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Net greenhouse gas fluxes in Brazilian ethanol production systems

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Abstract

Biofuels are both a promising solution to global warming mitigation and a potential contributor to the problem. Several life cycle assessments of bioethanol have been conducted to address these questions. We performed a synthesis of the available data on Brazilian ethanol production focusing on greenhouse gas (GHG) emissions and carbon (C) sinks in the agricultural and industrial phases. Emissions of carbon dioxide (CO_2) from fossil fuels, methane (CH_4) and nitrous oxide (N_2O) from sources commonly included in C footprints, such as fossil fuel usage, biomass burning, nitrogen fertilizer application, liming and litter decomposition were accounted for. In addition, black carbon (BC) emissions from burning biomass and soil C sequestration were included in the balance. Most of the annual emissions per hectare are in the agricultural phase, both in the burned system (2209 out of a total of 2398 kg C_{eq}), and in the unburned system (559 out of 748 kg C_{eq}). Although nitrogen fertilizer emissions are large, 111 kg C_{eq} ha^{-1} yr^{-1}, the largest single source of emissions is biomass burning in the manual harvest system, with a large amount of both GHG (196 kg C_{eq} ha^{-1} yr^{-1}). and BC (1536 kg C_{eq} ha^{-1} yr^{-1}). Besides avoiding emissions from biomass burning, harvesting sugarcane mechanically without burning tends to increase soil C stocks, providing a C sink of 1500 kg C ha^{-1} yr^{-1} in the 30 cm layer. The data show a C output: input ratio of 1.4 for ethanol produced under the conventionally burned and manual harvest compared with 6.5 for the mechanized harvest without burning, signifying the importance of conservation agricultural systems in bioethanol feedstock production.

Keywords: biofuel, carbon footprint, global warming, life cycle assessment, soil carbon sequestration

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Introduction

Of the 66 billion liters (BL) of bioethanol produced globally in 2008, ~90% were produced in the United States (mainly corn ethanol) and Brazil (sugarcane ethanol) (Renewable Fuels Association, 2009). Sugarcane (*Saccharum officinarum*) has vigorous growth, high photosynthetic efficiency and a production system which often includes the use of crop residues to generate power for the processing mills. Thus, it is one of the most attractive feedstocks for bioethanol production, considering both energy output: input ratios and greenhouse gas (GHG) emission reductions compared with fossil fuels (Goldemberg *et al.*, 2008). There has been a steady increase in production of Brazilian ethanol, from 10.6 BL in 2000, to 27.5 BL in 2008 (União da Indústria de Cana-de-açúcar, 2009). The rapidly increasing global demand for bioethanol necessitates detailed assessment of the sustainability of biofuels based on all components of C inputs and outputs. This article provides a full C balance of sugarcane-derived ethanol production in Brazil including all the major sources and sinks, such as CH_4 and N_2O emissions, fossil CO_2, soil C sequestration, black carbon (BC) emissions and biochar deposition from biomass burning.

Burning residues is a common practice of sugarcane production in Brazil, to facilitate more efficient manual

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harvest and transport. However, burning plant residues leads to emissions of GHGs (e.g., CO_2, CH_4 and N_2O) besides the release of charcoal (BC) particles into the atmosphere. The latter poses health hazards (Cançado *et al.*, 2006) and impacts regional and local climate. Burning also keeps organic matter (OM) and nutrients from returning to the soil, and may adversely impact soil quality. Thus, burning phase-out laws are being implemented throughout Brazil because of economic and environmental concerns. As manual harvest of sugarcane without burning is not economically feasible, mechanical harvesters that can collect the stalks and leave the residues on the field have been developed. By 2014, 80% of the cane harvested in the main production regions in Brazil will be harvested without burning (Centro de Gestão de Estudos Estratégicos, 2004). There exists a positive correlation between the maintenance of sugarcane trash and the increase in soil organic carbon (SOC) content, influenced by time since adoption of the unburned harvest, soil texture and soil disturbance (Galdos *et al.*, 2009a,b).

Materials and methods

Burned and unburned harvest systems

In the sugarcane production system, burning the residues has been a common practice in order to facilitate more efficient manual harvest and transport operations. After burning, the partially burned tops are separated from the stalks and left on the field. Besides the public health and environmental problems associated with burning biomass, the low quantities of remaining crop residues left on the field can lead to poor soil quality. The combination of low soil cover and erosive precipitation events can lead to soil losses by surface runoff.

Because of environmental, agronomic and economical reasons, the manual harvest of sugarcane with burning has been gradually replaced by mechanical harvest with maintenance of the dry leaves and tops on the field, in a system called green cane management. The green management of sugarcane includes the deposition of large amounts of plant litter on the soil after each harvest, ranging from 10 to 20 tons of dry matter per hectare. The mulch formed impacts the whole production process of sugarcane, influencing cane yields, weed control, fertilizer management, soil erosion, soil water infiltration rates and soil OM dynamics, among other factors.

Hidden C emissions

The GHG emissions from fossil fuel used in agricultural operations (e.g., planting, disking, harrowing, tilling, harvesting and input application) and transport of sugarcane stalks to the mill were used to assess the ecosystem C budget. Hidden C emissions from the production, transport and storage of seeds, lime, fertilizers, pesticides, industrial chemicals, buildings, machinery and equipments were also accounted for (Lal, 2004). Because the focus was the comparison between manual and mechanized harvesting systems, hidden C emissions due to human labor were also included in the balance, assuming a 70% reduction in labor in the mechanized harvest (Boddey *et al.*, 2008). Human labor, which is not usually included in GHG balances, was calculated by Boddey *et al.* (2008) based on a $128\,h^{-1}\,ha^{-1}\,yr^{-1}$ estimate by Pimentel & Patzek (2007), and fossil energy used in field labor of $7.84\,MJ\,man\,h^{-1}$ (Giampietro & Pimentel, 1990).

N_2O emissions from fertilizer application

Direct and indirect N_2O emissions from organic and mineral fertilizer applications, as well as from the decomposition of crop residues were calculated using Intergovernmental Panel on Climate Change (IPCC) (2006) default emission factors. Although using global default factors imply in large uncertainties, there are currently very few regional or site-specific N_2O emissions data for nitrogen fertilizer application in sugarcane. Considering that roughly 60% of the nitrogen fertilizer in sugarcane in Brazil is applied as urea, CO_2 emissions from urea application were also calculated. Similarly, emissions from liming and non-CO_2 emissions from organic materials such as filter cake, vinasse and crop residues were also included in computing the GHG balance. Importantly, N_2O emissions from litter decomposition were also calculated for the burned harvest system, based on the data from field experiments (Cerri, 1986). In the manual harvest, although most of the leaves are burned, part of the upper portion of the stalks (the tops) and remaining leaves are left on the soil surface.

Avoided emissions

The data used to calculate the avoided emissions from ethanol production, surplus bagasse and surplus electricity was obtained from a database which included typical technology used in 2005/2006 in the Center-South region of the country, where most of the ethanol is produced (Macedo *et al.*, 2008). Under those conditions, a surplus of 9.6% of the total amount of bagasse generated was not used for energy in the plant's own operations. This surplus bagasse production has been used in other industries as fuel in stationary combustion, thus computed as avoided emissions of fossil fuels. The avoided emissions from surplus bagasse were calculated considering the substitution of biomass-fueled boilers (efficiency = 79%; LHV) for oil-fuelled boilers (efficiency = 92%; LHV) (Macedo *et al.*, 2008). The surplus electricity, $\sim$9.2 kWh Mg cane^{-1}, is exported into the grid primarily substituting electricity generated by natural gas (efficiency = 40%; LHV) in periods of low water levels in hydroelectric dams (Macedo *et al.*, 2008). Therefore, global average emission factors for electricity generation were used.

Global warming potential (GWP)

The GWP values of the GHGs included in this assessment were updated to the Fourth Assessment Report values, 25 for CH_4 and 298 for N_2O. The main existing assessments were performed using the second assessment report values for CH_4 (21) and N_2O (310) (Boddey *et al.*, 2008), and third assessment report GWP values for CH_4 (23) and N_2O (296) (Macedo *et al.*, 2008). CH_4, N_2O and BC emissions were converted to CO_2 equivalent using GWP values, and then converted to C equivalent (C_{eq})

Soil C stocks

The dataset used in this study was obtained from a literature review on the influence of the adoption of the harvest without burning on SOC content in the soils under sugarcane in Brazil. A summary of all data used in this paper with information about location, geographic coordinate, soil type and study source is provided in Table 1. All selected studies provided data on SOC stocks (or C concentration and bulk density used to calculate the stocks), depth of sampling and time since the management change. The studies were observational (i.e. not agronomic experiments) paired comparisons and each site within a paired comparison was similar with respect to dominant soil type, topography and climate. While there is less control of some variables than in an agronomic experiment, the paired comparisons allow an assessment of the actual management systems used by farmers.

Biochar

Biochar has been defined as a C-rich organic material derived from incomplete combustion of fossil fuels and vegetation and from weathering of graphitic C in rocks (Nguyen *et al.*, 2009). Biochar input to soils was included in this assessment, with data obtained from field measurements of C in ashes deposited on the soil after preharvest burning.

BC

Another factor that has been commonly missing in ethanol GHG balances is BC from the incomplete combustion of biomass. As a component of aerosol, BC has both scattering and absorption effects on the atmosphere, but the net effect is warming of the atmosphere, with a 100-year GWP of 500 (Hansen *et al.*, 2007). This assessment included BC emissions from the combustion of both crop residues in the agricultural phase and bagasse in boilers in the industrial phase. BC emission factors for trash burning are in the 0.7−1.4 kg Mg trash (db) range; for bagasse, assuming a 90% emissions control in the boilers, the factors are in the 10−14 kg TJ^{-1} range (Sanhueza, 2009). For simplification purposes, the mean values of these ranges were used in our calculations.

Table 1 General characteristics of the sites used to estimate the potential carbon sequestration in the conversion from burned to unburned management in Brazil

Site	Location City	State	Geographic coordinate	Soil type (FAO)	Source
1	Matão	SP	21°36S, 48°22W	Ferric Alisol	Cerri *et al.* (2004)
2	Serrana	SP	21°12S, 47°35W	Haplic Arenosol	Cerri *et al.* (2004)
3	Jaboticabal	SP	21°19S, 48°11W	Haplic Ferralsol	Souza *et al.* (2005)
4	Matão	SP	21°36S, 48°22W	Haplic Ferralsol	Cerri *et al.* (2004)
5	Timbaúba	PE	08°02S, 35°55W	Chromic Luvisol	(Resende *et al.*, 2006)
6	Goianésia	GO	15°19S, 49°07W	Rhodic Ferralsol	Szakács (2007)
7	Ourinhos	SP	22°58S, 49°52W	Rhodic Ferralsol	Szakács (2007)
8	Pradópolis	SP	21°22S, 48°03W	Rhodic Ferralsol	Cerri *et al.* (2004)
9	Pradópolis	SP	21°22S, 48°03W	Rhodic Ferralsol	Szakács (2007)
10	Pradópolis	SP	21°22S, 48°03W	Rhodic Ferralsol	Czycza, (2009)
11	Pradópolis	SP	21°22S, 48°03W	Rhodic Ferralsol	Galdos *et al.* (2009 a, b)
12	Pradópolis	SP	21°22S, 48°03W	Rhodic Ferralsol	Czycza, (2009)

SP, São Paulo; PE, Pernambuco; GO, Goiás.

Vinasse

Vinasse (or stillage) is a liquid residue resulting from the production of ethanol. Currently, vinasse is applied in fertirrigation soon after its production, with short storage time under anaerobic conditions, and open air transportation channels are progressively being replaced by pipelines in the transportation for field application. Therefore, methane emissions from vinasse were considered insignificant and not included in this assessment. However, field measurements under current storage and transportation systems are needed to accurately estimate these emissions.

Results and discussion

Soil C

The soil C data (Table 2) were divided into two sets: clayey soils (clay content > 35%) with mean C accumulation rate (2.04 Mg ha^{-1} yr^{-1}) higher than that for sandy soils (0.73 Mg ha^{-1} yr^{-1}). Soils with the highest clay content had the highest annual rates of C accumulation, and vice-versa. The two distinct groups highlight the importance of soil texture regarding the potential for soil C sequestration (Hao & Kravchenko, 2007). The mean annual C accumulation rate of 1.5 Mg ha^{-1} yr^{-1} for the first 30 cm depth with the conversion of burned to unburned harvest was used in the present C balance assessment. The overall increase in soil C stocks in the system with trash retention is mainly related the large input of organic material in the conservation management system in sugarcane production. There is an annual input of 5–10 Mg of C left on the soil surface as dry sugarcane leaves and tops. As the litter is decomposed, part of the C is emitted as CO_2 into the atmosphere, and part is incorporated into the soil, increasing the SOC pool. However, there are several factors which must be taken into account when assessing the potential for increases in soil C. Soils have a finite C sink capacity, eventually reaching equilibrium with respect to management (Six *et al.*, 2002). The temporal dynamics of soil C stocks are influenced by antecedent C stocks, soil texture, mineral fertilizer and organic material application. Soil C stocks are also dependent on the degree of soil disturbance during the replanting operation.

GHG balances of sugarcane-derived ethanol produced in Brazil

The boundaries considered in this assessment encompassed the agricultural and industrial processing phases, from producing and planting the cane setts all the way to the final product in the mill. In addition to the 'seed to gate' GHG emissions and removals flow chart of sugarcane-derived ethanol production systems shown in Fig. 1, there are also emissions in the distribution and use phases, which vary widely according to the target market and the proportion of ethanol used in the fuel mix. Furthermore, the agricultural and industrial phases account for most of the emissions in the full life cycle of ethanol (Larson, 2006).

Table 2 Annual carbon stock change (0–30 cm) under burned and unburned sugarcane harvesting systems in Brazil

		Clay content (%)		Carbon stock (Mg ha^{-1})		Annual carbon (Mg ha^{-1} yr^{-1})
Site	Time span (years)	Burned	Unburned	Burned	Unburned	Stock change
Sandy soils						
1	4	21	20	33.7	38.7	1.25
2	4	09	10	28.8	32.5	0.93
3	4	28	28	34.6	40.4	1.45
4	12	34	34	59.0	57.3	−0.14
5	16	20	20	53.6	56.2	0.16
Mean						0.73 (± 0.69)
Clayey soils						
6	3	56	51	49.8	56.6	2.27
7	4	72	71	60.7	68.4	1.93
8	4	68	66	68.0	77.5	2.38
9	6	67	70	69.8	82.9	2.18
10	6	69	66	44.4	57.5	2.18
11	8	67	78	50.1	64.4	1.79
12	12	68	64	60.4	79.5	1.59
Mean						2.04 (± 0.28)
Overall mean						1.50 (± 0.82)

Rather than expressing the GHG balance in kilogram C_{eq} per unit of mass, volume or energy, all values are presented in terms of emissions and removals per unit of area (hectares), to facilitate comparisons with alternative land uses.

The previous life cycle assessments of ethanol production in Brazil have aggregated data from burned and unburned systems, considering the proportion of area harvested by each system. The approach used in this assessment was to disaggregate the inputs and outputs of the two main harvesting systems: sugarcane harvested manually with preharvest burning, and mechanized harvest with crops residues left on the field. Average sugarcane and ethanol yields for Brazil were used, considering five harvests in 6 years (one plant crop and four ratoon crops) (Boddey *et al*., 2008). All of the inputs used in the agricultural phase were normalized in this manner, in order to estimate annual applications.

The annual C inputs and outputs (kg C_{eq}) of sugarcane-derived ethanol production in Brazil under burned and unburned harvesting systems are presented in Table 3, along with the energy content of inputs and outputs in MJ ha^{-1} yr^{-1}. When considering fossil emissions in the agricultural phase, unburned harvest

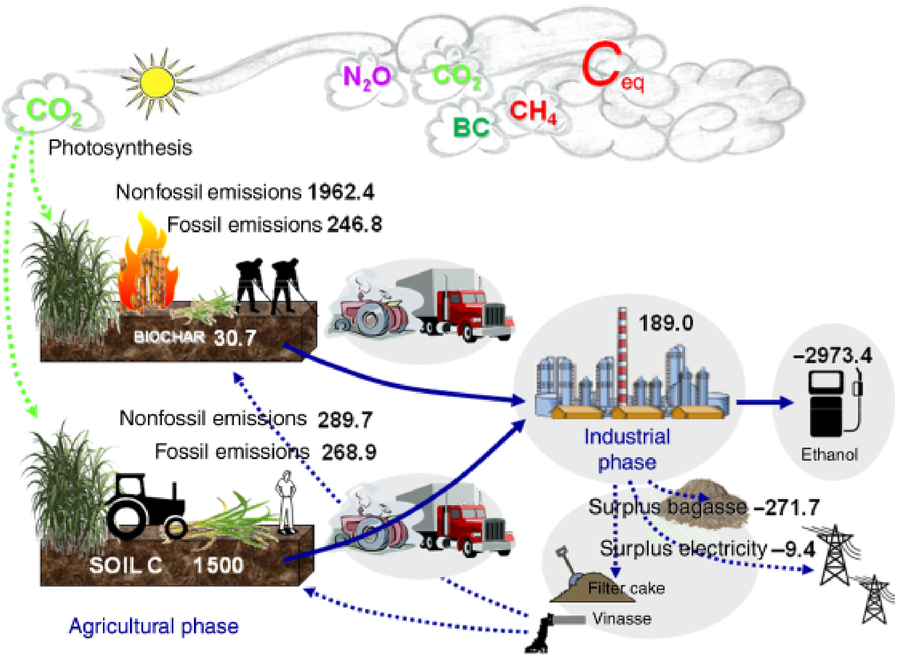

Fig. 1 Greenhouse gas emissions and removals in the 'seed to gate' phase of sugarcane-derived ethanol production.

Table 3 Carbon inputs and outputs of sugarcane-derived ethanol production in Brazil under burned and unburned harvesting systems

	Energy (MJ ha^{-1} yr^{-1})*		Carbon equivalent (kg C_{eq} ha^{-1} yr^{-1})†	
Carbon inputs and outputs	Burned	Unburned	Burned	Unburned
Inputs				
Agricultural phase‡				
Fossil emissions				
Labor	1003.5	301.2	20.2	6.1
Machinery	1324.5	1378.7	26.7	27.8
Diesel	1064.4	2806.5	21.4	56.6
Nitrogen	3061.8	3061.8	61.7	61.7
Phosphorus	51.0	51.0	1.0	1.0
Potassium	488.9	488.9	9.9	9.9
Lime	478.9	478.9	9.6	9.6
Seeds	252.2	252.2	5.1	5.1

Continued

Table 3. (*Contd.*)

Carbon inputs and outputs	Energy ($MJ\,ha^{-1}\,yr^{-1}$)*		Carbon equivalent ($kg\,C_{eq}\,ha^{-1}\,yr^{-1}$)†	
	Burned	Unburned	Burned	Unburned
Herbicides	1445.3	1445.3	29.1	29.1
Insecticides	87.3	87.3	1.8	1.8
Vinasse disposal	656.0	656.0	13.2	13.2
Transport of consumables	276.8	276.8	5.6	5.6
Cane transport	2058.0	2058.0	41.5	41.5
Subtotal fossil emissions	12248.6	13342.6	246.8	268.9
Nonfossil emissions:§				
CH_4 and N_2O from preharvest burning			196.0	0.0
Black carbon from preharvest burning¶			1535.5	0.0
Litter decomposition‖			11.6	70.4
Nitrogen fertilizer**			110.7	110.7
Liming			47.7	47.7
Vinasse††			41.9	41.9
Filter cake‡‡			18.9	18.9
Subtotal nonfossil emissions			1962.4	289.7
Subtotal agricultural phase	12248.6	13342.6	2209.2	558.5
Industrial phase				
Chemicals used in factory	487.6	487.6	9.8	9.8
Cement	75.9	75.9	1.5	1.5
Structural mild steel	841.8	841.8	17.0	17.0
Mild steel and light equipment	693.5	693.5	14.0	14.0
Stainless steel	287.1	287.1	5.8	5.8
95% ethanol to 99.5%	225.3	225.3	4.5	4.5
Black carbon from burning bagasse§§			136.4	136.4
Subtotal industrial phase	2611.2	2611.2	189.0	189.0
Total inputs			2398.3	747.6
Outputs				
Total ethanol yield¶¶	147562.2	147562.2	2973.4	2973.4
Surplus bagasse‖‖	13481.6	13481.6	271.7	271.7
Surplus electricity***	6342.5	6342.5	111.3	111.3
Soil carbon†††				1500.0
Biochar‡‡‡			30.7	
Total outputs			3387.0	4856.3
Ratio output/input			1.4	6.5

*Embedded energy includes production, transportation and storage (Lal, 2004).
†Used emission factor of $20.15\,kg\,C_{eq}\,GJ^{-1}$ to convert energy to carbon emissions (Lal, 2004) and global warming potentials of 25 (CH_4) and 298 (N_2O) (IPCC, 2007).
‡Assuming sugarcane yield of $76.7\,Mg\,ha^{-1}$, and the following annual applications per hectare: $56.7\,kg\,N\,ha^{-1}$, $16\,kg\,P_2O_5\,ha^{-1}$, $83\,kg\,K_2O\,ha^{-1}$, $367\,kg$ lime ha^{-1}, $3.2\,kg$ herbicide ha^{-1}, $0.24\,kg$ insecticide ha^{-1} (Boddey *et al.*, 2008).
§Nonfossil emissions calculated using IPCC (2006) default values, except for black C.
¶Factor for black carbon emissions from burning trash: 1.0 kg BC Mg trash (db) (Sanhueza, 2009).
‖Amount of N in crop residues remaining on the soil after mechanized harvest (10). $45\,kg\,N\,ha^{-1}$; and after preharvest fire (Cerri, 1986): $7\,kg\,N\,ha^{-1}$.
**Assumed 60% of N fertilizer in the form of urea over the 6-year cycle.
††Amount of N added with vinasse application (Resende *et al.*, 2006): $23\,kg\,N\,ha^{-1}\,yr^{-1}$.
‡‡Amount of N added with filter cake application (Macedo *et al.*, 2008): $10\,kg\,N\,ha^{-1}\,yr^{-1}$.
§§Factor for black carbon emissions from burning bagasse, assuming a 90% emissions control in the furnace: $12\,kg\,BC\,TJ^{-1}$ (db) (Sanhueza, 2009).
¶¶Ethanol yield of $6281\,L\,ha^{-1}$, energy content of ethanol: $21.45\,MJ\,L^{-1}$ (Boddey *et al.*, 2008).
‖‖Surplus bagasse of 9.6% (Macedo *et al.*, 2008).
***Surplus electricity of $9.3\,kWh\,Mg\,cane^{-1}$ and global average emission factor of $579\,Mg\,CO_{2\,eq}\,GWh^{-1}$ (Macedo *et al.*, 2008).
†††Annual increase in soil carbon stocks (0–30 cm), from Table 1.
‡‡‡Annual input of carbon deposited as ashes in the soil after preharvest burning (Cerri, 1986).

systems present slightly higher values than the manually harvest burned system, due to higher emissions related to the mechanized harvesting (machinery and diesel). These emissions are offset by the lower input of human labor. When all the emissions in the agricultural phase are computed, there is a large difference between burned, 2209.2 kg C_{eq} ha^{-1} yr^{-1} and unburned systems, 558.5 kg C_{eq} ha^{-1} yr^{-1}. This difference is mainly due to the large amount of BC – and to a lesser extent CH_4 and N_2O – emitted in preharvest burning.

The two harvest systems do not affect the industrial phase emissions, because only the cane stalks are currently used for first generation ethanol production. There is a relatively high contribution of BC emissions in the bagasse-burning furnaces, which represent 72% of C_{eq} emissions in the industrial phase, especially considering that this has not been included in most GHG balances.

The 1500 kg C ha^{-1} stored annually in the top 30 cm strongly impact the total balance of C inputs and outputs. The increase in soil C stocks in the unburned harvest, which has also been omitted from biofuel GHG balances, represents a third of the C outputs in this system. This is especially important in the context of the biomass burning ban supported by the Brazilian government and industry, which will eliminate preharvest burning, and the dominance of mechanized unburned harvest.

There is a need for further research in the uncertainty assessment of GHG balances in biofuel production, in order to address variability on both activity data and emission factors throughout the product life cycle. For instance, the large uncertainty in soil N_2O emissions from nitrogen fertilizer application would be decreased by regional and site-specific emission factors obtained by field measurements and process-based modeling. Methane emissions from organic residues of ethanol production such as vinasse need further research in order to be estimated and included in future assessments. Finally, soil C sequestration, an important C sink, must be further assessed considering soil, climate and management-related variables.

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