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Carbon footprint of sugar production in Mexico

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ABSTRACT

Global warming, caused mainly by increased worldwide emissions of greenhouse gases, is currently one of the greatest threats to the environment and human societies. Mexico has set an ambitious goal of reducing 30% of its greenhouse gases emissions by year 2020. The sugar agroindustry has been identified as one of the opportunities for mitigating emissions in this country. The aim of this work is to contribute towards identifying policy measures and practices for low-carbon sugar production by assessing the carbon footprint of sugar produced in four sugar mills in Mexico using a life cycle assessment method. System boundaries include agricultural practices, sugarcane harvesting, cane milling and sugar conversion. The results show that sugar production has carbon footprint values in the range of 0.45–0.63 kg CO_2e/kg sugar. In these four cases, the agricultural stage contributes the majority of carbon emissions (59–74%). Most greenhouse gases emissions in the agricultural stage were from fertilizer production, nitrous oxide (N_2O) emissions and biomass burning. The industrial stage contributed with 14–30% of total greenhouse gases emissions, mainly due to fossil fuel and bagasse use. The carbon footprint value is particularly sensitive to nitrogen fertilization, nitrous oxide emissions from the soil and sugarcane yields. Cogeneration in sugar mills could become an important way to reduce the carbon footprint of sugar and to produce electricity with low carbon emissions. We show the impact of different carbon footprint performance of sugar production process in Mexico. Data used on this manuscript came from real field measurements, and our results are accompanied by sensibility and uncertainty analyses. This is the first time that life cycle assessment has been used to estimate the carbon footprint of sugar production in Mexico including agricultural, industrial and transportation boundaries, to identify greenhouse gases mitigation opportunities. Studying techniques for improving sugar cane yield, making fertilizer use more efficient, minimizing cane burning and developing efficient cogeneration in sugar mills with bagasse as fuel is scientifically relevant. Applying concrete public policy measures to these areas of opportunity would allow production of low carbon sugar in Mexico. The results of this study may also be used as reference by other countries with similar sugar production conditions.

1. Introduction

Reversing the effects of environmental degradation caused by human activities is one of the greatest challenges currently faced by humanity (Rockström et al., 2009). Global warming, which is mainly caused by the increased use of energy derived from fossil fuels, is one of the most concerning phenomena that could have severe effects on the environment and human societies (IPCC, 2014a, 2013).

Mexico's Climate Change Law was enacted as part of this nation's efforts to combat climate change (Diario Oficial de la Federación, 2012). Here, an ambitious goal of reducing 30% of greenhouse gas (GHG) emissions by year 2020 was established. This has led to the development of a number of studies that evaluate possibilities for mitigating GHG emission in this economy (Johnson et al., 2010; Octaviano et al., n.d.; Veysey et al., n.d.). Some

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of these studies point towards the sugar agroindustry as an opportunity for GHG emission mitigation (Islas et al., 2007; Johnson et al., 2010; Riegelhapt et al., 2012).

Mexico is the world's seventh largest sugarcane (*Saccharum officinarum*) producer. Spanish settlers brought the first sugarcane plants to Mexico from Cuba in the early 16th century, and the first sugar mill was established in 1536 in the village of San Andres Tuxtla, Veracruz. Nowadays, cultivation of sugarcane is concentrated in six different regions in Mexico, which provide sugarcane to 54 sugar mills and two autonomous distilleries (UNC, 2014). Around 61 million tons per year of sugarcane are cultivated in 780,254 ha, which produce nearly 7 million tons of sugar (3% of worldwide production) and about 16.7 million liters (ML) of ethanol. The sugarcane agroindustry represents 0.5% of Mexico's gross domestic product (GDP), 2.5% of the manufacturing sector and 11.5% of the primary sector. It also provides significant full time and temporary employment for more than 2.2 million people in 227 municipalities (9.2% of all municipalities in Mexico) (Sentíes-Herrera et al., 2014).

With the increasing threat of global warming and climate change, minimizing carbon emissions during product elaboration has become increasingly important in recent years (Fang et al., 2014; Wiedmann and Minx, 2007). Researchers have quantified GHG emissions using an indicator known as the carbon footprint (CF), which is the sum of all direct and indirect GHG emissions generated throughout the life cycle of a product (Wiedmann and Minx, 2007). To evaluate the CF, a life cycle assessment (LCA) method has been applied. LCA is a useful standardized method (with ISO 14040 and 14044 standards) for estimating the environmental impact of processes and products. This tool has been widely employed to identify products with fewer negative impacts on the environment, or to locate the production stages where the greatest environmental impacts occur.

Numerous studies have been done in recent years involving the use of LCA for carbon emissions quantification in agroindustry products. Relevant studies have assessed the CF of sugar produced from different feedstocks (De Figueiredo et al., 2010; Klenk et al., 2012; Rein, 2010; Seabra et al., 2011; Yuttitham et al., 2011), calculated carbon emissions of ethanol and electricity produced from sugarcane (Campbell et al., 2009; Dunkelberg et al., 2014; Khatiwada and Silveira, 2011; Nguyen et al., 2010; Ramjeawon, 2008; Seabra et al., 2011; Soam et al., 2015); compared environmental impacts of sugarcane product diversification (Renouf et al., 2013); and analyzed the influence of methodological variations on results of carbon emissions (Cherubini and Strømman, 2011; Cherubini et al., 2009; Plassmann et al., 2010).

The aim of this paper is to assess the CF of sugar produced in four sugar mills in Mexico using LCA method. This is the first assessment of how sugar production contributes towards carbon emissions in Mexico that also identifies the main sources of GHG emissions during the production cycle. Additionally, uncertainty and sensitivity analysis were performed using Monte Carlo Simulation, and two scenarios were developed to explore the impact of efficient cogeneration on the CF of sugar production. This information is useful because it contributes towards identifying concrete policy measures and practices for low-carbon sugar production, which in turn brings Mexico closer to its mitigation goals. The results of this study may also be used as reference by other countries with similar sugar production conditions.

2. Materials and methods

In this section we present the methods, data and information sources used to calculate the carbon footprint (CF) in four case studies. We also explain the methods for performing uncertainty and sensibility analysis, through which the changes in CF due to variations in the initial system parameter values were calculated. Finally, we explore the effects that efficient cogeneration in sugar mills can have on the CF.

2.1. Cases

The criteria used to select the cases for assessment were: 1) That the cases have similar sugarcane milling capacities; 2) That they cover different geographic regions; 3) That data for all life cycle stages were available for assessment. The latter criterion was particularly important because in Mexico there are no databases containing information on fuel consumption for agricultural and transportation machinery. The assessment was limited to four sugar mills that fulfill these criteria. Table 1 shows the location, total industrialized area and mean sugar production of the four case studies used to calculate the carbon footprint of sugar production in Mexico. Note that these mills might not be a statistically representative sample of all mills in Mexico, since significant differences exist in levels of technology in cane production (from low to high mechanization and fertilization), in industrialized area (ranging from about 2400–39,000 ha/y) and in net cane crushed (229,000–2,200,000 ton cane/y).

Sugarcane is generally cultivated in five-year cycles followed by replanting. Cane yields vary between 64 and 106 t/ha a year. Irrigation is by gravity or pumping (or both) while soil tillage is fully mechanized and harvest is mostly manual in almost all our cases. This last practice makes it necessary to burn sugarcane trash in the fields before and after harvesting to ease the cutter's work and to clear residues. Truck loading is mechanized.

The industrial process starts with sugarcane crushing to extract juice, which is then clarified and concentrated. On the concentrated juice, up to three successive crystallizations are carried out, followed by separation of sucrose crystals and molasses by centrifugation (sugar and molasses are produced in each centrifugation). The latter can be used for ethanol production.

2.2. Life cycle assessment

The life cycle assessment (LCA) method can be used to measure total environmental performance of a product from cradle to grave (Khatiwada and Silveira, 2011). This method accounts for energy and material inputs required in the development of a product as well as by-products and emissions that occur during the production process. In our four case studies, the system boundaries are consistent with other studies and include agricultural practices, sugarcane harvesting, cane milling and sugar conversion (Fig. 1) (Khatiwada and Silveira, 2011; Nguyen et al., 2010; Yuttitham et al., 2011).

The agricultural stage includes the following sources of emissions: From fuel used for farm machinery, from the production of fertilizers and pesticides, nitrogen monoxide (N_2O) emissions from nitrogen fertilizer volatilization (calculated as 1% of the N applied; IPCC, 2006), emissions from energy for irrigation, from harvest machinery and from sugarcane burning for harvesting. The industrial stage (sugar milling and sugar conversion) includes emissions from electricity generation and fuel use. Emissions from transport correspond to the use of trucks for carrying sugarcane (Fig. 1).

CO_2 emissions from biomass burning were considered to be neutral since photosynthesis during plant growth involves carbon fixation from the atmosphere (Khatiwada and Silveira, 2011). For biomass combustion, only CH_4 and N_2O emissions were considered. In all the cases studied, the agricultural fields had been cleared prior to 1960, so land use change emissions were not included in