

# Bioethanol production from sugarcane and emissions of greenhouse gases – known and unknowns

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## Abstract

Bioethanol production from sugarcane is discussed as an alternative energy source to reduce dependencies of regional economies on fossil fuels. Even though bioethanol production from sugarcane is considered to be a beneficial and cost-effective greenhouse gas (GHG) mitigation strategy, it is still a matter of controversy due to insufficient information on the total GHG balance of this system. Aside from the necessity to account for the impact of land use change (LUC), soil N<sub>2</sub>O emissions during sugarcane production and emissions of GHG due to preharvest burning may significantly impact the GHG balance. Based on a thorough literature review, we show that direct N<sub>2</sub>O emissions from sugarcane fields due to nitrogen (N) fertilization result in an emission factor of  $3.87 \pm 1.16\%$  which is much higher than suggested by IPCC (1%). N<sub>2</sub>O emissions from N fertilization accounted for 40% of the total GHG emissions from ethanol–sugarcane production, with an additional 17% from trash burning. If LUC-related GHG emissions are considered, the total GHG balance turns negative mainly due to vegetation carbon losses. Our study also shows that major gaps in knowledge still exist about GHG sources related to agricultural management during sugarcane production, e.g. effects of irrigation, vinasse and filter cake application. Therefore, more studies are needed to assess if bioethanol from sugarcane is a viable option to reduce energy-related GHG emissions.

**Keywords:** biofuel, ethanol, global warming, land use change, LCA, N<sub>2</sub>O, sugarcane

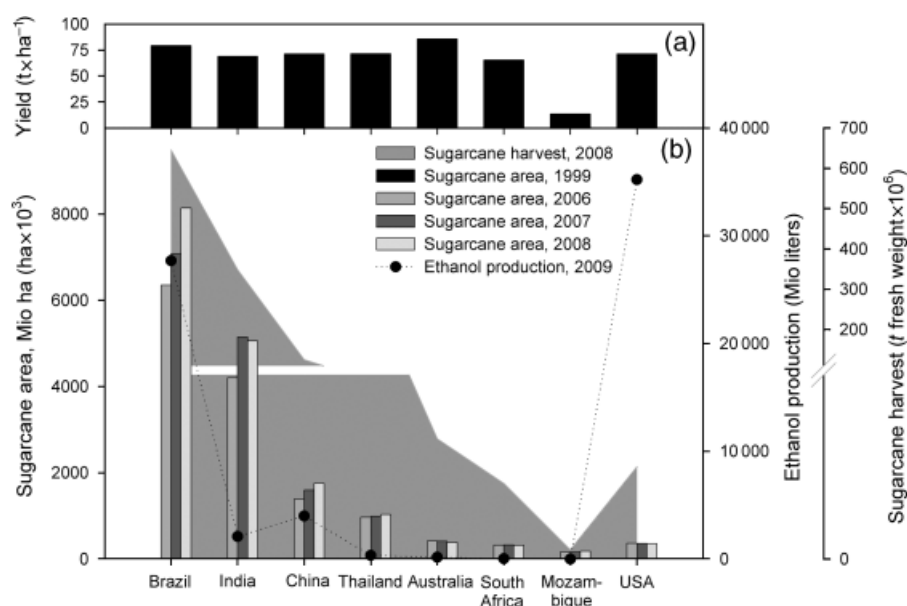
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## Introduction

It is very well established that the observed increase in atmospheric CO<sub>2</sub> concentrations is a result mainly of fossil fuel combustion but also volatilization of carbon (C) stocks following conversion from natural to agricultural land [Intergovernmental Panel on Climate Change (IPCC), 2007]. The resultant impact on climate is threatening the global environment and underpinning worldwide efforts for alternative sustainable energy sources. The production of biofuels from crop biomass has been promoted as an alternative source of renewable energy [Goldemberg, 2007; Food and Agriculture Organization (FAO), 2008] even though there are potential land conflicts between bioenergy food and feed production (Kates *et al.*, 2001; FAO, 2008; Fargione *et al.*, 2008; Solomon, 2010).

One of the most popular biofuels is ethanol. Ethanol is mainly produced from crops as sugarcane, beets and grains. In the last decade, the United States of America (corn-based ethanol production) and Brazil (sugarcane-based ethanol production) were the leading countries in world-wide bioethanol production (Fig. 1). However, production of ethanol from corn-based cropping systems may directly compete with food and feed production and requires higher rates of nitrogen (N) fertilizers, contributing to local and regional eutrophication and resulting in increased soil N<sub>2</sub>O emissions (Crutzen *et al.*, 2008; Fargione *et al.*, 2008). Alternatively, ethanol from sugarcane may be more suitable to cover the energy demand of regional economies and here specifically for biofuels. Additionally, it has been indicated that 'first generation' bioethanol from sugarcane has a better energy balance and highest potential to net greenhouse gas (GHG) emission savings as compared with other noncellulosic biofuels [Goldemberg, 2007; Crutzen *et al.*, 2008; International Food Policy Research Institute (IF-

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**Fig. 1** (a) Average sugarcane yield in different countries in 2008 and (b) total global area for sugarcane production and tons of sugarcane harvested in 1999 and 2006/08 by country (FAOSTAT, 2010). In addition ethanol production by country for the year 2009 is given (OECD-FAO, 2010).

PRI, 2010]. This may change in the future when cellulosic ('second generation') ethanol becomes available, i.e. when instead of starch or sugar in the case of corn or sugarcane the whole plant biomass can be used for bioethanol production (Farrell *et al.*, 2006).

Sugarcane is an indigenous crop originally from New Guinea, Southeast Asia, and now grows in regions located from 35°N to 35°S (Barnes, 1974). As a C4 plant, sugarcane is a species with a photosynthetic pathway which has a high efficiency for converting solar radiation into biomass (Black *et al.*, 1969). World ethanol production from sugarcane has risen steadily over the last decade, e.g. Brazil has increased its ethanol production between 2002 and 2009 on average by 13% yr<sup>-1</sup> [União da Indústria de Cana-de-Açúcar (UNICA), 2009]. At present, 54.6% of the sugarcane production in Brazil and 39% in India is used for bioethanol production [United States Department of Agriculture, 2009; Companhia Nacional de Abastecimento (CONAB), 2010], whereas for other countries statistical data on the fate of sugarcane production is hardly available. Together Brazil, India and China were responsible for more than 60% of the global sugarcane production in 2008 [FAO Statistics Division (FAOSTAT), 2010]. Moreover, Asia, South Africa, Mozambique and Australia have been showing a significant growth in sugarcane production, however, mainly driven by the rapidly increasing demand for sugar in China and India (Fig. 1). Ethanol production from sugarcane has played a minor role in these countries, whereas the domestic

and international demand for bioethanol is a major driver for the expansion of sugarcane production in Brazil (Fischer *et al.*, 2008).

Since ethanol production from sugarcane is considered as an environmentally sustainable fuel by many international agencies and researchers (Goldemberg, 2007; Crutzen *et al.*, 2008; IFPRI, 2010) many countries have promoted the use of ethanol for the transport sector by introducing mandatory or voluntary targets for the blending of ethanol with gasoline. For example, in Brazil there is a mandatory target of 25% blending of ethanol (E25) with gasoline. Furthermore, in 2008 the European Union proposed a mandatory target for bioethanol blending of 10% by 2020. Aside from the argument of combating global warming there are also other issues supporting bioethanol production e.g. rising oil prices and the ambition for energy security (Leite *et al.*, 2009).

In contrast, bioethanol production from sugarcane, may create a 'biofuel carbon debt' if release of C from ecosystem stocks due to land use changes (LUCs) are considered (Fargione *et al.*, 2008). There are only a limited number of studies (Kates *et al.*, 2001; Crutzen *et al.*, 2008; Fargione *et al.*, 2008; Zuurbier & de Vooren, 2008; IFPRI, 2010) which provide background information with respect to environmental consequences of bioethanol production from sugarcane, thus, an objective assessment of the advantages and disadvantages of sugarcane-based biofuel production, trading and consumption is still missing.

The aim of this paper is to synthesize available information on land use management, C stock changes and N<sub>2</sub>O exchange in sugarcane ethanol production systems in order to improve our understanding on environmental impacts of sugarcane production, to identify gaps in knowledge and to guide future research.

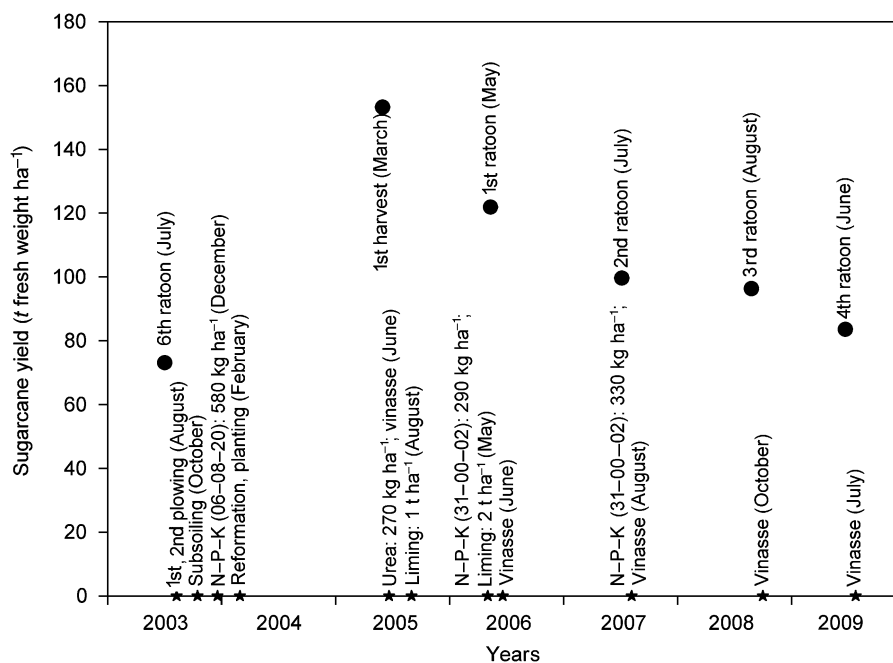
## Production systems

Sugarcane is an annual crop commercially cultivated in monoculture without rotation in five to seven ratoon cycles (Fig. 2). Sugarcane has a growth period ranging from 9 to 24 months depending on the variety, environmental conditions and management (Humbert, 1968; Câmara & Oliveira, 1993). After five to seven ratoon cycles sugarcane fields are 'reformed' or replanted, requiring the elimination of stalks (mechanically with or without application of chemicals), soil tillage and re-establishment of the crop by placing freshly cut sugarcane sprouts in the prepared soil. Traditionally, soil preparation for sugarcane requires full tillage. During the last decade, the full tillage has been replaced by minimum tillage practices in some regions of Brazil and Australia – i.e. the soil is only slightly tilled in the planting row. Occasionally, legumes are planted during the reformation period to improve soil fertility and/or

soil physical properties (Mascarenhas *et al.*, 1994; Bell & Garside, 2005; Hernwong *et al.*, 2008).

In order to maximize biomass production a significant input of agrochemicals is required. This includes fertilizer (N–P–K) application, liming as well as application of herbicides and pesticides. Regional recommendations for the use of N fertilizers for sugarcane production cover a wide range (e.g. 45–300 kg N ha<sup>-1</sup> in Srivastava & Suarez, 1992) with average application rates in Australia and South Africa of higher than 100 kg N ha<sup>-1</sup> yr<sup>-1</sup> (Bholah & Ng Kee Kwong, 1997; Hartemink, 2008; Denmead *et al.*, 2010) and <100 kg N ha<sup>-1</sup> yr<sup>-1</sup> for China and Brazil (Macedo *et al.*, 2008; Zhou *et al.*, 2009). In Brazil, there are indications that sugarcane varieties used in combination with soil conditions may have a significant amount of their N demand met by biological N fixation (Döbereiner *et al.*, 1972; Boddey *et al.*, 2001; Medeiros *et al.*, 2006). For example, Lima *et al.* (1987) estimated that biological N<sub>2</sub> fixation in Brazilian sugarcane plantations may be as high as 150 kg N ha<sup>-1</sup> yr<sup>-1</sup>, thus covering up to 60% of the N demand of the crop.

In order to facilitate harvest, it has been a common practice worldwide to burn the crop at the harvest stage and to manually cut the remaining standing stalks. As a result of global market forces pushing public, political, sugarcane growers sectors to improve the environmental aspects of sugarcane production



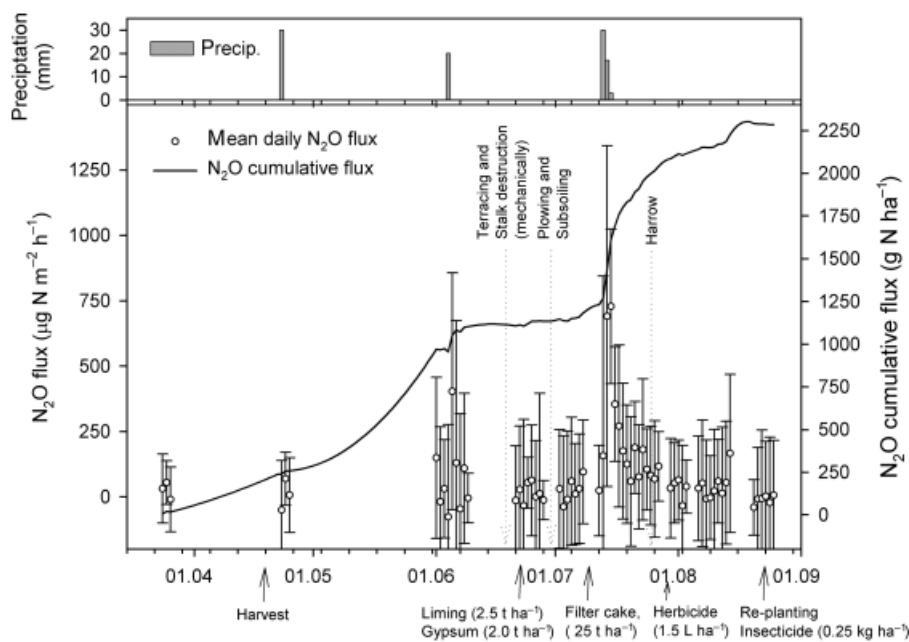
**Fig. 2** Example of the development of sugarcane yields over time with successive ratoon. Land use management in the different years are given in the graph. The data provided here is for a typical sugarcane field at Iracemópolis-SP, Brazil (Usina Iracema, São Martinho Industry) which has been cultivated for > 10 years without burning prior to harvest. The soil type at this site is a clayed Oxisol (45% clay + 40% sand).

there is a trend to change common preburning systems to *green systems* – in which burning is phased out. Additionally, cost efficiency is also promoting this change from burnt systems into *green systems* (without burning). The sugarcane *green system* has been adopted in some areas of Australia since 1930 and now practiced on 70% of the entire area planted to sugarcane cultivation area. In order to promote the sugarcane *green systems*, São Paulo state in Brazil has prescribed that preharvest burning needs to be eliminated by 2021 for all areas which do allow mechanized harvests (slope gradient <12%) and by 2030 for all areas of sugarcane production. Nowadays, approximately 40% of the cane area in Brazil has adopted the *green system* management.

During the industrial sugarcane processing for both ethanol and sugar, several residues are generated: vinasse (only from ethanol production), bagasse and filtercake. Vinasse is an organic liquid, a subproduct of the alcohol distillation by fermentation, containing high amounts of organic C (6000–23 000 mg C L<sup>-1</sup>; Companhia Ambiental do Estado de São Paulo, 2006). For each liter of ethanol, 10–15 L of vinasse are generated. Vinasse is mostly used for fertigation, which describes combined fertilization and irrigation. Vinasse is stored for a short period of time in open tanks in order to cool down from temperatures >80 °C to about 30–50 °C. Following cooling, the vinasse is pumped into open

channels and sprayed onto fields mainly in close vicinity of the industrial plants. The prevailing anaerobic environment in the open tanks and channels may stimulate CH<sub>4</sub> production. Vinasse contains significant amounts of nutrients: potassium (K) (1.17 kg m<sup>-3</sup>); N (0.28 kg m<sup>-3</sup>), calcium (0.33 kg m<sup>-3</sup>), phosphorus (P) (0.10 kg m<sup>-3</sup>) and magnesium (0.13 kg m<sup>-3</sup>) (Resende *et al.*, 2006). In order to avoid soil salinization and ground and surface water contamination application rates are recommended to be <300 m<sup>3</sup> ha<sup>-1</sup>. The average rate in Brazil is 100 m<sup>3</sup> ha<sup>-1</sup> (Macedo *et al.*, 2008).

Another organic fibrous residue from industrial sugarcane processing is bagasse, which is obtained after extracting the juice (Pandey *et al.*, 2000). Bagasse has a high C (45%) but relatively low N content (0.5%), resulting in a high C:N ratio of approximately 90 (Agnihotri *et al.*, 2010). For each ton of processed sugarcane, 200–300 kg of bagasse (Centro de Tecnologia Canavieira, 2010, Cardona *et al.*, 2010) and 8 kg of filtercake are generated (Macedo *et al.*, 2008). In Brazil in the process of cogeneration more than 90% of bagasse is re-used for heating in the distillery plant (Macedo, 2005). Bagasse is stockpiled and a proportion is composted and finally used as filter cake in field applications. Rasul *et al.* (2008) reported that filter cake in Pakistan contains approximately 34 kg N t<sup>-1</sup> (total N). For Brazilian sugarcane mills somewhat lower N contents for filter cake are reported: 12.5 kg N t<sup>-1</sup> Donzelli



**Fig. 3** Daily ( $\pm$  SD) and cumulative N<sub>2</sub>O emissions of a Brazilian sugarcane field experiencing all typical management practices of reformation. Measurements cover a 5 months period and are based on eddy-covariance technique measurements with a Campbell TGA-100A as described in Pihlatie *et al.* (2010). Data were processed using the flux processing software TK2 (Mauder *et al.*, 2006) taking into account standard features of quality control.

(2005) or  $29.9 \text{ kg N t}^{-1}$  (Busato *et al.*, 2010). Furthermore, filter cake has a high organic matter content  $>48\%$  (Meunchang *et al.*, 2005) with total C contents ranging from  $420 \text{ kg t}^{-1}$  (Rasul *et al.*, 2008) to  $466 \text{ kg t}^{-1}$  (Busato *et al.*, 2010). Typical filter cake application rates in Brazilian sugarcane fields are  $5 \text{ t (dry matter) ha}^{-1}$  at cane plantation or during reforming periods (Macedo *et al.*, 2008). The filter cake application on the field might represent a potential, but still unquantified source of GHG emissions particularly  $\text{N}_2\text{O}$  emissions (see also Fig. 3). In the future, there is a great potential for bagasse to be alternatively used for fuel production, i.e. so-called second generation ethanol biofuels – which might represent an economic and environmental advantage for sugarcane mills (Cardona *et al.*, 2010).

### Global sugarcane yield

In 2009, the global agricultural area planted with sugarcane was approximately 24 Mio ha, representing 1.74% of the total global arable land. Total sugarcane production was in excess of 1683 Mt (fresh weight) and the average yield was  $70.9 \text{ t fresh weight ha}^{-1}$  (FAO-STAT, 2010). Sugarcane yields across the different producer countries are highly variable (Fig. 1). Reasons for this variability are climatic conditions, soil physico-chemical properties, length of the ratoon cycle, sugarcane variety and the relation between imbalanced plant nutrition and occurrence of pests and diseases (Hartemink, 2008). Sugarcane is highly dependent on the availability of sufficient amounts of rainfall on a seasonal cycle of wet and dry periods. Without irrigation it grows best in regions with annual rainfall in the range of 1500–2500 mm (Doorenbos & Kassam, 1979) and annual solar radiation of  $6350 \text{ MJ m}^{-2}$  (Ramanujam & Venkataramana, 1999). The radiation use efficiency (RUE) is between 1.7 and  $2 \text{ g MJ}^{-1}$  (Robertson *et al.*, 1996; Muchow *et al.*, 1997). In South Africa and Mozambique where average yields are generally low compared with the rest of the world, sugarcane production is mainly limited by water availability. In South Africa, 40% of the total cropped area is irrigated (Inman-Bamber & Smith, 2005). In Australia, about 66% of the sugarcane fields require irrigation (Bell *et al.*, 2007). In Swaziland, irrigation is essential (Knox *et al.*, 2010). In Brazil, 5% of sugarcane lands are irrigated – full, supplementary or rescue irrigation – and 36% of the sugarcane area receives fertigation, i.e. vinasse application (CTC, personal communication).

### Emission of GHGs

One of the key components to evaluate the climate sustainability of bioethanol from sugarcane is the as-

essment of the net GHG savings as compared with the use of fossil fuels (IFPRI, 2010). During the production of bioethanol from sugarcane GHGs can be produced at several stages and can be attributed to two different categories: (a) biogenic GHG emissions from the plant–soil system related to crop production and (b) anthropogenic GHG emissions due to energy use related to farm operations, fertilizer production, processing and, transportation. Sources from category (b) can be estimated with a higher certainty than those from category (a). In our methodology, we have concentrated on summarizing literature on biogenic GHGs emissions from the plant–soil system, before we use standard data on nonbiogenic source to develop a full GHG life cycle assessment (LCA) for sugarcane.

Biogenic GHG emissions from sugarcane production can originate from various sources and a full assessment must consider  $\text{CO}_2$ , as well as  $\text{N}_2\text{O}$  and  $\text{CH}_4$  exchange. The most important sources are associated with:

- (a) LUC or conversion and its effects on ecosystem C and N stocks,
- (b) fertilization, fertigation and irrigation,
- (c) residue management including preharvest burning,
- (d) tillage operations.

### GHG emissions due to LUC/conversion

Soil organic C (SOC) stocks are representing the largest terrestrial organic C pool ( $>1550 \text{ Pg C}$ ) followed by the vegetation pool (500–650 Pg) (Lal, 2008). The capacity of soils to store C is largely affected by land use and management (Trumbore, 1997; Lal, 2003). Any changes in land use and management may feedback on SOC and N dynamics potentially altering stocks. Thus,  $\text{CO}_2$  emission resulting from cleaning of soil and vegetation due to the expansion of sugarcane production may represent one of the major sources of GHG emissions. Indirect emissions due to indirect land use change (iLUC) also need to be considered, i.e. biofuel production can displace cropland and/or pasture, indirectly causing GHG emissions since native land may be converted to cropland and pastures elsewhere (Searchinger *et al.*, 2008). C losses due to LUC have only rarely been considered in previous LCA studies evaluating the GHG balance of ethanol production from sugarcane (Fargione *et al.*, 2008).

In Brazil – the globally largest sugarcane producer (Fig. 1) – the increasing demand for bioethanol from sugarcane has led to a continuous expansion of land used for sugarcane production. It is estimated that approximately 8 Mio ha in 2008 ( $<2\%$  of currently available agricultural land) is under sugarcane production and an additional 3.9 Mio ha will be grown with sugarcane in 2020 in order to achieve the projected

**Table 1** Soil carbon stocks of different types of Cerrado under natural vegetation and agricultural management

Location (state)	Land use	Soil type	Soil depth (cm)	Soil C Stock (t ha <sup>-1</sup> )	Soil N Stock (t ha <sup>-1</sup> )	Reference
MT	Cerrado	Podizol	0–40	21.80	1.03	Fernandes <i>et al.</i> (1999)
	Pasture, 10 years			19.00	1.04	
	Pasture, 20 years			15.70	1.01	
MT	Cerrado	Sandy*	0–30	18.09	1.18	Frazão <i>et al.</i> (2008)
	FT† Soybean, 1 year			23.40	1.47	
	NT‡ Soybean, 5 years			16.74	1.34	
	Pasture, 22 years			19.67	1.52	
MT	Cerrado <i>sensu stricto</i>	Oxisol	0–30	48.99	§	Maia <i>et al.</i> (2009)
	Pasture			51.81	§	
	Cerrado <i>sensu stricto</i>	Sandy*		27.92	§	
	Pasture			28.36	§	
	Cerradão	Oxisol		61.41	§	
	Pasture			57.97	§	
RO	Cerradão	Hapludox	0–30	49.00	§	Carvalho <i>et al.</i> (2009)
	FT <sup>1</sup> Rice, 1 year			47.60	§	
	FT <sup>1</sup> Rice, 2 years			55.40	§	
	NT <sup>2</sup> Soybean, 1 year			66.50	§	
	NT <sup>2</sup> Soybean, 3 years			67.50	§	
GO	Cerradão	Oxisol	0–10	12.00	0.67	Costa (2010)
	Sugarcane burnt			8.30	0.38	
	Sugarcane unburnt			20.83	1.18	
GO	Cerrado	Oxisol	0–20	37.89	4.97	D’Andréa <i>et al.</i> (2004)
	Pasture > 15 years			40.67	4.02	
	FT <sup>1</sup>			34.06	4.22	
	NT <sup>2</sup> (corn/beans)			40.16	5.02	

MT, Mato Grosso; RO, Rondônia; GO, Goiás.

\*Quartzsamment.

†Full tillage.

‡No tillage.

§No data available.

annual 52 billion liters of ethanol production (Ministério de Minas e Energia, 2007). According to the CONAB (2008), about 69% of the most recent sugarcane expansion in São Paulo state took place on pastures, 17% in annual crops (soybean and corn) and 2.2% on new lands. For Mato Grosso state, 31% of sugarcane expansion occurred on pasture, 68% on former arable land cultivated with soybean and 1.3% on new lands (CONAB, 2008). The regional focus of sugarcane production is on south-central Brazil, which is responsible for 90% of the national ethanol production (UNICA, 2009). The impact on C stocks as a result of LUC and tillage management (Table 1) on those regions is poorly understood, particularly the impact of expansion of sugarcane land. Maia *et al.* (2009) calculated the potential change in soil C stocks if land use was changed from native vegetation to grassland in Amazon and Cerrado regions. Information on changes in soil C stocks due to the expansion of sugarcane production is generally limited since direct measurements are not available.

**Table 2** Estimates for aboveground biomass as estimated by stereo-photographs (Ottmar *et al.*, 2001), for different types of Cerrado in Goiás, Mato Grosso, Distrito Federal and Minas Gerais states

Vegetation type	Biomass stocks (t C ha <sup>-1</sup> )
<i>'Grassy' vegetation</i>	
Campo limpo	3.78–16.57
Campo sujo	6.68–15.77
<i>'Woody' vegetation</i>	
Cerrado (open forest)	12.55–39.05
Cerrado <i>sensu stricto</i>	20.90–58.01
Cerradão (dense vegetation)	29.90–71.89

Moreover, with respect to the Cerrado region there is still a great uncertainty about soil C storage and biomass values for the different types of Cerrado (Fearnside *et al.*, 2009). In a recent review, Batlle-Bayer *et al.* (2010) reported that the soil C stock down to

1 m soil depth for Brazilian savanna can range between 100 and 174 Mg C ha<sup>-1</sup> for native Cerrado. Variations in soil C stocks are driven by Cerrado type, being classified based on vegetation characteristics and biomass C stocks (Eiten, 1972): (1) 'woody' vegetation: Cerradão (dense vegetation), Cerrado *sensu stricto*, Cerrado (open vegetation) and (2) 'grassy' vegetation (Campo sujo, Campo limpo) (Ottmar *et al.*, 2001) (Table 2).

The cane production in Australia is expected to not leading to further deforestation. During the last 10–15 years, sugarcane production has expanded from the predominantly wet tropical parts of Northern Queensland to the more dryer areas (e.g. the Atherton Tablelands) requiring supplemental irrigation. Little is known about LUC derived emissions in Africa, India and China.

### GHG emissions due to fertilization, fertigation and irrigation

Fertilizer application is a regular practice in order to increase biomass production and yields and to maintain soil fertility. N-use efficiency in sugarcane production has been reported to be in the range of 6–40% (Reichardt *et al.*, 1982; Ng Kee Kwong & Deville, 1984; Salcedo *et al.*, 1988; de Oliveira *et al.*, 2002), i.e. more than 60% of applied N fertilizer is lost to the environment. Part of this loss occurs directly – i.e. from the soil of the fertilized field – or indirectly – i.e. following cascading of reactive N compounds downwind and downstream of the application site being a significant part of the GHG balance of sugarcane production systems which have to be accounted for.

The main source of N<sub>2</sub>O emissions in sugarcane fields is the application of N fertilizers, both mineral N fertilizer and/or organic fertilizers such as bagasse, vinasse or manure. Only a few studies (mainly from Australia) are available with direct field measurements of N<sub>2</sub>O emissions from sugarcane soils (Table 3). In two of the Australian studies, N<sub>2</sub>O emissions were assessed over an entire year with annual emission rates ranging from 2.8 kg N<sub>2</sub>O-N ha<sup>-1</sup> for unfertilized sugarcane fields (Allen *et al.*, 2010) to >45 kg N<sub>2</sub>O-N ha<sup>-1</sup> for a sugarcane field fertilized with 160 kg N applied in form of urea (Denmead *et al.*, 2010). Weier (1998) reported that 45–78% of N<sub>2</sub>O emissions were due to denitrification of applied N following N fertilization. All other available studies are short-term measurements covering measuring periods from days to a few months. To consider also these studies in our assessment, we used simplified approaches for calculation of annual emission rates (see Table 3). Macedo *et al.* (2008) reported annual N<sub>2</sub>O Emissions from Brazilian sugarcane cultivation of

1.7 ± 0.5 kg N<sub>2</sub>O-N ha<sup>-1</sup>. In Fig. 3, we summarize own N<sub>2</sub>O emission measurements based on eddy-covariance technique in combination with tunable diode laser spectroscopy (TGA 100, Campbell Sci, Logan, UT, USA, for details see Pihlatie *et al.*, 2010) which resulted in emissions of 2.1 kg N<sub>2</sub>O-N ha<sup>-1</sup> for a 5-month period (April 1–October 30, 2010) including the full reformation practice of a sugarcane field such as stalk destruction, plowing, subsoiling, harrowing and application of filtercake (Fig. 3). To derive an average emission factor (EF) for N<sub>2</sub>O emissions from sugarcane fields due to N fertilization, we plotted published values of annual N<sub>2</sub>O losses as a function of the N fertilizer application rate. The average EF for N<sub>2</sub>O is 3.87 ± 1.16%, i.e. 3.87 kg N<sub>2</sub>O-N (1800 kg CO<sub>2eq</sub> ha<sup>-1</sup>) are emitted per 100 kg N-fertilizer application (Fig. 4). Considering of background N<sub>2</sub>O emission from savanna soils, which are close to zero (Bruemmer *et al.*, 2008), would hardly change the calculated EF. The EF was not corrected for N<sub>2</sub>O emissions at zero N-fertilizer application since only one study is available. Furthermore, the high N<sub>2</sub>O emissions of 45.9 and 21.7 kg N<sub>2</sub>O-N ha<sup>-1</sup> yr<sup>-1</sup> in the Denmead *et al.* (2010) and Matson *et al.* (1996) were considered to be outliers (due to very specific site conditions) and not included in the regression calculation as well. Past studies (Farrell *et al.*, 2006; Adler *et al.*, 2007; Macedo *et al.*, 2008; Galdos *et al.*, 2010) which have included a LCA for bioethanol from sugarcane are based on the default value from IPCC where the direct emission of N<sub>2</sub>O due to N fertilizer use is 1% (IPCC, 2006) or 1.25% (IPCC, 2001). Compared with our assessment of available data of N<sub>2</sub>O emissions from sugarcane the IPCC EF is considered to be low.

Soils under native vegetation can be either sources or sinks of atmospheric CH<sub>4</sub>. There are only a few studies covering tropical and subtropical regions in which CH<sub>4</sub> exchange rates were quantified. Published data is inconclusive with both net CH<sub>4</sub> uptake (Steudler *et al.*, 1989; Keller & Reinert, 1994; Verchot *et al.*, 2000; Kiese *et al.*, 2008; Castaldi *et al.*, 2006; Carvalho *et al.*, 2009) and net CH<sub>4</sub> emissions from tropical and subtropical soils. For savanna, CH<sub>4</sub> fluxes could possibly range from –632 to 98 µg CH<sub>4</sub>-C m<sup>-2</sup> h<sup>-1</sup> (Castaldi *et al.*, 2004, 2006).

Denmead *et al.* (2010) as well as Crutzen & Andreae (1990) reported that under conditions of high soil moisture sugarcane fields can be significant emitters of CH<sub>4</sub> with annual fluxes being in a range of 0–19.9 kg CH<sub>4</sub> ha<sup>-1</sup> (0–458.12 kg CO<sub>2eq</sub> ha<sup>-1</sup>). In addition, Mosier *et al.* (1991) and Bronson & Mosier (1994) have reported a detrimental effect of ammonium-based fertilizer on soil CH<sub>4</sub> uptake, whereas on the other hand nitrate fertilizer forms were found to stimulate soil CH<sub>4</sub> uptake (Nesbit & Breitenbeck, 1992). Weier (1999) observed that sugarcane fields functioned either as net sinks or

**Table 3** Soil N<sub>2</sub>O emissions from sugarcane fields

Site	Soil type	Rainfall (mm)	N-fertilizer	N rate (kg N ha <sup>-1</sup> )	N <sub>2</sub> O emission (original data) N <sub>2</sub> O–N g ha <sup>-1</sup>	Annual N <sub>2</sub> O emission estimates <sup>1</sup> kg N <sub>2</sub> O–N ha <sup>-1</sup> yr <sup>-1</sup>	Reference
Ingham, Queensland, Australia	Bleached clay soil	2250	Urea	80 + 80	1143 (104 days) <sup>-1</sup>	1.14 × 365/104 = 4.0 × 0.7 or × 1.3 = 4.0 ± 1.2	Weier (1999)
			Urea	160	1082 (104 days) <sup>-1</sup>	1.08 × 365/104 = 3.8 × 0.7 or × 1.3 = 3.8 ± 1.1	
			(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	160	1562 (104 days) <sup>-1</sup>	1.14 × 365/104 = 5.5 × 0.7 or × 1.3 = 5.5 ± 1.6	
New South Wales, Mackay, Queensland, Australia	Sulfaquets and Humaquets	1879	Urea	160	45 900 (year) <sup>-1</sup>	45.9 ± 13.8	Denmead <i>et al.</i> (2010)
	Chromosol	2142		150	4700 (year) <sup>-1</sup>	4.7 ± 1.4	
East Brisbane, Australia	Hydrosol	1017	Urea	0	2860 (year) <sup>-1</sup>	2.9 ± 0.9	Allen <i>et al.</i> (2010)
				50 + 50	3860 (year) <sup>-1</sup>	3.9 ± 1.2	
				100	3930 (year) <sup>-1</sup>	3.9 ± 1.2	
				100	5810 (year) <sup>-1</sup>	5.8 ± 1.7	
				200	9560 (year) <sup>-1</sup>	9.6 ± 2.9	
Maui, Hawaii, USA	Inceptisol	1000–1500	Urea	84	11 (96 hours) <sup>-1</sup>	Data not used since observation period < 10 days	Matson <i>et al.</i> (1996)
	Mollisol	1000–1250		34	110 (144 hours) <sup>-1</sup>	Data not used since observation period < 10 days	
	Mollisol	1000–1250		22	13 (240 hours) <sup>-1</sup>	0.01 × 365/10 = 0.45 × 0.7 or × 1.3 = 0.45 ± 0.14	
	Mollisol	250–300		45	52 (217 hours) <sup>-1</sup>	Data not used since observation period < 10 days	
	Mollisol	250–300		35	170 (218 hours) <sup>-1</sup>	Data not used since observation period < 10 days	
	Mollisol	250–300		39	92 (240 hours) <sup>-1</sup>	0.09 × 365/10 = 3.29 × 0.7 or × 1.3 = 3.29 ± 1.0	
	Mollisol	250–300		20	6 (163 hours) <sup>-1</sup>	Data not used since observation period < 10 days	
	Andisol	1100		95	380 (695 hours) <sup>-1</sup>	0.38 × 365/29 = 3.29 × 0.7 or × 1.3 = 4.78 ± 1.4	
	Andisol	3810		124	1250 (509 hours) <sup>-1</sup>	1.25 × 365/21 = 21.7 × 0.7 or × 1.3 = 21.7 ± 6.5	
	Andisol	3800		94	330 (382 hours) <sup>-1</sup>	0.33 × 365/16 = 7.5 × 0.7 or × 1.3 = 7.5 ± 2.3	
Brazil	–	–	NO <sub>3</sub> or (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	75	1700 (year) <sup>-1</sup>	1.7 ± 0.5	Macedo <i>et al.</i> (2008)

<sup>1</sup>If annual emission estimates were not provided, values were estimates based on simple extrapolation of the mean value for the given observation period for the entire year.

Uncertainty of estimates was assumed to be ± 30%.

sources for CH<sub>4</sub> over a 104 days period of measurements: CH<sub>4</sub> emissions after urea application (at 160 kg N ha<sup>-1</sup>) were 297–1005 g CH<sub>4</sub>-C ha<sup>-1</sup> (6.8–23.1 kg CO<sub>2eq</sub>

ha<sup>-1</sup>) whereas at a site receiving ammonium sulfate (160 kg N ha<sup>-1</sup>) CH<sub>4</sub> uptake was in a range of 442–467 g CH<sub>4</sub>-C ha<sup>-1</sup> (10.2–10.7 kg CO<sub>2eq</sub> ha<sup>-1</sup>). Based on



the available information, field site  $\text{CH}_4$  fluxes do play only a minor role for the total GHG balance of bioethanol from sugarcane. However, more studies at a range of sites are needed to finally confirm this statement and to reduce uncertainties.

Fertigation, i.e. simultaneous provision of irrigation water and fertilizer, has been reported as the most efficient method of fertilizer application (Feigin *et al.*, 1982), particularly for N, since fertigation allows the reduction of fertilizer rates in sugarcane production systems (Thorburn *et al.*, 2003). The type of N fertilizer in fertigation is important to determine recovery rates, nutrient mobility (Haynes, 1990) and stimulation of soil organic matter mineralization and GHG emission. Furthermore, the fertigation by vinasse application also represents a high potential for GHG emission. Vinasse has a very high C content and contains significant amounts of nutrients and is microbiologically active (biological oxygen demand  $> 20\,000\text{ mg L}^{-1}$ ), even though anaerobic bacteria prevail. First measurements in Brazil show that  $\text{CH}_4$  is produced and emitted during the transport of vinasse in open channels to application sites.  $\text{CH}_4$  emissions from open channels are approximately in the  $0\text{--}10\text{ mg CH}_4\text{-C m}^{-2}\text{ h}^{-1}$  range. If one assumes that the share of open irrigation channels per ha sugarcane field is approximately 1% and that vinasse is applied at  $30\text{ days yr}^{-1}$  the total  $\text{CH}_4$  emission would be in maximum  $720\text{ g CH}_4\text{-C ha}^{-1}\text{ sugarcane yr}^{-1}$ . The use of vinasse as fertilizer may stimulate soil GHG emissions either directly or by priming decomposition of soil organic matter due to extra decomposition of organic C after addition of easily decomposable organic substance to the soil (Bingemann *et al.*, 1953; Jenkinson *et al.*, 1985; Dalenberg & Jager, 1989; Kuzyakov *et al.*, 2000). As a consequence increased GHG emissions or nutrient leaching may occur. However, available knowledge on the effects of fertigation of sugarcane fields on GHG exchange is scarce and not at all quantitative. The same applies for irrigation. In some regions such as South Africa, Swaziland or parts of Australia irrigation is essential to produce sugarcane. Irrigation increases soil moisture, reduces soil aeration and, thus, is likely to stimulate  $\text{N}_2\text{O}$  production by denitrification. For example, Denmead *et al.* (2010) reported very high  $\text{N}_2\text{O}$  losses (21% of total N application) in sugarcane fields with high moisture levels between 60% and 80% water field pore space (WFPS). Since fertigation as well as irrigation may represent major drivers for increased GHG fluxes, targeted measurements on effects of fertigation/irrigation on GHG fluxes and soil C and N stocks – covering entire years, different sites and fertigation/irrigation intensities – are urgently needed for a thorough GHG assessment of bioethanol from sugarcane.

## Residue management and burning

The traditional sugarcane production system with pre-harvest burning of residues has been found to significantly enhance GHG emissions. In the Brazilian GHG inventory (Lima *et al.*, 1999), sugarcane burning is reported to be responsible for 98% of total GHG emission from agricultural burning activities. Marques *et al.* (2009) estimated C release into the atmosphere at a rate of  $4.81\text{ t CO}_{2\text{eq}}\text{ ha}^{-1}$  by burning  $10.4\text{ t}$  of biomass. The direct loss of  $\text{CO}_2$  upon burning is not accountable; however, the reduced litter input to soils potentially lowers soil C stocks (see Table 1). What is accountable in the GHG balance is the production of  $\text{N}_2\text{O}$  and  $\text{CH}_4$  during biomass burning. The IPCC (2006) emission factors to quantify  $\text{N}_2\text{O}$  and  $\text{CH}_4$  emission due to burning of biomass are  $0.07\text{ kg N}_2\text{O t}^{-1}$  dry matter burnt and  $2.7\text{ kg CH}_4\text{ t}^{-1}$  dry matter burnt. For example, burning a sugarcane field with  $10\text{--}20\text{ t dry matter ha}^{-1}$  will produce approximately  $4.2\text{ kg N}_2\text{O}$  (or  $1243\text{ kg CO}_{2\text{eq}}\text{ ha}^{-1}$ ) and  $162\text{ kg CH}_4$  (or  $3726\text{ kg CO}_{2\text{eq}}\text{ ha}^{-1}$ ). In recent years there is a tendency to eliminate preharvest burning, i.e. that the trash remains at the site. Also this management practice may affect the overall GHG balance. The trash has a high C:N ratio in excess of 70, and N can be immobilized by soil microorganisms (Robertson & Thorburn, 2007). On the other hand, the trash layer will also promote higher soil moisture in the mineral soil and promote anaerobically conditions in the soil potentially stimulating denitrification and  $\text{N}_2\text{O}$  formation (Meier *et al.*, 2006). Weier (1996) reported higher  $\text{N}_2\text{O}$  emissions from unburnt fields ( $36.5\text{ g N}_2\text{O-N ha}^{-1}\text{ day}^{-1}$ ) compared with burnt fields ( $31\text{ g N}_2\text{O-N ha}^{-1}\text{ day}^{-1}$ ). With respect to  $\text{CH}_4$  exchange it is reported that unburnt soils exhibit higher  $\text{CH}_4$  uptake rates of  $0.8\text{ kg CH}_4\text{ ha}^{-1}\text{ day}^{-1}$  (Weier, 1998). The major impact of ceasing preharvest burning has been the increased organic matter inputs which in turn increase soil C stocks (Galdos *et al.*, 2009a,b; Robertson & Thorburn, 2007). Galdos *et al.* (2009a) reported an annual C increase of  $1.2\text{ t ha}^{-1}$  for the first 20 cm topsoil after 8 years of unburnt management. Suman *et al.* (2009) reported for a sugarcane field in India an increase from  $2.3$  to  $17.1\text{ t ha}^{-1}$  after 5 years of organic fertilization with  $10\text{ t organic manure ha}^{-1}\text{ yr}^{-1}$  plus N-P-K application ( $150\text{--}60\text{--}60\text{ kg ha}^{-1}$ ) at tillage operation (first year). In many cases, a portion of the trash residue is used for energy production in the sugar mills. The potential impact of this practice on GHG emissions and changes in soil C stocks has so far not been reported.

## Tillage and harvest operations

It is well established that during tillage operations (e.g. plowing, subsoiling and harrowing) soil aggregates can

be disrupted leading to an accelerated mineralization of soil organic matter (Fernandes *et al.*, 1997). Tillage operations are normally performed after five to seven ratoon cycles in order to re-plant the sugarcane. It is important to notice that a significant amount of the sequestered soil C (Galdos *et al.*, 2009a, b) over the years of sugarcane re-growth might be lost during the field reformation (soil preparation with tillage operations). Therefore, the conversion from full tillage to minimum or no-tillage may play a significant role in maintaining soil C and N stocks. In a short-term study (4 weeks), La Scala *et al.* (2006) reported that soil CO<sub>2</sub> emissions from Brazilian sugarcane are reduced under improved management with 523, 895 and 1362 g CO<sub>2</sub> m<sup>-2</sup> for no-till, reduced tillage and conventional tillage, respectively.

Furthermore with the increase in *green systems*, which includes the use of mechanical harvesters soil compac-

tion is a possibility. Soil compaction may increase N<sub>2</sub>O emissions due to decreased aeration and stimulation of anaerobiosis and denitrification (Kelliher *et al.*, 2003; Bessou *et al.*, 2010). Only limited information is available about how the use of heavy machinery affects soil compaction in sugarcane production systems and how this may finally affect soil C stocks and GHG emissions.

### GHG emissions due to field operations and sugarcane processing

The industrial processing of sugarcane in the mills for ethanol production requires energy. Macedo *et al.* (2008) calculated total GHG emissions during processing for a typical Brazilian sugarcane mill to be 2.2 kg CO<sub>2</sub> t<sup>-1</sup> sugarcane. Furthermore, there are GHG emissions – mainly CO<sub>2</sub> – from machinery at harvest and field

**Table 4** Greenhouse gases (GHGs) emissions from ethanol–sugarcane production

GHG sources	kg CO <sub>2eq</sub> ha <sup>-1</sup> yr <sup>-1</sup>		t C <sub>eq</sub> ha <sup>-1</sup> yr <sup>-1</sup>	
	Burnt	Unburnt	Burnt	Unburnt
Field operations (fossil fuel emissions)				
Farming inputs*	470	470	0.128	0.128
Farm machinery†	44	88‡	0.012	0.024
Transport and agricultural operations§	880	880	0.240	0.240
<i>Subtotal1</i>	1394	1437	0.380	0.392
Industrial phase				
Chemicals¶	157	157	0.043	0.043
Buildings and equipments¶	26	26	0.007	0.007
<i>Subtotal2</i>	183	183	0.050	0.050
Trash burning				
N <sub>2</sub> O emissions**	217		0.059	
CH <sub>4</sub> emissions††	651		0.177	
<i>Subtotal3</i>	868		0.237	
Soil emissions				
N <sub>2</sub> O emissions				
Trash decomposition‡‡	42	373	0.011	0.102
N-fertilization (IPCC default value: EF <sub>N<sub>2</sub>O</sub> 1.0)§§	465	465	0.127	0.127
N-fertilization (this study: EF <sub>N<sub>2</sub>O</sub> 3.87)¶¶	1800 ± 540	1800 ± 540	0.49 ± 0.147	0.49 ± 0.147
P <sub>2</sub> O <sub>5</sub> and K <sub>2</sub> O fertilization				
Liming				
Irrigation				
Vinasse***	160	160	0.044	0.044
Filter cake‡‡‡	59	59	0.016	0.016
Indirect N <sub>2</sub> O emissions†††				
NH <sub>3</sub> -N volatilized	47	47	0.013	0.013
NO <sub>3</sub> -N leached	349	349	0.095	0.095
<i>Subtotal I.1 (using EF<sub>N<sub>2</sub>O</sub> 3.87 without trash decomposition)</i>	2414	2414	0.658	0.658
<i>Subtotal II.1 (using IPCC EF<sub>N<sub>2</sub>O</sub> 1.0 + trash decomposition)</i>	1121	1453	0.306	0.396
CH <sub>4</sub> emissions				
No information available on effects of trash decomposition, N-/P <sub>2</sub> O <sub>5</sub> or K <sub>2</sub> O fertilization, liming, irrigation, vinasse or filter cake application on CH <sub>4</sub> fluxes				

*Continued*

Table 4 (Continued)

GHG sources	kg CO <sub>2eq</sub> ha <sup>-1</sup> yr <sup>-1</sup>		t C <sub>eq</sub> ha <sup>-1</sup> yr <sup>-1</sup>	
	Burnt	Unburnt	Burnt	Unburnt
Soil C-stock changes/CO <sub>2</sub> emissions				
SOC change (burnt → unburnt)§§§		-5500		-1.500
C-volatilization from Urea-fertilization¶¶¶	73	73	0.020	0.020
P <sub>2</sub> O <sub>5</sub> and K <sub>2</sub> O fertilization				
Liming	0.17	0.17	5 × 10 <sup>-5</sup>	5 × 10 <sup>-5</sup>
Irrigation				
Vinasse				
Filter cake				
Subtotal I.2 (without SOC change, burnt → unburnt)	74	74	0.020	0.020
Subtotal II.2 (with SOC change, burnt → unburnt)	74	-5426	0.020	-1.480
Subtotal EF <sub>N<sub>2</sub>O</sub> 3.87 (∑ subtotals 1–4 + ∑ subtotals I.1–I.2)	4976	4151	1.357	1.132
Subtotal EF <sub>N<sub>2</sub>O</sub> 1.0 (∑ subtotals 1–4 + ∑ subtotals II.1–II.2)	3682	-2311	1.004	-0.630
Outputs (avoided emissions)****				
Hydrous ethanol	-15 547	-15 547	-4.240	-4.240
Use of biomass surplus for process energy generation	-1124	-1124	-0.306	-0.306
Energy surplus in form of electricity due to the use of biomass surplus	-462	-462	-0.126	-0.126
Subtotal	-17 133	-17 133	-4.673	-4.673
Total EF <sub>N<sub>2</sub>O</sub> 3.87 (subtotal EF <sub>N<sub>2</sub>O</sub> 3.87 + avoided emissions)	-12 184	-13 068	-3.320	-3.564
Total EF <sub>N<sub>2</sub>O</sub> 1.0 (subtotal EF <sub>N<sub>2</sub>O</sub> 1.0 + avoided emissions)	-13 477	-19 530	-3.675	-5.326

\*Data from Macedo *et al.* (2008) from scenario 2005/2006. Emissions related to fossil energy consumption due to the production of fertilizer, herbicides, insecticides, lime, and seeds.

†Data from Macedo *et al.* (2008) from scenario 2005/2006. Emissions related to fossil energy consumption by farm machinery.

‡Data for farm machinery for unburnt systems we double the values reported by Macedo *et al.* (2008) since they adopted 50% mechanical harvesting for scenario 2005/2006 and for this study we consider 100% mechanical harvesting for unburnt fields.

§Data from Macedo *et al.* (2008) from scenario 2005/2006. Emissions related to fossil fuel consumption due the use of agricultural operations, harvesting, cane transportation, inputs transportation and other activities.

¶Data from Macedo *et al.* (2008) from scenario 2005/2006. Emissions due to fossil energy consumption during the production of ethanol.

||IPCC (2006) default values. Trash input: 13.1 t ha<sup>-1</sup> with 80% of burning efficiency (Embrapa, 2009).

\*\*Emission factor: 0.07 kg N<sub>2</sub>O/t dry matter burnt.

††Emission factor: 2.70 kg CH<sub>4</sub>/t dry matter burnt.

‡‡Trash N content: 0.5% at unburnt sugarcane field and 0.07% (Macedo, 2005), at burnt sugarcane field (Cerri, 1986). Trash input: 13.1 t ha<sup>-1</sup> (Embrapa, 2009). IPCC (2006) default emission factor for residues: 1.225% of N in residue is converted to N<sub>2</sub>O.

§§IPCC (2006) default emission factor for N-fertilization: 1% of N-fertilizer applied is converted to N<sub>2</sub>O. N-fertilization rate: 100 kg N ha<sup>-1</sup>.

¶¶Emission factor for this study: 3.87 ± 1.16% of N-fertilizer applied is converted to N<sub>2</sub>O. N-fertilization rate: 100 kg N ha<sup>-1</sup>.

|||No data available.

\*\*\*Vinasse application rate of 100 m<sup>3</sup> ha<sup>-1</sup> (Macedo *et al.*, 2008). Vinasse N content: 0.28 kg N m<sup>-3</sup> (Resende *et al.*, 2006). IPCC (2006) default emission factor for residues: 1.225% of N in residue is converted to N<sub>2</sub>O.

†††Filter cake application rate of 5 t ha<sup>-1</sup>, at planting phase or first year of sugarcane cultivation (Macedo *et al.*, 2008). Filter cake N content: 12.5 kg N t<sup>-1</sup> (Donzelli, 2005). N inputs due filter cake application per year: (12.5 kg N × 5 years)/6 growth season. IPCC (2006) default emission factor for residues: 1.225% of N in residue is converted to N<sub>2</sub>O.

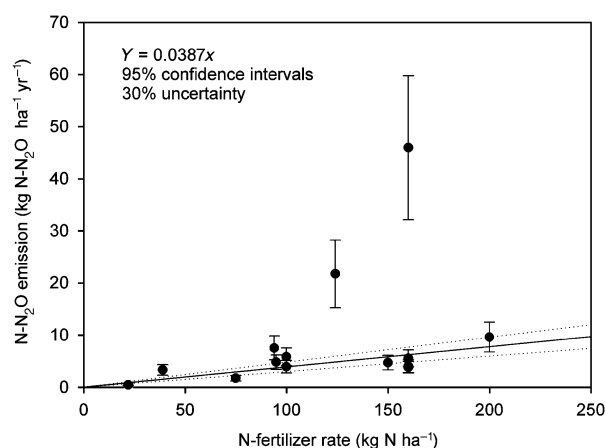
‡‡‡IPCC (2006) default emission factor due to indirect emissions. NH<sub>3</sub>-N due volatilization: 10% of N-fertilization is volatilized, i.e. 10 kg N ha<sup>-1</sup> yr<sup>-1</sup>, 1% of N volatilized is converted to N<sub>2</sub>O. NO<sub>3</sub>-N leaching: 2.5% of N-fertilization is leached, 30% of N nonvolatilized is converted to N<sub>2</sub>O.

§§§Annual increase in SOC stocks 0–30 cm depth 1.5 ± 0.8 t C ha<sup>-1</sup> yr<sup>-1</sup> (Galdos *et al.*, 2010).

¶¶¶IPCC (2006) default emission factor: 0.2 kg C (kg urea)<sup>-1</sup>.

||||IPCC (2006) default emission factor for dolomite: 0.13 kg C (kg urea)<sup>-1</sup>. Annual liming input: 0.367 t ha<sup>-1</sup> (Macedo *et al.*, 2008).

\*\*\*\*(a) Avoided emissions due ethanol use as a substitute of gasoline (hydrous ethanol, dedicated ethanol engines: 1 L ethanol = 0.75 L gasoline). (b) Avoided emissions due the substitution of biomass-fuelled boilers [79% efficiency, low heating value (LHV)] for oil-fuelled boilers (92% efficiency, LHV). (c) Avoided emissions due use of bagasse to generate electricity, considering emission factor for power generation in 2002 was ~579 t CO<sub>2eq</sub>GWh<sub>e</sub><sup>-1</sup> (Macedo *et al.*, 2008; from scenario 2005/2006).



**Fig. 4** Reported annual  $\text{N}_2\text{O}$  emissions in dependence of N fertilizer application rate, confidence interval=95%. Calculation are based on reported original data from Denmead *et al.* (2010), Allen *et al.* (2010), Macedo *et al.* (2008), Weier (1999) and Matson *et al.* (1996) (see Table 3).

management which has been estimated to be 10.1–12.5  $\text{kg CO}_2 \text{ t}^{-1}$  sugarcane (Macedo *et al.*, 2008). Additionally, GHG emissions due to the production of fertilizers should be considered. Macedo *et al.* (2008) estimated this source of GHG for the Brazilian situation to be in a range of 4.4–5.4  $\text{kg CO}_2 \text{ t}^{-1}$  sugarcane. Furthermore,  $\text{CO}_2$  is released during the fermentation process of the sugarcane juice, which has not been quantified yet.

### Total balance of GHG emissions for ethanol–sugarcane

Within the GHG inventory of the ethanol–sugarcane system, the major contribution (excluding LUC) is from N fertilization (Table 4). Considering the  $\text{N}_2\text{O}$  EF of  $3.87 \pm 1.16\%$  determined in this synthesis the N-fertilizer-induced GHG emissions accounted for  $\sim 40\%$  ( $0.49 \pm 0.15 \text{ t C}_{\text{eq}} \text{ ha}^{-1}$ ) of the total GHG emissions of bioethanol production from sugarcane, with 35% for unburnt and 43% for burnt systems. These  $\text{N}_2\text{O}$  emissions are equivalent to 30% of the annual gain in soil C stocks in the unburnt system ( $1.5 \text{ t C}_{\text{eq}} \text{ ha}^{-1} \text{ yr}^{-1}$ , Galdos *et al.*, 2010). If we consider the IPCC default value (1%) for  $\text{N}_2\text{O}$  emission from N fertilization, total  $\text{N}_2\text{O}$  emissions would only be 11% ( $0.13 \text{ t C}_{\text{eq}} \text{ ha}^{-1}$ ) of the total GHG emission. The secondary source of GHG emissions ( $\sim 30\%$ ) are fossil fuels associated with the production of farm inputs and those combusted in the course of product transportation and agricultural operations. Apart from these two sources, the trash burning before harvesting is contributing approximately 17% to the total GHG from ethanol–sugarcane production in our calculations. Our synthesis identifies a lack

**Table 5** Changes in total ecosystem C-stocks following the conversion of different land use forms to ethanol-sugarcane production

LUC	Natural vegetation		Sugarcane		C-changes due to LUC	
	Aboveground biomass* ( $\text{t C ha}^{-1}$ )	Soil C stocks† ( $\text{t C ha}^{-1}$ )	Soil C stocks‡ ( $\text{t C ha}^{-1}$ )	Unburnt ( $\text{t C ha}^{-1}$ )	Burnt ( $\text{t C}_{\text{eq}} \text{ ha}^{-1}$ )	Unburnt ( $\text{t C}_{\text{eq}} \text{ ha}^{-1}$ )
Cerradão → sugarcane	50.9 (29.9–71.9)	56.5 (49.0–64.1)	51.1 (28.8–69.8)	59.3 (32.5–82.9)	–56.3	–48.1
Cerrado <i>sensu stricto</i> → sugarcane	39.4 (20.9–58.0)	38.4 (27.9–49.0)	51.1 (28.8–69.8)	59.3 (32.5–82.9)	–26.7	–18.5
Cerrado → sugarcane	25.9 (12.6–39.1)	28 (18.1–37.9)	51.1 (28.8–69.8)	59.3 (32.5–82.9)	–2.8	+5.4
Pastagem → sugarcane		37.3 (15.7–58.0)	51.1 (28.8–69.8)	59.3 (32.5–82.9)	+13.8	+22.0
Crop → sugarcane		42.1 (16.7–67.5)	51.1 (28.8–69.8)	59.3 (32.5–82.9)	+9.0	+17.2

\*Data from Ottmar *et al.* (2001), Table 2.

†Data from Table 1.

‡Data from Galdos *et al.* (2010), 0–30 cm.

of information regarding CH<sub>4</sub> emissions from e.g. vinasse and possible other sources of GHG emissions (see omissions in Table 4). Those potential CH<sub>4</sub> emissions needs to be identified and better understood since they may significantly impact the LCA for bioethanol from sugarcane. Quantification is specifically needed for CH<sub>4</sub> and GHG fluxes (a) following organic fertilizer application, i.e. vinasse and filter cake, (b) due to vinasse storage at the industrial phase and, further transportation till the field, (c) due to trash decomposition following mechanized harvest and (d) following liming and N–P–K fertilization.

Our study suggests improvements in land use management, particularly with respect to improvements of the N-use efficiency of sugarcane and elimination of preharvest burning of sugarcane fields, are needed to further improve the GHG balance of bioethanol. Our study also indicates that we know little about N<sub>2</sub>O emissions from sugarcane soils and that it is important to address the regional variability of N<sub>2</sub>O emissions carefully to better assess the role of N<sub>2</sub>O in the total GHG balance of bioethanol.

As previously suggested by Fargione *et al.* (2008), the potential climate benefit of bioethanol from sugarcane is diminished when emissions due to LUCs are accounted for (see Table 5). Here, main driver are C losses from biomass vegetation, whereas changes in soil C stocks seem to be of less importance. That is, soil C stocks under sugarcane, at least if mechanized harvest is applied are comparable to soil C stocks under natural vegetation. However, this statement still requires a thorough analysis and paired site comparison which is beyond the scope of this paper. For our synthesis we used a rather simple and direct calculation to estimate the C debt from LUC for bioethanol production, particularly for Brazil. The worst case scenario in our study was the conversion of natural Cerradão to sugarcane, in which it would take nearly 45 years to pay the C debt due to losses in vegetation C stocks (Tables 4 and 5). In general, the better scenario would be the conversion from pasture areas or crop land to sugarcane fields. Here, even net gains in soil C stocks are visible if unburnt sugarcane systems are adopted. However, it is important to emphasize that the direct conversion of native vegetation to sugarcane fields is unlikely to occur in Brazil, whereas for other countries no information is available. Following clearing the land is normally used for cropping legume or rice or for pasture. Only following several years of such cultivations fields may finally be used for sugarcane production.

In summary, there is still a large uncertainty on the total GHG balance of bioethanol from sugarcane which is due to the paucity of available data. Furthermore, the complexity and variability of the land management and

the impact of LUC and also iLUC need to be considered to estimate total GHG emission of sugarcane production at regional and site-specific scales.

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