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Assessing GHG Emissions, Ecological Footprint, and Water Linkage for Different Fuels

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Currently, transport is highly dependent on fossil fuels and responsible for about 23% of world energy-related GHG (greenhouse gas) emissions. Ethanol from sugar cane and corn emerges as an alternative for gasoline in order to mitigate GHG emissions. Additionally, deeper offshore drilling projects such as in the Brazilian Pre-Salt reservoirs and mining projects of nonconventional sources like Tar Sands in Canada could be a solution for supplying demand of fossil fuels in the short and midterm. Based on updated literature, this paper presents an assessment of GHG emissions for four different fuels: ethanol from sugar cane and from corn and gasoline from conventional crude oil and from tar sands. An Ecological Footprint analysis is also presented, which shows that ethanol from sugar cane has the lowest GHG emissions and requires the lowest biocapacity per unit of energy produced among these fuels. Finally, an analysis using the Embodied Water concept is made with the introduction of a new concept, the "CO_2—Water", to illustrate the impacts of releasing carbon from underground to atmosphere and of the water needed to sequestrate it over the life cycle of the assessed fuels. Using this method resulted that gasoline from fossil fuels would indirectly "require" on average as much water as ethanol from sugar cane per unit of fuel energy produced.

Introduction

According to the International Energy Agency (IEA), transport accounts for about 19% of global energy use and 23% of energy-related carbon dioxide emissions, and these shares will likely rise in the future. Currently petroleum-based fuels supply about 90% of all transport fuel needs, and in the baseline scenarios of IEA this share is expected to be maintained. Even in the BLUE Map scenario (the most aggressive scenario for the reduction of GHG emissions), the share of petroleum and other fossil fuels is expected to be around 50% by 2050 (*1*).

In addition to the global warming effect, observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems (*2*).

Large-scale biofuel industries are being promoted to decrease the dependence on petroleum in response to an abrupt rise in oil prices and to develop transportation fuels that reduce GHG emissions (CO_2, CH_4, and N_2O), compared to petroleum-derived gasoline and diesel fuels (*3*). In addition, biofuels contribute to rural economies and provide an opportunity for developing countries to create jobs and generate income.

However, criticisms on biofuels focus on topics such as land use change, water uses, net carbon and energy savings, and competition with food. If these criticisms are valid, they could prevent biofuels from being sustainable fuels.

Apart from that, projects in petroleum sector, like Brazilian Pre-Salt and Canadian oil sands, are enhancing new sources to supply the demand for fossil fuels in the short and midterm.

This paper intends to compare the life cycle requirements of land and water resources of four different energy resources: ethanol from sugar cane in Brazil, ethanol from corn in the US, gasoline from Conventional Crude Oil, and gasoline from Tar Sands Oil. The concepts of Ecological Footprint and Embodied Water are used. Additionally, the CO_2-Water concept is introduced to take into account the water needed to sequestrate carbon emissions.

Database

Data from the main studies on well-to-wheel Life Cycle Assessments (LCA) for the four energy resources was used for the GHG emissions analysis of this work.

Three different greenhouse gases are considered: CO_2, CH_4, and N_2O, which are converted to CO_2-equivalent by the Global Warming Potential recommended by IPCC (*3*).

For biofuels, the GHG emissions from the combustion stage are considered zero by definition. For gasoline from fossil fuels, a value of $72.91\ gCO_2\backslash MJ$ is considered, estimated for Reformulated Gasoline Blendstock for Oxygenate Blending (CARBOB) (*4*). Since ethanol and gasoline have different heating values, emissions are expressed in terms of energy (TJ).

In the case of Brazilian anhydrous ethanol, the study by Seabra (*5*) was chosen, which compiles data from 2006 for a sample of 44 mills from the Brazilian Center-South region, the main production area. In the calculation of GHG emissions and mitigation, the following supply chain stages were considered: sugar cane production (fuel used in agriculture, N2O soil emission from N-fertilizer and residues), cane transportation to the industrial conversion unit, the industrial unit, and ethanol distribution. For comparison, the results for ethanol from sugar cane by EPA (*6*) were chosen, which considers a sugar cane mill totally dedicated to ethanol production (*6*); presents an average of 61% of reduction in GHG emissions, for the 2022 sugar cane ethanol lifecycle GHG emissions, without residue collection, compared to the gasoline 2005 baseline.

In the case of ethanol from corn, the study considered the life cycle analysis made by the California Air Resources Board (CARB) (*7*) as representative of an average Mid-Western dry mill for corn ethanol production. Also, the results for ethanol from corn presented by EPA (*6*) are considered, which are calculated for an average natural gas fired dry mill plant in 2022, resulting in a 21% reduction in GHG emissions compared to gasoline 2005 baseline. As in the case of Brazilian ethanol, the data for calculating GHG emissions of corn ethanol include farming, production of agricultural chemicals, feedstock transport, and ethanol production and distribution.

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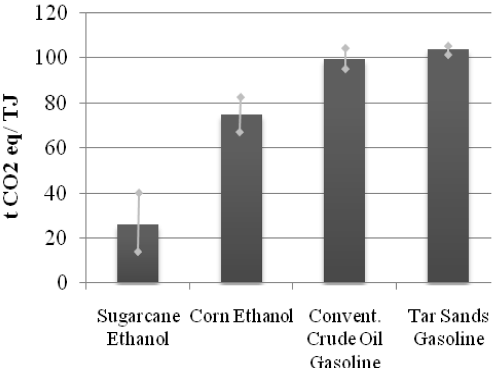

FIGURE 1. GHG emissions in the LCA analysis for the fuels assessed.

The sustainability issue considered more relevant for the assessment of biofuels, besides GHG emissions, is the Land Use Change, considering both direct and indirect environmental impacts and socioeconomic impacts of ethanol production at regional level (*8*).

For instance, Searchinger et al. (*9*) state that using a worldwide agricultural model to estimate emissions from land use change, corn-based ethanol, instead of producing 20% of savings of GHG, nearly doubles greenhouse emissions over 30 years and increase them for 167 years. This study estimated the emissions due to land use change for corn-based ethanol as 104 g CO_2eq/MJ (*9*).

However, subsequent studies include additional issues such as yield increase over time and a land use credit for distiller's grain (a coproduct of corn-based ethanol production used to feed livestock), whose results consider that new forest or grassland would not be converted by increasing the production to 15 billion gallons per year in 2015 in the United States (*10*). In Brazil, an annual production of 15.85 billion gallons in 2020 would correspond to a relatively small requirement of new cane areas (~5 Mha), which must be considered in combination with a probable release of areas due to the progressive increase of pasture productivities (*11*). The EPA's results (*6*), considered in this paper as conservative, are taken into account for the calculation of Land Use Changes effects.

For gasoline from fossil fuels, two different sources are assessed: conventional crude oil and tar sands.

For conventional crude oil, default inputs in the GREET model for gasoline on U.S. average values are used and for crude oil recovery energy, flaring/venting emissions, and refining energy are considered (*4*). In addition, the 2009 analysis performed by the National Technology Laboratory (NETL) (*12*) is used, which was specifically directed to establish the 2005 baseline; this baseline year is requested by the "Energy Independence and Security Act" in order to compare renewable fuels.

To assess GHG emissions from oil sands, the GREET default value for surface mining technique was chosen. In this model, it is considered that large earthmoving devices are utilized to first remove the overburden and then excavate and load the tar sands onto large trucks for transport to a processing facility. It is considered also the in situ thermal recovery where bitumen is upgraded to Synthetic Crude Oil onsite and sent to the refinery.

Land Use Change penalties related to tar sands production are reported in ref *13*: values of 1858 gCO_2/bbl for surface mining and 487 gCO_2/bbl for in situ thermal recovery are considered.

Figure 1 resumes the different GHG emissions reported in the different studies previously cited (*4*−*7*, *12*) for ethanol and gasoline according to their sources.

On a first approach sugar cane ethanol seems to be an appropriate fuel in order to mitigate GHG emissions. Although ethanol from corn emits more GHG per unit of energy than ethanol from sugar cane, the corn ethanol life cycle can be improved by technological advances (*14*), while it also contributes to the energy security of the producer country.

Using Ecological Footprint

The Ecological Footprint measures the amount of biologically productive land and water area required to produce all the resources that an individual, a population, or an activity consumes, considering also the absorption of residues they generate. This can be compared to the biocapacity, the amount of productive area that is available to generate these resources and to absorb the residues (*15*).

The major advantage of the Ecological Footprint concept is its clarity and easily understandable message, which has the "potential to affect behavioral change" in a wider public (*16*). According to Vos (*17*), using the Ecological Footprint as a metric is an elegant approach to bring the three dimensions of energy-balance, food vs fuel, and climate change together into a single expression, providing insight on the long-term sustainability of a biofuel.

Nevertheless, the presentation of Ecological Footprint needs to be greatly improved. Ecological Footprint is a static measure; it ignores technological changes, underground resources, and biodiversity issue. It is a stock measure and does not evaluate flows, and it lacks measures of equity.

According to Stachowiak (*18*), more work needs to be done on the troublesome question of forest yield factors and sustainability. But despite the many objections, tremendous potential remains in the use of ecological footprints to estimate how many people each nation can support, considering specified consumption and production patterns.

Works assessing fuels impacts using Ecological Footprint (EF) approach have been done in the past, reaching different conclusions. For instance, Oliveira et al. (*19*) conclude that the use of ethanol as a substitute for gasoline proved to be neither a sustainable nor an environmentally friendly option considering Ecological Footprint values. There authors sustained also that the favorable considerations of CO_2 offset and net energy "seemed to be relatively unimportant" when compared to ecological footprint results.

In the same direction, using the same approach, Vos (*17*) sustains that with the exception of biodiesel made from waste vegetable oil, first generation biodiesel and ethanol are not sustainable solutions. Only companies that have a regional or a specific supply chain for using them should use these fuels.

On the other hand, to answer the question how sustainable biofuels are, Stoeglehner and Narodoslawsky (*20*), using the EF approach, stated that biofuels can offer huge environmental benefits compared to fossil fuels. Yet, whether and to which extent biofuels production is sustainable depends on the amount of available land and, therefore, can only be decided in a regional context. Ecological footprint can significantly support these regional decisions (*20*).

Finally, Holden and Hoyer (*21*), assessing different kinds of fuels, concluded that only a strategic combination of fuel substitution, new means of transportation, promotion, and reduction strategy to diminish the growth of transport are compatible with long-term sustainability requirements.

Two components are considered for the calculation of the ecological footprint of fuels in this study: the "production land", which is defined as the area needed for energy production, and the "carbon uptake land", which is defined as the biocapacity required to sequestrate the emission of greenhouse gases. For a National Ecological Footprint calculation, cropland is the most bioproductive of all the

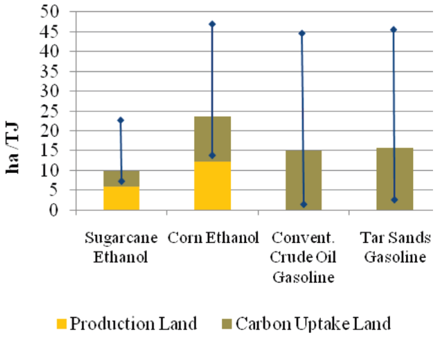

FIGURE 2. Ecological Footprint analysis for the fuels assessed. *The dots mean the maximum and minimum values per unit of energy for dryland forest and tropical forests. respectively. Idem for Figure 4.

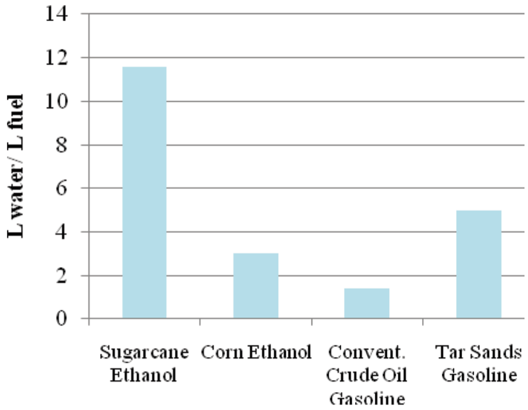

FIGURE 3. Fresh water consumed in conversion processes.

land types and consists of areas used to produce food and fiber for human consumption, feed for livestock, oil crops, and rubber (*15*). Besides, land dedicated to agriculture plays an important role within a strategy to address climate change, because it can reduce its own emissions and offset emissions from other sectors by removing CO_2 from atmosphere and storing carbon in soils.

However, reaching these objectives depends on the way producers manage the crop land. For instance, average values of carbon stock change with the tillage practice: from 0.104 tons of stored carbon per hectare for intensive tillage to 0.552 tons per hectare when no tillage is practiced (*22*). However, the capacity of agricultural soils is neglected in ecological footprint calculations, on which unharvested forests are typically considered for the carbon uptake land (*19, 23, 24*). Hence, in order to compare the results with other works and to simplify calculations, the value reported by Wackernagel and Rees (*24*) for the carbon uptake land is adopted, with an average value of 6.6 t per ha for CO_2 sequestration by forests in the world. Carbon sequestration rates of 2.3 tCO_2/ha for dryland forests (*25*) and 200 tCO_2/ha for tropical forests (*26*) are considered in order to compare different sequestration rates for the carbon uptake land.

Agricultural yields and industrial efficiency conversion for sugar cane and corn ethanol are taken from refs *5* and *10*. For conventional oil the value of area for energy production was not considered due to the lack of data, but it is estimated as being very small. Data from Jordaan et al. (*13*) take into account the tar sands production area, resulting in a value of 0.024 ha/TJ.

Data from Figure 1 are used to calculate the carbon uptake land for each fuel. Figure 2 summarizes the results. It must be remarked that hectares per unit of energy in Figure 2 are not converted to global hectares in order to report the original values of land requirements.

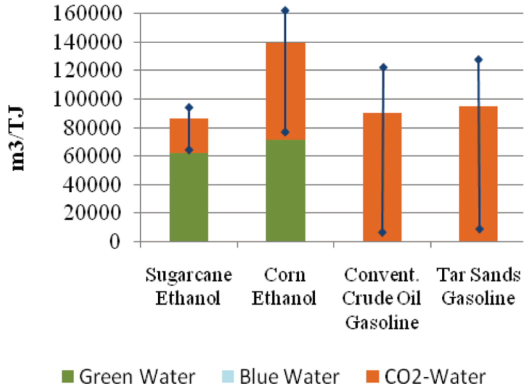

FIGURE 4. Embodied Water including the CO_2—Water.

Figure 2 shows the ecological footprint analysis for the fuels assessed. The values presented could be interpreted as the total land that would be needed in an economy of zero GHG emissions. From these results, sugar cane ethanol is the most efficient pertained to the need of land area. Comparing the results of other studies on ecological footprints of fuels, for instance the data reported by ref *19* (sugar cane ethanol: 10.6 ha/TJ; corn ethanol (E85): 23.1 ha/TJ; gasoline from conventional crude oil: 13 ha/TJ, converted to the same units), it could be observed that they are in the range of the results reported in Figure 2.

The Water Linkage

Water is a resource needed for several processes in the production chain of fuels (*27, 28*).

Biofuels are often criticized for the need of large amounts of water for their feedstock production, and this could cause large-scale water scarcity (*29*—*31*). For instance, Gerbens-Leenes (*30*) estimates water-content values for biomass energy carriers in Brazil and USA as of 61 m^3/GJ and 58 m^3/GJ, respectively, and for crude oil, 1.1 m^3/GJ, concluding that a shift toward biomass energy would promote a reduction on the environmental impact of fossil fuels but on the other hand would represent a substantial increase of water requirement, which consequently would raise a conflict between 'water for food' and 'water for energy'.

The amount of water used to produce oil from tar sands has been reported as being much higher than for the production of conventional oil. Values of 7 m^3 water/m^3 oil for in situ tar sands mining compared to 0.42 m^3 water/m^3 oil for conventional oil are reported by King and Webber (*32*).

Average values for fresh water needs in raw materials conversion process into fuel from the literature (*33*—*36*) are summarized in Figure 3, where these values are shown in terms of liters of water/liter of fuel, i.e. they must be correspondingly interpreted as liter of water per liter of ethanol or gasoline.

Separating blue fresh water use (e.g., withdrawn from surface or underground) from green water (e.g., rainwater) is important, because the first one has an economical value and legal environmental constraints. For instance, in Sao Paulo State, the main Brazilian producer region, sugar cane mills are obliged to reduce their consumption of "fresh" water to 1 m^3/ton of sugar cane (*37*), or 11.6 L of water per liter of ethanol, considering an industrial yield of 86.3 L of ethanol per ton of cane (*5*).

Compared with the other fuels, ethanol from sugar cane stands out for its higher water demand in the industrial stage. However, Chavez-Rodriguez et al. (*38*) report that taking measures of water reduction and reuse in the industrial processes could reduce that value to 3.6 L of water per liter of ethanol. Moreover, by evaporating vinasse, a byproduct of ethanol production, and reusing its condensates, sugar cane plants could produce a surplus of 3 L of water per liter of ethanol produced.

In order to take into account the water used in the feedstock production in the fuel life cycle, the Virtual Water or Embodied Water concept can be used. It is defined as the water used in the production of a good or service (*39*). The Embodied Water content of a product consists of three components. Green water refers to the volume of rainwater consumed during the feedstock production process. Blue Water is the water withdrawn from rivers, lakes, or underground and used for crop irrigation and in the extraction, transport, and industrial processes. Gray Water is defined as the volume of freshwater required to assimilate the pollutant load based on existing ambient water quality standards. Due to lack of data, especially for conventional oil and tar sands, gray water is not taken into account in this study.

A fourth component is introduced in this study, the CO_2−Water, defined as the water consumed in the process to neutralize the equivalent CO_2 emissions over the life cycle of a product. In this paper, it is considered the specific case of CO_2eq sequestration of fuels emissions by new forest lands, being the CO_2−Water calculated on the basis of evapotranspiration rates of these forests, reported by amount of CO_2 sequestrated.

Average values of evapotranspiration for deciduous forest are reported between 505 mmy-1 and 640 mmy-1 (*40*). Furthermore, evapotranspiration rates and carbon sequestration are related. For instance, in dry land forest, for evapotranspiration and carbon sequestration, averages values of 280 mmy-1 and 2.3 tCO_2/ha (*25*) are reported, compared to tropical forest values of 1176 mmy-1 (*41*) and 200 tCO_2/ha (*26*), respectively. For the calculation of the CO_2−Water, an average value of 600 mmy-1 is assigned for forest and 6.6 tCO_2/ha for carbon sequestration.

Since sugar cane in Sao Paulo State is usually not irrigated, reported evapotranspiration values around 1062 mmy-1, with precipitation rates of 1345 mmy-1, are considered as green water (*42*).

Based on the fact that 96% of corn used for ethanol production is not irrigated (*43*), registered average evapotranspiration rates of 584 mmy-1 for rainfed corn are used for the analysis (*44*).

Figure 4 summarizes results for the Embodied Water including the CO_2−Water concept in terms of water per energy (m^3/TJ).

As shown in Figure 4, blue water becomes insignificant when compared to evapotranspiration rates. The results can be interpreted as follows: the carbon extracted underground in oil or bitumen released into the atmosphere would need around 90,000 m^3/TJ of water evapotranspirated by average forests for CO_2eq sequestration.

At the same time, ethanol from sugar cane in Brazil presents values of 61,800 m^3/TJ of green water evaporated by crops, consumption of 520 m^3/TJ of blue water in the sugar cane mill, and around 23,800 m^3/TJ of CO_2−Water. However, the CO_2−Water will be highly dependent on the kind of forest or carbon sequestration form used to compensate the CO_2 emissions, as it can be seen in the wide range of results obtained considering forest evaporation and sequestration rates reported in refs *25, 26, and 41.* For instance in the case of Conventional Crude Oil Gasoline, if CO_2 emissions are compensated by tropical forests, 0.5 ha/TJ would be required and 5800 m^3/TJ would be evapotranspirated. These values can be compared with those of dry land forest, which are, respectively, 43 ha/TJ and 120,000 m^3/TJ.

Hence, forest with higher water use efficiency (WUE), like tropical forests, would be prioritized in the "reforestation strategy for CO_2 sequestration".

In the case of corn ethanol, the high values reported are not actually due to green water, corn crops have similar evapotranspiration rates per energy produced as sugar cane, but it is explained by the high rates of GHG emissions over its life cycle.

Results Discussion and Policy Opportunities

GHG emissions, Ecological Footprint, and Embodied Water, including CO_2 Analysis, have been used to compare the production and use of different fuels like ethanol from sugar cane and corn and gasoline from crude oil and tar sands.

The study shows that the lowest GHG emissions correspond to ethanol from sugar cane, followed by ethanol from corn. Also, the best result for the ecological footprint is for the ethanol from sugar cane, followed by the gasoline produced from conventional oil.

The results in Figure 2 mean that in a scenario of zero emissions, where the GHG emissions would be compensated through reforestation, the gasoline from conventional oil or from tar sands needs less land area than ethanol from corn.

Walter et al. (*45*) estimated the fuel consumption per year by 2030 as 1924 GL for gasoline and 444 GL for ethanol. Combining these values with those in Figure 2, the necessary reforestation area to neutralize the GHG emissions from gasoline would be 30.2 Mha of tropical forest or 2737 Mha of dryland forest. It means that 0.76% (tropical forests) or 69.5% (dryland forests) of the total forest land in the world would be dedicated to achieve the objective of gasoline GHG neutralization (*46*).

If total ethanol demand was supplied by sugar cane ethanol, an area of 57.7 Mha of production land would be required as well as 1.3 Mha of tropical forests or 174 Mha of dryland forests as carbon uptake land.

Relative to water consumption, to meet the demand for gasoline and sugar cane ethanol in 2030, according to Figure 4, the following values would be needed: 613.2 km^3/year of green water to cultivate the sugar cane and 370 or 1254 km^3/year of CO_2-water for tropical and dry land forests, respectively, dedicated to neutralize CO_2 emissions of both ethanol and gasoline. Summing up these green water and CO_2-water values, the estimated annual evapotranspiration would be in a range of 0.2−0.372% of the global evapotranspiration (including evaporation rates from the oceans) (*46*). This estimated increment in the global evapotranspiration, combined with the effects of climate change (*46*), could contribute for accelerating the Earth's hydrologic cycle. Further studies are needed to model the consequences of these changes in the Earth's water fluxes.

Just taking into account the production land required to supply the total future ethanol demand, it would represent about 1.7% of all land dedicated to permanent meadows and pastures or 1.2% of all world agricultural land (2007) (*47*), although technological improvements is predicted to lower these values in the future.

The results presented could also lead to a strategic decision relative to land use: employing the available land for fuel and food production, leaving intact the high quality forests.

Hence, policy makers should be able to conduct investments for expansion land for biofuels production in a way that this expansion does not compete with crops for food lands or forest, but with pasture and fallow lands, with instruments like the Sugar cane Agroecological Zoning in Brazil (*48*).

The quantity of water used in the industrial process is very high in the case of ethanol from sugar cane, but the consumption could be greatly reduced, reaching values comparable to that of gasoline from conventional crude oil, which presented the lowest ones. Actually, blue water is the most important in the life cycle of a product because it has been endowed with an economic value, and its increasing use could eventually cause water scarcity and, consequently, social conflicts. For instance, Elia Neto (*49*) reports that there are water basins from which sugar cane industry, with a consumption rate of 2 m^3/t of cane, is responsible for around 35% of the total water withdrawal. Policy instruments such as water use charges, granting of water usage rights, and mechanisms to stimulate water reuse are good policies to encourage water conservation in biofuels production plants (*50*).

This work made a first effort to account the linkage between GHG emissions and water, introducing the CO_2−Water concept, with the objective to illustrate to policy makers the impacts of releasing carbon from the underground to the atmosphere and how processes to sequestrate this carbon would consume water resources to neutralize these emissions. These aspects of water consumption over the life cycle must be taken into account when comparisons between fuels are made.

Considering the case when new forests are used to mitigate the gasoline CO2 emissions, if the embodied and the evapotranspirated water of these forests and the total water needed for the gasoline production are summed up, this total would be similar to the water needed to produce ethanol from sugar cane.

However, it must be remarked that the concept of CO_2−Water is not restricted to this case, and it could be used for other cases of CO_2 neutralizing ways such as geological storage, algae capture, agricultural soils, and reuse of CO_2 in other processes, etc. Furthermore, extending the CO_2−Water concept, a calculation could be made of the average value of the CO_2−Water demanded by a global hectare, as defined in the Ecological Footprint scope, for the capture of CO_2.

This paper showed that the production of ethanol from sugar cane is very efficient in terms of use of land and water. It can be suggested that in new lands projected for biofuels production with weather and rain rates suitable for sugar cane, this crop should be prioritized. However, an opportunity emerges for the oil sector: to use carbon dioxide capture techniques, such as CO_2 enhanced oil recovery, and CO_2 storage, which would require less land and CO_2−Water than reforestation to neutralize their emissions.

Although ethanol from corn has the lowest efficiency compared with the other three fuels assessed, biofuels could increase energy security in countries with low oil resources. Another favorable aspect is that ethanol from corn is renewable and improves rural economies.

These aspects must be taken into account for public policy decisions. Finally, the assessments presented in this paper are only one side of the problem. Policy decisions must also incorporate both economical and social impacts as well as local and regional aspects.

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Appendix A

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CARB	California Air Resources Board
CO_2eq	carbon dioxide-equivalent
EPA	United States Environmental Protection Agency
GHG	greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
Ha	hectare
IEA	International Energy Agency
mmy-1	millimeters per year

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