

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

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Short Abstract

Energy policies are taken throughout the world to reduce fossil fuel emissions from transportation sources. Agriculturally based biofuels from food crops are currently the only alternatives to liquid fossil fuels that are being produced. However, as biofuel production spreads around the world, so too do its cascading indirect ecological impacts, and on food security. This paper analyses the impact of Mexican ethanol-sugarcane policy on water resources. The water footprint of sugarcane (WF_{sc}) is quantified for a Mexican agricultural region, based on a water balance model and local climate conditions to estimate crop water requirements. The water availability and demand on water services are also estimated for the region to evaluate the present impact of WF_{sc} on water resources. The total WF_{sc} estimated was 182 m³/ton, the annual water availability was estimated as 367 Mm³, and the total anthropogenic water demand, was estimated as 257.5 Mm³. These estimations showed that the blue water scarcity index (86%) indicates a current water stress conditions in the region. Therefore, additional research is needed to consider the specific conditions for all Mexican sugarcane regions with less favourable conditions than the one evaluated, in order to evaluate the benefits and obstacles to ethanol for transportation policy type your abstract here – your abstract should be 200 words maximum. Your abstract should briefly specify the aims of the work, the main results obtained, and the conclusions drawn.

Keywords: biofuel, climate change, ethanol, sugarcane, water footprint

Introduction

Increasing energy use, climate change, and carbon dioxide (CO₂) emissions from fossil fuels make switching to low-carbon fuels a high priority. The use of fossil fuels—primarily oil—for transportation contribute to the greenhouse effect; one way to slow this phenomenon is to increase energy efficiency and develop and use clean, sustainable energy sources. Therefore, energy policies throughout the world seek to reduce fossil fuel emissions. Some proposed alternatives are the use of fuel cells, hybrid electric vehicle technologies, and the use of alternative fuels such as bioethanol and biodiesel. These biofuels contribute to reduce greenhouse gas emissions. Relative to

the fossil fuels they displace, greenhouse gas emissions are reduced 12% by the production and combustion of ethanol, and 41% by biodiesel (Hill et al., 2006).

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 (WWI, 2009).

Agriculturally based biofuels from food crops, such as corn, sugarcane, soybeans, and palms, 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 a 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 do its cascading indirect impacts at the social, economic, and environmental levels.

The growing demand for cleaner burning fuels, such as ethanol, is likely to generate changes in agricultural cropping patterns and land management practices. Many feedstocks require a large area; for example sugarcane and corn (for ethanol), and soybean, jatropha and oil palm (for biodiesel). Their efficient large-scale production generally involves monocultures (Sawyer, 2008).

Depending on the crop, location, previous land use and technology, the direct ecological effects of expansion of cane monoculture (Honty & Gudynas, 2007) 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. 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 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 (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 crop production, known also as the 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 per ton of crop increases from sugar crops (roughly 200 m³/ton), vegetables (300 m³/ton), roots and tubers (400 m³/ton), fruits (1000 m³/ton), cereals (1600 m³/ton), and oil crops (2400 m³/ton), to pulses (4000 m³/ton). They found that the water footprint varies inside crop categories as well as by production region. In fact, they estimated that the water footprint for sugarcane per ton in irrigated

agriculture of $104 \text{ m}^3/\text{ton}$ is smaller than for the global scale estimation of $200 \text{ m}^3/\text{ton}$.

In this context, and in keeping with international trends, Mexican energy policy has established goals to reduce the emission of greenhouse gasses. One of its strategies is the use of biofuels for transportation, with the short-term objective of producing ethanol from sugarcane (SEMARNAT-INE, 2009). This policy was based mainly on the average annual national production of 40 million of tons of sugarcane, rather than scientific analysis. Actually, there is no research done on the viability of producing sugarcane for ethanol production focused on water availability. Considering that Mexico is an arid and semi-arid country that consumes large volumes of water per capita, roughly $4,306 \text{ m}^3/\text{capita-year}$, and taking into consideration that the agricultural sector represents about 77% of the total blue water resources (SEMARNAT, 2011), this water topic is relevant when biofuel plans are put into practice.

This study quantifies the blue water footprint of sugarcane (WF_{sc}) production in a Mexican agricultural area for the year 2010. A water balance model was used, which takes into account local climate conditions for agricultural land in Tamazula, Mexico, to calculate, with a daily time step, crop water requirements over time, actual crop water use, and finally the blue water footprint. The water availability and the demand on water services are also estimated for the region in order to evaluate the actual impact of the WF_{sc} on the water resources.

Methods

Site description

The Tamazula region is located at the western part of Mexico, in Jalisco state, in

the municipality of Tamazula de Gordiano. 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 100 ton/ha - the second highest in Mexico. All the sugarcane land has complex irrigation systems, which have been progressively updated to be more efficient. In fifty percent of the land water is supplied by traditional flood irrigation systems, and twenty-five percent each by sprinkler and trickle 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.

Water footprint estimation

The approach proposed by Hoekstra et al. (2009) for the water footprinting 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) is 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 evapotranspiration under ideal growth conditions, measured from planting to harvest. '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 by the total daily evapotranspiration (ET_0 , mm/d) divided by the complete growing period of sugarcane. The factor of 10 in equation (2) is used to convert from water depths in mm to water volumes per unit area, in m^3/ha . The

summation is done over the period from the month of planting (month 1) to the month of harvest (where l_{gp} stands for length of growing period in months).

$$WF = \frac{EWU}{Y} \quad (1)$$

$$EWU = 10 \sum_{i=1}^{l_{gp}} ET_0 \quad (2)$$

The daily evapotranspiration, known as the reference crop evapotranspiration (ET_0), is the evapotranspiration rate from a reference surface. The reference is a hypothetical surface with specific characteristics, and it is only affected by climatic parameters. ET_0 expresses the evaporating power of the atmosphere at a specific location and time of the year, and does not consider the crop characteristics and 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.

$$ET_0 = \frac{\lambda (R_n - G) + \rho_a c_p (e_s - e_a) \left(\frac{e_s - e_a}{r_a} \right)}{\lambda + \gamma \left(1 + \frac{r_a}{r_s} \right)} \quad (3)$$

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 psychrometric 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.

Water availability estimation

Water availability was estimated for the annual irrigation season as natural renewable water, which is the amount of water that is replaced by precipitation each season minus the amount lost due to evapotranspiration. In this way, water availability (WA_{blue} , m^3/y) was estimated for the municipal area of Tamazula (A , km^2), considering the mean seasonal temperature (T °C); the seasonal accumulated precipitation (P , mm/y); and the related evapotranspiration (E , mm/y), which is a major component of the hydrological balance (Turc, 1954).

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

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

$$L = 300 + 25T + 0.05T^2$$

In order to know the impact of the water footprint of sugarcane production, 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 country z (WS_{blue}) is defined as the ratio of its total anthropogenic blue water demand (WD_{blue}) (which includes the blue biofuel demand),

to the available blue water resources in the country (WA_{blue}), as follows:

$$WS_{blue}(z) = WD_{blue}(z) / WA_{blue}(z)$$

A blue water scarcity of hundred percent means that all the available blue water has been consumed; any percentage above indicates excess demand and environmental stress, and water stress conditions are considered to have occurred for values over 20%.

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. Table 1 summarizes the parameter values applied for this research.

Symbol	Units	Values
Y	ton/ha	110
λ	MJ/kg	Min=2 max=3 μ =2
Δ	Kpa/°C	Min=0.009 max=0.05 μ =0.03
R_p	MJ/m ² d	Min=15 max=23 μ =20
G	MJ/m ² d	Min=-2 max=2 μ =-0.0014
ρ_a	Kg/m ³	Min=1 max=1 μ =1
c_p	MJ/kg°C	Min=0.0009 max=0.001 μ =0.001
γ	KPa/°C	0.058
r_s	s/m	70
r_a	KPa/°C	Min=58 max=1228 μ =210
u_2	m/s	Min=0 max=3 μ =1
T	°C/d	Min=13 max=25 μ =19
z	m	1152

Table. 1. Parameters values used for WF_{sc} for Tamazula region

Results and Discussion

The time of analysis was during the months when irrigation is practiced on 15,500 ha of Tamazulan sugarcane land, between February to September. The precipitation behaviour observed in the region showed a variation from 0.2 to 89 mm/d, and a daily

average of 3 mm with 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 1, the daily evapotranspiration ET_0 was estimated for the 2010 year (Figure 1). It showed a variation from 6 mm to 10 mm, with the highest values observed between April and September.



Figure 1. Daily evapotranspiration estimations and temperature pattern in Tamazula region

These results expressed for the irrigation months in Tamazula region (Table 2), were used to estimate the WF_{sc} for the 15,500 ha where sugarcane is grown. The estimated WF_{sc} for sugarcane was 182 m³/ton, or 20,020 m³/ha considering a sugarcane yield of 110 ton/ha in the region.

The annual water availability (WA_{blue}), based on precipitation and temperature recorded for the region, was estimated as 367 Mm³ for 2010. This available water is used to provide the main water services in the region, which are to supply drinking water to the 126,246 inhabitants, and irrigation for sugarcane production. Therefore, the total water demand, also

known as the anthropogenic blue water demand (WD_{blue}), is estimated as 257.5 Mm^3 during the irrigation period of 8 months per year, of which the municipal water demand is 4.5 Mm^3 (based on a per capita consumption of 150 L/d). It includes a total irrigation volume of 253 Mm^3 , given that the water footprint estimated applies to 50 percent of flooding irrigation land. In another 25%, trickle irrigation could achieve water savings of up to 44%, while sprinklers could be used in the final 25%, corresponding to a saving of 30% (Narayanamoorthy, 2004, 2005). These estimations show that the water services demand account of the 86 percent of available water, which means current water stress conditions that it is near the blue water scarcity (WS_{blue}) index of hundred percent in the region of Tamazula.

Month	Accumulated ET_0 [mm]	WF_{sc} [m^3/ton]	Cumulative WF_{sc} [m^3/ton]
February	203	18.5	18.5
March	458	23.2	41.7
April	729	24.6	66.3
May	1019	26.4	92.7
June	1178	13.7	103.4
July	1468	26.3	132.7
August	1750	25.7	158.4
September	2005	23.2	181.6

Table 2. Evotranspiration and WF_{sc} estimated for Tamazula region

The result of $182 \text{ m}^3/\text{ton}$ for the WF_{sc} for 2010 is 75% greater than the average global value ($104 \text{ m}^3/\text{ton}$) as estimated by Mekonnen and Hoekstra (2010). The total irrigation volume of 253 Mm^3 is an estimation of the actual irrigation practice for the Tamazula region, such that an accurate and specific evaluation should be done to quantify the water demand related with the sprinkler and trickle irrigation

systems, which require less volume of water and are in total applied to 50 percent of the land. Even with this accurate estimation, or estimations from historic data, an annual variability in the WF_{sc} is expected for sugarcane in this 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 WF_{sc} estimations are the national variations in the price of sugar and its indirect sub-products, as well as the raise of the price of other crops. For example, some years ago, the increase in the price of avocado encouraged its commercialization, and reduced the land area devoted to sugarcane in the space of a year. Thus, it is recognized that there is 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 pattern of production of sugarcane observed in Tamazula region is not the typical one in the country, and despite its high cane yield, it is not sufficient to meet the goals established by Mexican government. There is however, a potential approach to a water stress level in the region. Therefore, research on sugarcane water consumption and water availability estimations are needed for all the Mexican cane regions, since most of the regions are located in areas with critical water availability; many of them have not irrigation systems, and get a lower yield sugarcane production. This research should consider the specific conditions on irrigation

practice, cane yields, and social-economic viability, in order to find out the benefits and obstacles to the ethanol transportation policy.

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. 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. Mexico should research second generation biofuels in light of what has been found, and use them to replace the first generation technologies.

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