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

María Eugenia Haro[1], Ines Navarro[*], Ralph Thompson[1], Blanca Jimenez[1]

[1] Institute of Engineering, Universidad Nacional Autónoma de México, Apdo. Postal 70472, 04510 Coyoacán, México D.F. Tel: (+52) 55 5623 3600. Fax: 55 5616-2164. Email: INavarroG@iingen.unam.mx

* Corresponding author

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 analyses the impact of Mexican ethanol-sugarcane policy on water resources. The water footprint of sugarcane (WF_{sc}) 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 current water footprint of sugarcane was estimated as 98m^3/ton, a total water demand of 142.9Mm^3/year and a water scarcity index of 39%. Under climate change, the footprint might increase 2% by 2020 and 3-4% by 2050. The available water in the region is predicted to fall 3-32% by 2020, and 16-36% by 2050, with negative effect 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.

Keywords: 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 greenhouse gas 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 4.8 billion gallons in 2000 to 21 billion gallons in 2008. In the United States alone, the production of corn ethanol was estimated at 9 billion gallons 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 worlds 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 litres per litre 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 CO_2 emissions due to woodland clearing; greenhouse gas emissions (N_2O) 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 feedstock's 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 (Rosegrant and Rigler, 2000).

The recent major studies on global water consumption by agriculture were performed by Rost et al. (2008), Siebert and Döll (2008; 2010), Liu et al. (2009), Hanasaki et al. (2010), Liu and Yang (2010), and Mekonnen and Hoekstra (2010). 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 crops water footprint, is defined as the total volume of freshwater that is used to produce the product (Hoekstra et al., 2009).

Mekonnen and Hoekstra (2010) found that the global average water footprint varies according to the type of crop, increasing from sugar crops (roughly 200 m^3/ton), vegetables (300 m^3/ton), roots and tubers (400 m^3/ton), fruits (1000 m^3/ton), cereals (1600 m^3/ton), and oil crops (2400 m^3/ton), to pulses (4000 m^3/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 m^3/ton) was almost half the global average (200 m^3/ton).

In this context, and in keeping with international trends, Mexican energy policy has established 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 4,306 m^3/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 plans for biofuel production.

This study quantifies the blue water footprint of sugarcane (WF_{sc}) production in the agricultural area of Tamazula, Jalisco State, Mexico, for the year 2010. 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, 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 WF_{sc} on the 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 (CEA, 2011). Agriculture is the main activity in the region and sugarcane is one of the principal crops. It 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). 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. In the region there is also a sugar mill for sugar production, which during the 75 days of sugar harvesting in 2010 processed almost two million litres of ethylic alcohol as a secondary product (UNC, 2011).

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 during 2010. This technique provides a framework to analyze the link between human consumption and appropriation of local freshwater. Therefore, the water footprint of sugarcane (WF_{sc}, m^3/ton) was calculated by dividing the total volume of crop water requirement (CWU, m^3/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}, 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 (m^3/ha).

$$WF_{sc} = \frac{CWU}{Y} \qquad (1)$$

$$CWU = 10 \sum_{d=1}^{N} ET_{sc,d} \quad (2)$$

The daily evapotranspiration for sugarcane, ET_{sc}, was calculated from the reference crop evapotranspiration (ET_o), and the crop factor for sugarcane (K_{sc}) at the different stages in its growing cycle, as described by Brouwer & Heibloem (1986). ET_o 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, ET_0 was estimated with the Penman-Monteith method suggested by 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.

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

(3)

where λ is latent heat of vaporization; Δ represents slope of saturation vapour pressure temperature relationship, R_n is net radiation, G is soil heat flux, (e_s - e_a) represents vapour pressure deficit of the air, ρ_a is mean air density at constant pressure, c_p is specific heat of the air, γ is psychometric constant, and r_s and r_a are (bulk) surface and aerodynamic resistances.

The WF_{sc} calculated here 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 the evaporation of water from transport canals that bring the irrigation water from the place of abstraction to the field.

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:

$$WS_{blue} = \frac{WD_{blue}}{WA_{blue}} \quad (4)$$

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}, m^3/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:

$$WA_{blue} = |P - E| \cdot A \cdot f \quad (5)$$

Where: P is the cumulative precipitation (mm/yr); A is the area of the zone under consideration, in this case the Tamazula municipality (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):

$$E = \frac{P}{[0.9 + (P/L)^2]^{0.5}}$$

(6)

$$L = 300 + 25T + 0.05T^3$$

(7)

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

$$WD_{blue} = D_{mun} + D_{agri}$$

(8)

Where: D_{mun} 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:

$$D_{agri} = (WF_{sc} \times Y) \sum_{i=1} A_i f_i \qquad (9)$$

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.

Table 1: Values used in the calculation of agricultural water demand

Type of irrigation	i	Area (ha) A_i	Inefficiency factor [1] f_i
Flood	1	7750	1.00
Sprinkler	2	3875	0.70
Drip	3	3875	0.56

[1] Value from Narayanamoorthy, 2004; 2006

Climate change scenarios

Precipitation and temperature projections were used in this research to develop a future sugar cane production scenario. The projections were made for the A2 and B1 scenarios and the ECHAM and GFDL general circulation models, which are among those which give the best fit with Mexican historical climate behaviour (Conde et al., 2011). The projected monthly precipitation and temperature data for 2020 were obtained from PCIC (2012), and the data received is summarized in Table 2. Changed values for yield and the agricultural land area devoted to sugarcane production were also considered, and a regional balance was also analyzed with the future water availability calculation, using the methodology previously applied for 2010. The remainder of the parameters, needed to estimate the water footprint was left unchanged, because they have a complex relation with atmospheric process and any change would only increase the uncertainties in the estimations.

Table 2: Precipitation and temperature data, 2020

	Temperature anomalies [°C]				Precipitation anomalies [%]			
	GFDL		ECHAM 5		GFDL		ECHAM 5	
	A2	B1	A2	B1	A2	B1	A2	B1
Jan	0.7	1.2	0.9	1.0	-39	-33	25	-45
Feb	1.1	0.9	0.8	1.3	-23	18	-2	-22
Mar	1.6	1.3	1.3	1.1	-71	-45	-2	-13
Apr	1.6	1.4	1.3	0.7	-56	-66	17	12
May	1.4	1.9	1.3	0.9	-13	-50	-9	-2
Jun	1.3	1.5	1.1	0.7	-7	-3	2	4
Jul	1.3	1.1	1.2	0.9	2	8	-7	-11
Aug	1.1	1.1	1.2	0.9	19	19	-5	0
Sept	1.0	1.1	1.0	0.7	11	59	-3	5
Oct	1.0	0.9	0.6	0.5	10	-24	3	-23
Nov	0.7	1.1	1.1	0.6	-3	13	-9	-34
Dec	0.7	1.0	1.1	1.1	-30	-7	-17	-29

Data used

For crop evapotranspiration estimation, daily data recorded in the climate station ITS-Tamazula during 2010 was used (minimum, maximum, and average values of: temperature, precipitation, relative humidity, and wind speed), as well as other local data such as the altitude in Tamazula. Table 3 and Table 4 summarize the values used in this study.

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

Parameter	Symbol	Units	Min	Mean	Max
Latent heat of vaporization	λ	MJ/kg	2	2	3
Rate of change of saturation vapour pressure with temperature	Δ	Kpa/°C	0.009	0.03	0.05
Net radiation	R_n	MJ/m^2d	15	20	23
Soil heat flux	G	MJ/m^2d	-2	-0.0014	2
Mean air density	ρ_a	Kg/m^3	1	1	1
Specific heat capacity of air	c_p	MJ/kg°C	0.0009	0.001	0.001
Aerodynamic resistance	r_a	KPa/°C	58	210	1228
Wind speed	u_2	m/s	0	1	3
Temperature	T	°C/d	13	19	25

Table 4: Constants used to calculate the sugarcane water footprint in the Tamazula region

Constant	Symbol	Units	Value
Yield	Y	ton/ha	110
Psychometric constant	γ	KPa/°C	0.058
Bulk surface resistance	r_s	s/m	70
Altitude	z	m	1152

Results and Discussion

The analysis was performed for the period between February and September, during which irrigation is practiced on the 15,500 ha of Tamazula sugarcane land. The precipitation behaviour observed in the region varied from 0.2 to 89 mm/d, with a daily average of 3 mm and a drought period between the months of March and May. Daily temperature recorded by the climatic station varied from 13 to 25°C, with an average of 19°C. With this information, and for the parameters data listed in Table 3 and Table 4, the daily reference evapotranspiration ET_0 was estimated for

2010 (Figure 1). It showed a variation from 2.7 mm/day to 6 mm/day, with the highest values observed between April and September.

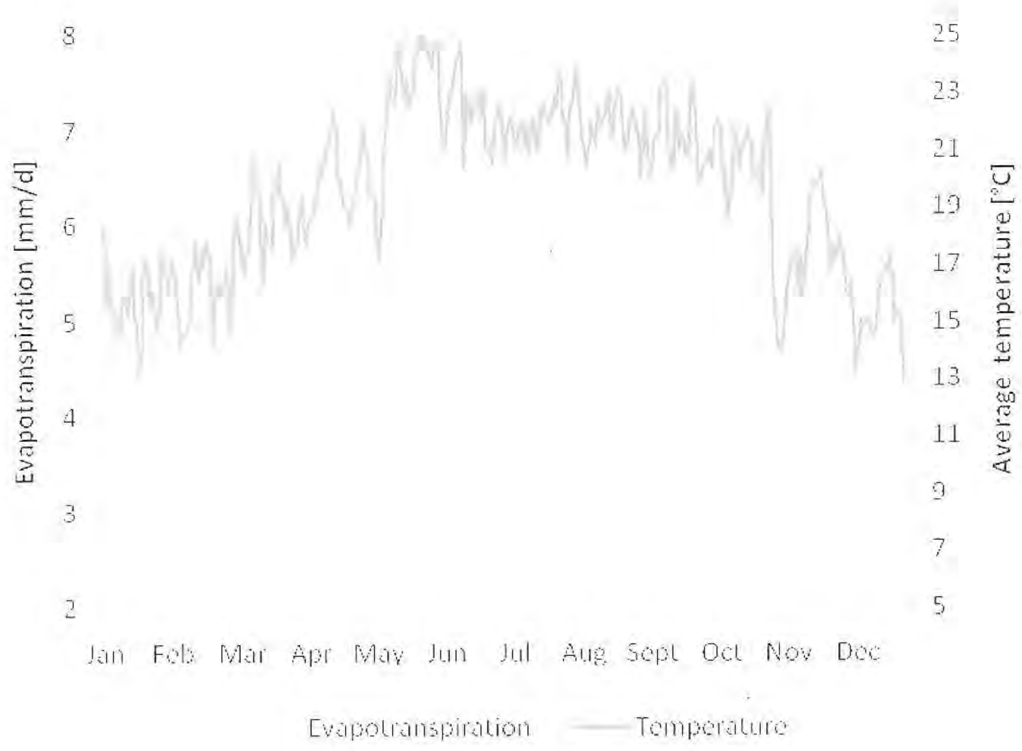

Figure 1: Daily evapotranspiration estimations and temperature pattern in Tamazula region, 2010

Applying the collected data as described in the methodology, the total available (renewable) water resource in the Tamazula region in 2010 was calculated to be 364 Mm^3/year. According to the climate models considered, this value is predicted to fall in the future (Table 5), generally to a greater extent under the B1 scenario, and with the ECHAM climate model predicting markedly higher changes than GFDL. Even in the best of the cases considered, the available water is expected to drop by more than 15% by 2050, a change which is likely to have a profound impact on the agriculture and way of life of the local population.

Table 5: Total available water in Tamazula (Mm^3/year), as projected under the four climate change models

	A2		B1	
Year	GFDL	ECHAM	GFDL	ECHAM
2020	296.5	245.8	352.1	236.5
2050	306.2	240.8	283.6	234.3

Using the historical weather data to calculate the crop water demand, and the current value of the yield (110 tons/ha), the sugarcane water footprint was calculated to be 98.1 m^3/ton, a value which is comparable to the estimated global average of 104 m^3/ton (Mekonnen and Hoekstra, 2010) and which leads to an estimate of 143.2 Mm^3/year for the total anthropologic water demand (of which, 136.3 Mm^3/year is related to the irrigation of sugar cane, and the remaining 6.9 Mm^3/year is the estimated municipal demand). 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 **¡Error! No se encuentra el origen de la referencia.**, 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 2010 (98.1 m^3/ton). The table also shows the predicted irrigation and total water demand, based on the average predicted water footprint of sugarcane, which show a similarly modest increment over time when compared to 2010 levels.

Table 6: Water footprint and total blue water demand under the four climate change scenarios

Year	Predicted water footprint [m^3/ton]				Total water demand [Mm^3/year]			
	A2		B1		A2		B1	
	GFDL	ECHAM	GFDL	ECHAM	GFDL	ECHAM	GFDL	ECHAM
2020	100.5	100.3	100.5	99.7	147.6	147.3	147.6	146.5
2050	102.5	102.5	101.2	102.1	150.3	150.3	148.6	149.8

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 a 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 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 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 available water and the total water demand, the water stress could be calculated for the different time periods considered. For 2010, the calculated value was 39.6%, which is higher than 20% and hence indicates a condition of water stress. 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.

Table 7: Water stress index in Tamazula, as projected under the four climate change models

Year	A2		B1	
	GFDL	ECHAM	GFDL	ECHAM
2020	49.8%	59.9%	41.9%	61.9%
2050	49.1%	62.4%	52.4%	63.9%

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 53% 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 9.5%. This has the effect of increasing the predicted water stress (Table 9).

Table 8: Predicted water footprint of sugarcane (m^3/ton) under climate change, assuming the yield drops to the national average (72 ton/ha)

	A2		B1	
Year	GFDL	ECHAM	GFDL	ECHAM
2020	153.6	153.2	153.6	152.3
2050	156.6	156.6	154.7	156.1

Table 9: Water stress index in Tamazula (m^3/ton) under climate change, assuming the yield drops to the national average (72 ton/ha) and the irrigated area increases by 10%.

	A2		B1	
Year	GFDL	ECHAM	GFDL	ECHAM
2020	54.5%	65.6%	45.9%	67.8%
2050	53.7%	68.3%	57.3%	70.0%

The results show that when using current values of yield and irrigated area, the water stress index is predicted to increase to between 42 and 62% by 2020, and between 49 and 64% 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 46 and 68% by 2020, and between 54 and 70% 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

As expected, when they require irrigation, for example in Mexico, biofuels represent a significant water demand. Even when using efficient irrigation techniques, the viability of producing ethanol from sugarcane will depend on the availability of water, the level of scarcity and the change in water demand for other uses, as well as the predicted effects of climate change on these factors. 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.

References

Allen R.G., Pereira L.S., Raes D. and Smith M. (2006). *Crop evapotranspiration. Guidelines for computing crop water requirements.* FAO Irrigation and drainage, Paper 56, Rome, pp298.

Aparicio, M.J., Lafragua, C.J., Gutiérrez, L.A., Mejía, Z. R., Aguilar, G.E. (2006). *Evaluación de los recursos hídricos.* UNESCO

Brouwer, C. & Heibloem, M., 1986. Irrigation Water Management: Irrigation Water Needs, Rome: FAO. Available online at: www.fao.org/docrep/S2022E/s2022e00.htm#Contents [Accessed May 8, 2012].

CEA (2011). Región OS Sureste. Sistema de Información del Agua, Comisión Estatal del Agua, Jalisco. Available online at: www.ceajalisco.gob.mx [Accessed May 15, 2012].

Conde, C., Estrada, F., Martínez, B., Sánchez, O., Gay, C. (2011). Regional climate change scenarios for México. *Atmósfera* **24**(1), 125-140.

Earley, J., McKeown, A. (2009). *Red, White, and Green: Transforming U.S. Biofuels.* Worldwatch Institute. ISBN 13: 978-1-878071-90-3

Gleick, P.H. (2000). The changing water paradigm: a look at twenty-first century water resources development. *Water International*, **25**(1), 127-138.

Hanasaki, N., Inuzuka, T., Kanae, S. and Oki, T. (2010). An estimation of global virtual water flow and sources of water withdrawal for major crops and livestock products using a global hydrological model. *Journal of Hydrology*, **384**, 232-244.

Hill, J., Nelson, E., Tilman, D., Polasky, S. and Tiffany, D. (2006). Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. Proceedings of the National Academy of Science, **103**(30), 11206–11210.

Himmel M E, Ding S-Y, Johnson D K, Adney W S, Nimlos M R, Brady J W and Foust T D (2007). Biomass recalcitrance: engineering plants and enzymes for biofuels production. *Science*, **315** 804–807

Hoekstra A.Y., Chapagain A.K., Aldaya M.M. and Mekonnen M.M. (2009). *Water Footprint Manual. State of the Art 2009*. Water Footprint Network, Enschede, Netherlands, pp 127.

Honty, G. and Gudynas, E. (2007). Agrocombustibles y desarrollo sostenible en América Latina y el Caribe: situación, desafíos y opciones de acción. Observatorio del Desarrollo. Montevideo, Uruguay.

Lima, J.E. F.W. and da Silva, E.M. (2002). Contribuição hídrica do Cerrado para as grandes bacias hidrográficas brasileiras. Anais do II Simpósio de Recursos Hídricos do Centro-Oeste—SIPORH. Campo Grande, Brazil: ABRH.

Liu, J., Zehnder, A.J.B. and Yang, H. (2009). Global consumptive water use for crop production: The importance of green water and virtual water, *Water Resources Research*, **45**, W05428.

Liu J. and Yang H. (2010). Spatially explicit assessment of global consumptive water uses in cropland: green and blue water. *Journal of Hydrology*, **384**, 187-197.

Mekonnen, M.M. and Hoekstra, A.Y. (2010). *The green, blue and grey water footprint of crops and derived crop products, Volume 1: Main Report*. Value of Water Research Report Series No. 47, UNESCO-IHE, Delft, the Netherlands.

Narayanamoorthy, A. (2004). Impact Assessment of Drip Irrigation in India: The Case of Sugarcane, *Development Policy Review*, **22**(4), 443-462.

Narayanamoorthy, A. (2006). Potential for drip and sprinkler irrigation in India. Draft, IWMI-CPWF Project on Strategic Analyses of India's National River-Linking Project, Colombo, Sri Lanka: International Water Management Institute

PCIC, 2012. Pacific Climate Impacts Consortium Regional Analysis Tool (BETA). Available online at: http://pacificclimate.org/tools-and-data [Accessed 13 June 2012].

Rosegrant, M.W. and Ringler, C. (2000). Impact on food security and rural development of transferring water out of agriculture. *Water Policy*, **1**(6), 567-586.

Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., Schaphoff, S. (2008). Agricultural green and blue water consumption and its influence on the global water system. *Water Resources Research*, **44**, W09405.

Sawyer D. (2008). Climate change, biofuels and eco-social impacts in the Brazilian Amazon and Cerrado. *Phil. Trans. R. Soc. B*, **363**, 1747–1752.

SEMARNAT-INE (2009). Mexico's Fouth National Communication to the United Nations Framework. Convention on Climate Change. Comité Intersecretarial de Cambio Climático México.

SEMARNAT (2011). Estadísticas del Agua en México (2011). SEMARNAT - CONAGUA

Siebert, S. and Döll, P. (2008). The global crop water model (GCWM): Documentation and first results for irrigated crops. Frankfurt Hydrology Paper 07, Institute of Physical Geography, University of Frankfurt, Frankfurt am Main, Germany. Available online at: www.geo.unifrankfurt.de/ipg/ag/dl/f_publikationen/2008/FHP_07_Siebert_and_Doell_2008.pdf [Accessed 15 March 2011].

Siebert, S. and Döll, P. (2010). Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. *Journal of Hydrology*, **384**, 198-207.

Turc, L. (1954). Le bilan d'eau sols. Relation entre les precipitation, l'évaporation et l'écoulement. *Ann Agron*. **5**, 491-596; **6**, 5-131.

UNC (2011). Estadísticas de la Agroindustria de la caña de azúcar, 2002-2011 (Ingenio: Tamazula). Unión Nacional de Cañeros, A.C. – CNPR. Available online at: http://www.caneros.org.mx/site_caneros/estadisticas/ingenios/tamazula.pdf [Accessed 7 July 2012].