tamazula region is atypical nationally in terms of its high yield, and may represent a best case scenario for Mexico in terms of its water footprint. Furthermore, despite the high yield, the production is insufficient to meet the goals established by Mexican government.

Using the estimates for the total historical average available water, 255 Mm$^3$/year, and the total water demand, the water stress could be calculated for the different time periods considered. For the historical scenario, the calculated average value was 59.7%, which is higher than 20% and hence indicates a condition of water stress, although it is less than the 2009 estimation (see site description). The results of the analysis under the different climate change scenarios are shown in Table 7. The models vary in the severity of their predictions, but all predict an increase in water stress in the future under climate change, with ECHAM predicting higher values as a result of its lower predictions for available water.

The predicted values for the water stress index were calculated assuming that the irrigation area and sugarcane yield per hectare remain constant at their 2010 values. However, this may not be the case – changing climatic conditions may reduce the yield, which may lead to a corresponding increase in irrigated area in order to compensate. In an attempt to analyze some of the potential effects of this, the calculations were redone, firstly just assuming a reduced yield of 72 tons/ha (the national average), and secondly assuming a reduced yield and a compensated 10% increase in the irrigated area. The first scenario leads to a 55% increase in the sugarcane water footprint (Table 8). The second scenario gives the same increase in water footprint, and also increases the total water demand by 29%. This has the effect of increasing the predicted water stress (Table 9).

The results show that when using current values of yield and irrigated area, the water stress index is predicted to increase to between 51 and 77% by 2020, and between 60

### Table 6: Water footprint and total blue water demand under A2 and B1 climate change scenarios

<table>
<thead>
<tr>
<th>Year</th>
<th>Predicted water footprint [m$^3$/ton]</th>
<th>Total water demand [Mm$^3$/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>107.2</td>
<td>107.0</td>
</tr>
<tr>
<td>2050</td>
<td>109.0</td>
<td>109.0</td>
</tr>
</tbody>
</table>

### Table 7: Water stress index in Tamazula, as projected under A2 and B1 climate change scenarios

<table>
<thead>
<tr>
<th>Year</th>
<th>A2 [%]</th>
<th>B1 [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GFDL</td>
<td>ECHAM</td>
</tr>
<tr>
<td>2020</td>
<td>61.6</td>
<td>74.2</td>
</tr>
<tr>
<td>2050</td>
<td>60.7</td>
<td>77.2</td>
</tr>
</tbody>
</table>

### Table 8: Predicted water footprint of sugarcane under climate change, assuming the yield drops to the national average (72 ton/ha)

<table>
<thead>
<tr>
<th>Year</th>
<th>A2 [m$^3$/ton]</th>
<th>B1 [m$^3$/ton]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GFDL</td>
<td>ECHAM</td>
</tr>
<tr>
<td>2020</td>
<td>163.8</td>
<td>163.4</td>
</tr>
<tr>
<td>2050</td>
<td>166.6</td>
<td>166.5</td>
</tr>
</tbody>
</table>

### Table 9: Water stress index in Tamazula under climate change, assuming the yield drops to the national average (72 ton/ha) and the irrigated area increases by 10%

<table>
<thead>
<tr>
<th>Year</th>
<th>A2 [%]</th>
<th>B1 [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GFDL</td>
<td>ECHAM</td>
</tr>
<tr>
<td>2020</td>
<td>67.8</td>
<td>81.6</td>
</tr>
<tr>
<td>2050</td>
<td>66.8</td>
<td>84.9</td>
</tr>
</tbody>
</table>
and 80% by 2050. If we assume that climate change or other factors lead to a drop in the local yield to the present national average, and that the irrigated area increases by 10% as a result, the predicted water stress is between 57 and 84% by 2020, and between 66 and 87% by 2050. Therefore, as water stress index is sensitive to local conditions, it needs to be calculated on a case by case basis for all sugarcane producing regions if a serious analysis of the feasibility of producing ethanol for transportation is to be undertaken.

CONCLUSIONS

This preliminary approach to water demand in one of the most productive sugarcane regions of the country, reveals that historical sugarcane water footprint for the irrigation period varies between 100 to 107 m³/ton with annual average of 104.9 m³/ton; but is has been improved to 58 and 73 m³/ton in agricultural Tamazula land where efficient irrigation systems are applied, showing that important amounts of water savings may be achieved as well. However, under future climate change scenarios and unpredictable agricultural conditions the water footprint is predicted to increase to between 106 and 167 m³/ton. In addition, the water model balance applied indicates that future predicted water stress index might be greater than 51%. Based on these results, local studies are suggested mainly in the low and medium water availability regions of the country, where 90% of the sugarcane surface is located. Any local study should compare the water footprint to an appropriate local water balance model at a monthly level in order to identify temporal or long-term water scarcity; it will contribute to formulation of strategies to reduce water footprints and associated local impacts, and will ensure national energy and water security when considering any biofuels mitigation measure.

For decision making purposes, this information should be combined with impact analyses for other types of alternative energy, such as wind or geothermal in the case of Mexico, although this depends on the final use of the energy, given biofuels can be easily used in existing transport systems while the others are limited to use in electric vehicles. In light of what has been found, Mexico should research second generation biofuels, and use them to replace the first generation technologies.

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