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Payback time for soil carbon and sugar-cane ethanol

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The effects of land-use change (LUC) on soil carbon (C) balance has to be taken into account in calculating the CO_2 savings attributed to bioenergy crops[1–3]. There have been few direct field measurements that quantify the effects of LUC on soil C for the most common land-use transitions into sugar cane in Brazil, the world's largest producer[1–3]. We quantified the C balance for LUC as a net loss (carbon debt) or net gain (carbon credit) in soil C for sugar-cane expansion in Brazil. We sampled 135 field sites to 1 m depth, representing three major LUC scenarios. Our results demonstrate that soil C stocks decrease following LUC from native vegetation and pastures, and increase where cropland is converted to sugar cane. The payback time for the soil C debt was eight years for native vegetation and two to three years for pastures. With an increasing need for biofuels and the potential for Brazil to help meet global demand[4], our results will be invaluable for guiding expansion policies of sugar-cane production towards greater sustainability.

Energy crops have expanded significantly in Brazil during recent years. Between 2000 and 2012, nearly 5 Mha of sugar cane were added, bringing the current total to 9.7 Mha (ref. 5), half of which is used for the production of energy. This expansion has made sugar cane the main source of renewable energy in Brazil[6].

However, the full impact of sugar cane on greenhouse gas (GHG) emissions requires that the effects of converting land to sugar cane also be considered. Several studies indicate that energy crop expansion may result in a carbon debt[1–3] due to significant carbon losses as CO_2, promoted by activities such as slash and burn of native vegetation[7] or by the accelerated decomposition of soil organic matter (SOM) due primarily to the disturbance of the soil structure or reduced inputs[8].

The replacement of degraded lands with low soil carbon (C) stocks, with high productivity energy crops, may reduce the payback period of the C debt incurred from land-use change (LUC), or even eliminate the payback[1–3], resulting in a positive soil carbon balance or a biofuel carbon credit. Gains in soil C could be achieved with proper soil management and high rates of organic matter input from plant residues, allowing soils to contribute to GHG mitigation of biofuel-related land use and LUC[9,10].

Brazilian sugar-cane production is concentrated in the south-central region of the country, comprising almost 90% of the national production[11]. In terms of LUC to sugar cane, there are indications that more than 95% of recent expansion has been from pasture (∼70%), grain crops (∼25%) and citrus (∼1%; refs 12,13). The conversion of natural vegetation into sugar cane has occurred in the past, but represents less than 1% of the expansion in this area from 2000 to 2009[13].

Here we investigate the effect of LUC on soil C stocks and calculate the carbon payback time for sugar-cane ethanol production in Brazil. Measurements from 135 study sites, forming 75 comparison pairs (CP), and ∼6,000 soil samples in south-central Brazil were analysed, for three types of land use conversion into sugar cane from: native vegetation, pastures and annual cropland. Measurements were taken for multiple soil depth increments to facilitate comparisons with previous studies, which are often restricted to surface layers (for example, 0–30 cm), but also to provide a more complete C inventory encompassing the near full depth of rooting (for example, 0–100 cm).

Measurements for the 75 CP were distributed across 13 regions in south-central Brazil (Fig. 1). The majority were areas in which sugar cane replaced pastures (57 CP) followed by conversions from annual cropland (13 CP) and cerrado (5 CP), known as Brazilian savannah. Soil C stocks were determined for each of the 75 CP for 0–30 cm, 0–50 cm and 0–100 cm depth increments (Supplementary Table 1). Soil C stock changes were calculated from response ratios, referred to as LUC factors, which represent the relative change in SOC stocks due to LUC. A response ratio equal to 1 represents no change, values <1 mean loss and values >1 mean gain. The LUC factors were derived for five-year time blocks, to coincide with sugar-cane regeneration cycles, for up to 20 years (IPCC timeframe to approximate equilibrium of soil C stocks). The LUC factors were calculated for a 20-year time span to estimate carbon debt (or credit) and payback times (Table 1).

The LUC factors calculated for cerrado to sugar cane, after 20 years, were 0.74 (±0.03), 0.80 (±0.03) and 0.93 (±0.04) for 0–30 cm, 0–50 cm and 0–100 cm layers respectively, indicating C losses following cerrado conversion (Fig. 2). However, net C losses for the five site pairs were only significant for the 0–30 cm depth (Supplementary Information and Supplementary Table 1), with C stock estimates below 30 cm under sugar cane being lower for three sites and higher for two sites. Thus a carbon debt was calculated only

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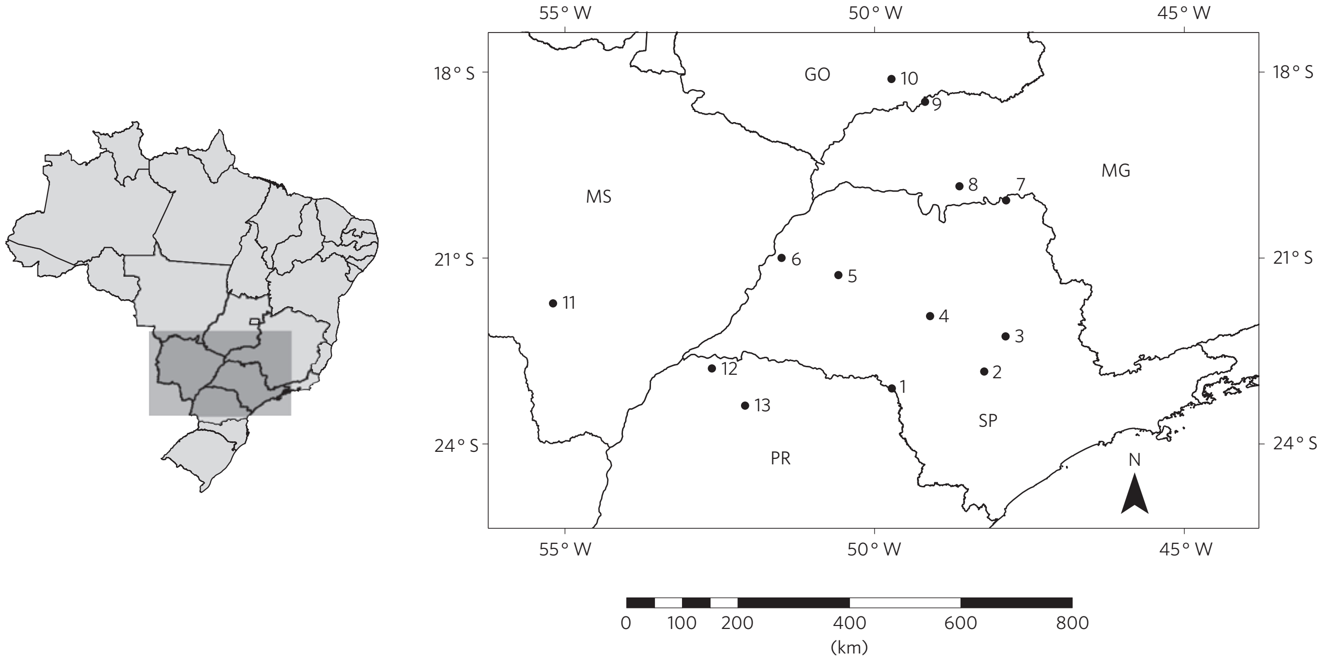

Figure 1 | Regions selected for soil sampling in south-central Brazil. São Paulo (SP; 1–7); Minas Gerais (MG; 8–9); Goiás (GO; 10); Mato Grosso do Sul (MS; 11); Paraná (PR; 12–13).

for the 0–30 cm depth, yielding a value of 77 Mg CO_2 ha^{-1} for the 20-year period following conversion (Table 1).

The LUC factors from pasture conversion to sugar cane for 0–30 cm, 0–50 cm and 0–100 cm were 0.90 (±0.03), 0.91 (±0.03) and 0.93 (±0.03; Fig. 2) respectively. The carbon debt was estimated at 21 Mg CO_2 ha^{-1} for 0–30 cm and 32 Mg CO_2 for 0–100 cm over 20 years, leading to a payback time of two to three years (Table 1). The response ratios (Fig. 3) indicate that soil C stocks decrease following LUC from pasture in the majority of the observed CP, and lower carbon stocks in sugar cane compared to pasture reference were noted in 41 out of 57 CP (72%) for 0–30 cm, in 38 out of 57 CP (67%) for 0–50 cm and in 34 out of 57 CP (60%) for 0–100 cm.

When sugar cane was converted from annual cropland, the LUC factors for soil C stock change for 0–30 cm, 0–50 cm and 0–100 cm after 20 years were 1.16 (±0.06), 1.17 (±0.06) and 1.17 (±0.06), respectively, indicating an increase in the soil C stock (Table 1; Fig. 2). Response ratios for 0–30 cm and 0–50 cm (Fig. 3) showed that in 6 of 13 CP the soil carbon stocks increased when compared to agricultural land uses. For 0–100 cm, soil carbon increased in seven sites following conversion to sugar cane, whereas six sites decreased.

Historically, LUC associated with deforestation has been the major source of GHG emissions in Brazil[14], making up 52% of total emissions in 2005 (ref. 15). Our observations show that the substitution of cerrado areas by sugar cane decreases soil C stocks, with losses of up to 26% (0–30 cm), within the range of previously reported losses (13–30%) for this depth[1,16]. Because LUC is likely to involve conversion between vegetation with differing rooting depths, management practices and productivity, assessing soil carbon losses from 0 to 30 cm could result in under- or overestimation of the likely stock changes. For our five site pairs of cerrado to sugar cane conversions, soil C losses were significant only for upper soil layers (0–30 cm), suggesting that deeper layers can maintain more of the original SOM, at least for the first 20 years following land conversion. However, a larger sample size of cerrado

Table 1 | Effects of LUC on soil carbon debt, carbon sequestration potential and payback times for LUC into sugar cane in Brazil.

Land use conversion	Soil layer (cm)	C stocks* Mean (s.d.) (Mg ha^{-1})	LUC factor (s.d.) (20 years)	C debt (Mg CO_2 ha^{-1})	C sequestration (Mg CO_2 ha^{-1})	Payback time†	
						Average (years)	Range (years)
Pasture	0–30	56.6 (21.9)	0.90 (±0.03)	20.7	0.0	2.1	1–6
	0–50	81.3 (31.6)	0.91 (±0.03)	26.8	0.0	2.7	1–8
	0–100	124.1 (48.6)	0.93 (±0.03)	31.8	0.0	3.2	1–9
Cerrado	0–30	81.0 (28.6)	0.74 (±0.03)	77.2	0.0	7.9	3–12
	0–50	110.1 (38.3)	0.80 (±0.03)	ND	0.0	ND	ND
	0–100	158.7 (53.7)	0.93 (±0.04)	ND	0.0	ND	ND
Cropland	0–30	62.0 (18.9)	1.16 (±0.06)	0.0	36.4	0	0
	0–50	86.0 (25.8)	1.17 (±0.06)	0.0	53.6	0	0
	0–100	126.7 (36.5)	1.17 (±0.06)	0.0	79.0	0	0

ND, -not determined; owing to a non-significant stock changes below 30 cm depth, carbon debt and payback time were not calculated. *Based on Supplementary Table 1. s.d. = standard deviation from the mean values. †Based on sugar-cane ethanol offset; estimated at 9.8 Mg CO_2 ha^{-1} yr^{-1} (ref. 1). Range based on maximum, minimum and mean values for soil carbon stocks presented in Supplementary Table 1 and considering the presented values for the s.d. of the LUC factors.

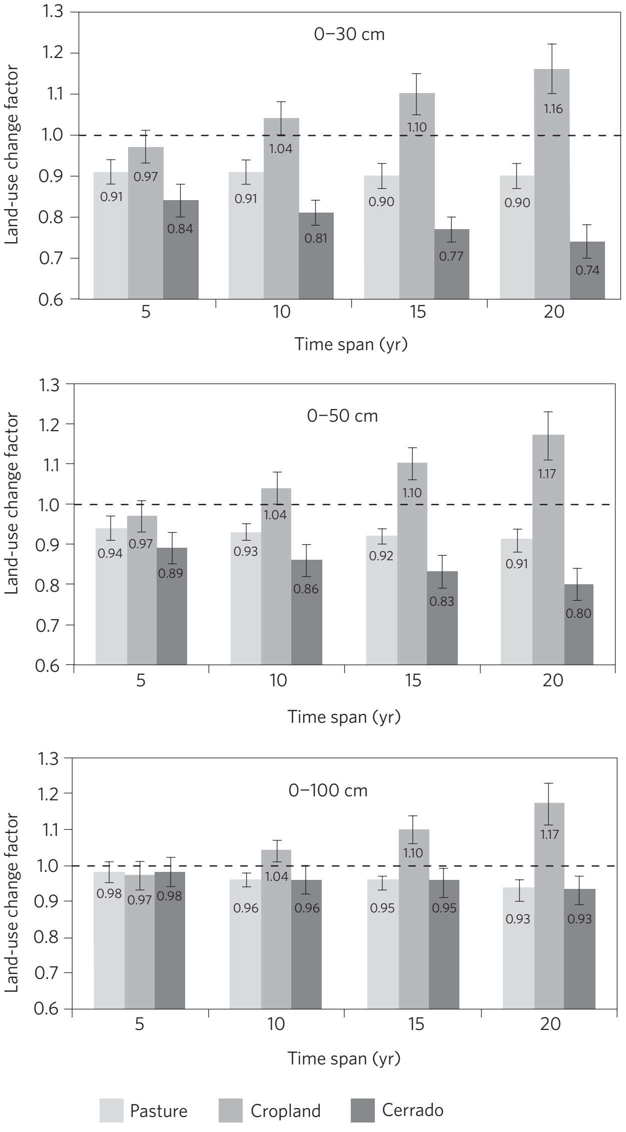

Figure 2 | Land-use change factors derived for 0–30 cm, 0–50 cm and 0–100 cm for incremental accounting periods of five-year blocks. A response equal to 1 represents no change, whereas values less than 1 and greater than 1 represent mean loss and mean gain, respectively. Bars represent the s.d. from the mean values.

to sugar-cane conversion would be needed to better evaluate soil C stock changes to a depth of 100 cm. Our loss rates for LUC from cerrado to sugar cane are similar to forest to pasture conversions in the Brazilian Amazon, where soil C stocks decreased by 16% for 0–20 cm and 8.4% for 20–100 cm (ref. 17).

Over 20 years, the soil carbon debt for cerrado conversion to sugar cane was estimated at 77 Mg CO_2 ha^{-1}, which is approximately three to four times greater than previous estimates of 21 Mg CO_2 ha^{-1} (ref. 1). Using an ethanol C offset of 9.8 Mg CO_2 ha^{-1} yr^{-1} (ref. 1), it would take eight years to offset soil carbon emissions due to LUC, after which point there would be gains of C due to the offset.

Including the emissions from biomass removal, estimated at 22.3 Mg CO_2 ha^{-1} for above ground biomass and 67.3 Mg CO_2 ha^{-1} for below ground biomass in Brazilian savannahs[18], the payback time increases by nine years for cerrado conversion to sugar cane. The total payback time would be 17 years, which is similar to payback times previously estimated for cerrado converted into sugar cane, but with a larger contribution from soils than in previous reports[1,2].

The conversion of pastures to sugar cane also resulted in soil C losses, reflecting the high amounts of SOM that pastures can maintain, which in some cases are close to amounts under cerrado (Supplementary Table 1). The LUC factors show that 20 years after the conversion, soil C stocks were reduced by 10% for 0–30 cm and 7% for 0–100 cm layers, which could be explained by the differences in land management for sugar cane compared to pastures. Sugar cane fields pass through a cultivation cycle every five years, with soil ploughing, fertilization and planting of new stem cuttings. It has been reported that up to 3.5 Mg CO_2 ha^{-1} could be released during soil preparation in sugar-cane fields[19]; in contrast, pastures can remain for long periods without any soil tillage.

The carbon debt incurred from pasture conversion does depend on the management and condition of the pasture. In some Southern Amazon improved pastures (using the IPCC definition; ref. 20) soil C stocks can be large, exceeding soil C stocks under native vegetation by 19–24% (ref. 21). On the other hand, soil C stocks under highly degraded pastures could be significantly less than those under sugar cane. Although the direct LUC is primarily from pasture to sugar cane, if the pasture had recently been converted from forest, then the carbon debt from this indirect LUC would be greater than the results presented in this paper[2].

For pastures, the inclusion of deeper layers (>30 cm) yielded greater C losses and longer payback times for the carbon debt, estimated at two years for 0–30 cm and three years for 0–100 cm layers. Above and below ground biomass carbon losses were estimated at 29.5 Mg CO_2 ha^{-1} after pasture conversion in tropical moist areas[20]. When biomass carbon losses are factored into the carbon balance the payback time is increased to five to six years when pastures are converted to sugar cane, similar to the payback time for rangelands conversion to sugar cane[2] and less than woody cerrado[1,3].

In contrast to both the conversion from cerrado and pastures, the LUC from annual cropland to sugar cane increased soil C stocks by 17% averaged over 20 years, with an accumulation of 36 Mg CO_2 ha^{-1} (0–30 cm) and 79 Mg CO_2 ha^{-1} (0–100 cm; Table 1). This could be due to annual tillage for croplands, resulting in greater carbon losses, as observed in studies evaluating agricultural intensification[22,23]. Our findings were not affected by the soil texture classification system (Supplementary Table 4), which emphasizes the strength of the presented data set.

In addition to the carbon losses associated with deforestation, the replacement of natural vegetation by crop-based land uses or pastures can result in biodiversity losses or even extinction[24]. Because maintaining biodiversity is a key factor to promote ecosystem services[25,26] and an important measure of sustainability[27], factors other than GHG need to be taken into account in evaluating the impact of converting native vegetation specifically to energy crops.

In Brazil, the sugar-cane industry employs about four million people, producing an annual income of US$28 billion, which represents 1.5% of Brazil's GDP. The expansion of this sector will be necessary to meet national and international demand for fuel and energy in the future[4,28]; it is therefore critical to evaluate the ecological impacts that this might entail to achieve a sustainable path for biofuels[29] while enhancing food security[9].

Our data suggests that converting cerrado and pastures to sugar cane will lead to soil C losses, whereas the substitution of annual crops will result in soil C accumulation. The payback time for LUC carbon debts ranged from 17 years for cerrado to 5–6 years for pasture conversion. We observed that carbon losses decreased as a percentage when the 0–100 cm layer was compared to the 0–30 cm layer. Our results demonstrate that the proportion of carbon lost is dependent on the depth measured; therefore the evaluation of

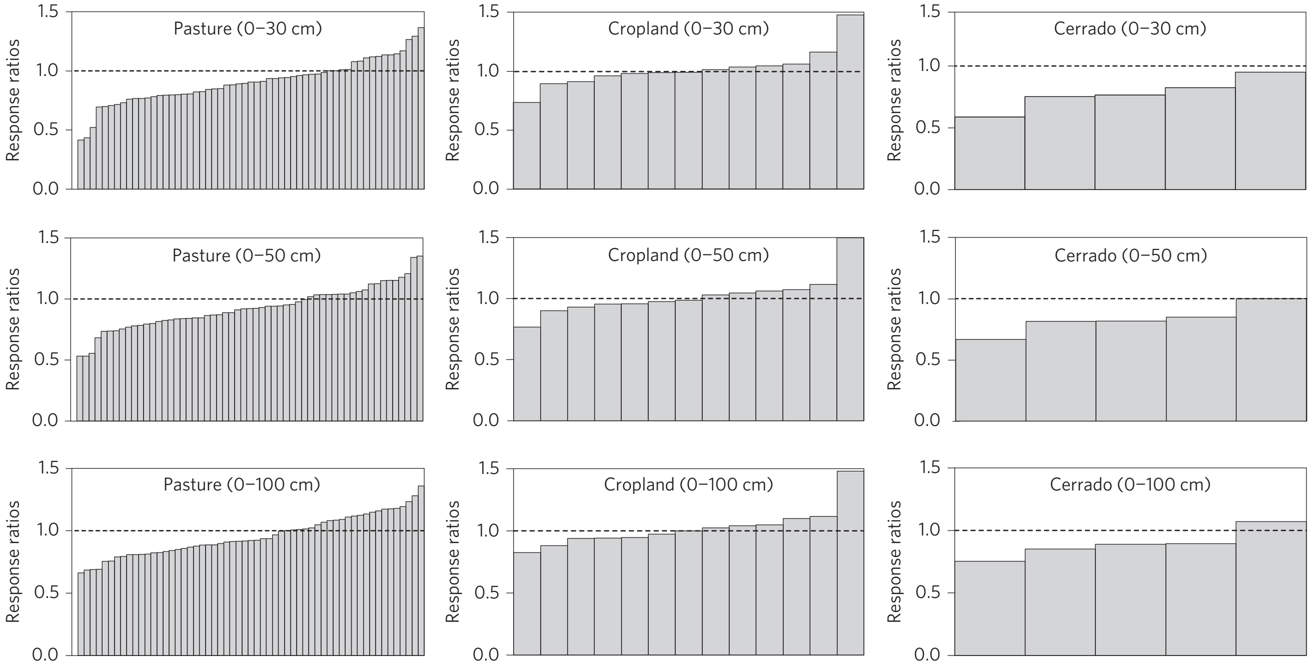

Figure 3 | Response ratios between soil carbon stocks found in sugar-cane fields and reference land uses in different soil layers. Number of observations: Pasture $n=57$; Cropland $n=13$; Cerrado, $n=5$.

deeper layers could either increase or decrease the carbon debt. The LUC factors generated based on sampling to a certain soil depth should be applied only to carbon stocks measured across the same depth.

In south-central Brazil more than 3 Mha of LUC occurred between 2000 and 2010 into sugar cane, from areas used as pasture (73.04%), annual cropland (25.08%) and cerrado (0.52%; ref. 13). Using the LUC factors derived here, together with the historical LUC and soil/biomass C losses, yields net ecosystem CO_2 emissions in the range 0.7–1.0 Mg CO_2 ha^{-1} yr^{-1} (Supplementary Table 5), which reduces but does not negate the biofuel offset of 9.8 Mg CO_2 ha^{-1} yr^{-1} (ref. 1) from sugar-cane ethanol. With future expansion projected to involve mainly pastures and cropland, Brazil could play a significant role in delivering low-carbon renewable fuels, provided that indirect LUC is minimized by improved management and productivity on residual agriculture lands.

Methods

Detailed methods are given in the Supplementary Information. We evaluated the soil carbon stock changes due to sugar-cane expansion in the south-central part of Brazil and determined the associated C debt/credit for sugar-cane ethanol. The soil C data were used to determine LUC factors using a linear mixed effect regression[30,31] to determine C stock changes after 20 years.

Soil carbon stock changes. Soil carbon stock changes were quantified based on the methodology outlined and recommended for national or regional GHG emissions due to LUC (ref. 20). The Tier 2 level was used to estimate soil carbon removal/inputs in south-central Brazil, for sugar-cane expansion.

Study site selection. An extensive site selection process involved detailed interviews with professionals from the sugar-cane industry to find appropriate study areas. This selection was based on the presence of: historical land use information, available reference areas (pasture, annual cropping or natural vegetation) older than 20 years with similar geomorphic characteristics (topography, soil type and so on) and adjacency to the sugar-cane sites (Supplementary Fig. 1). This assessment identified 135 areas (75 sugar-cane fields, 45 pastures, 10 cropland and 5 cerrado areas) that were suitable for soil sampling. This gave a total of 75 comparison pairs (CP)—some of the reference sites were adjacent to multiple land uses and used for comparison with multiple sugar-cane fields. This approach covered 335,000 hectares evaluated with the selection process.

Soil sampling. Sampling was undertaken from nine pits in a 3 × 3 grid for each study site over 100 m × 100 m representing 1 hectare (Supplementary Fig. 2). Six sampling pits were sampled every 10 cm from 0 to 30 cm, and three deeper sampling pits were sampled from 0–10, 10–20, 20–30, 40–50, 70–80, 90–100 cm to determine soil carbon and bulk density. Approximately 6,000 soil samples were taken and used to evaluate the LUC impact for sugar-cane conversions.

Soil carbon determination. Subsamples of the soil were sieved (2 mm), and ground and sieved at 150 μm for carbon determination by dry combustion. Total carbon was determined on a LECO CN elemental analyser (furnace at 1350 °C in pure oxygen).

Soil carbon stocks. The soil C stocks were determined by multiplying the carbon content by the soil bulk density and the layer thickness. Carbon stocks were estimated for the unsampled layers using the carbon contents derived from specific regression equations (per sampled site) and the bulk density was obtained using pedotransfer functions derived specifically for each land use (Supplementary Table 3). After calculating the soil C stocks for each soil depth, the stock was calculated for the site. The soil C stocks under sugar-cane sites were corrected according to the soil mass from reference sites (Supplementary Table 1).

Land use change factor. The dataset was analysed with a linear mixed-effect modelling approach[30,31]. A mixed-effects model consists of two parts—fixed effects and random effects. Fixed-effects terms are usually the conventional linear regression part and the random effects are associated with individual experimental units drawn at random from a population. The random effects have prior distributions whereas fixed effects do not. Our response variable was the ratio of the mean soil organic carbon (SOC, expressed in Mg ha^{-1}) observed in the sugar-cane fields and the mean SOC found in the reference areas. The LUC factors were derived in a manner consistent with the IPCC soil C method[20], which is based on the integrated effect of management for the top 30 cm of the profile after 20 years following the LUC to sugar-cane fields; however, to provide more complete information, factors were also derived for deeper layers (0–50 and 0–100 cm), and with different time spans, 5, 10, 15 and 20 years. This timeline was adopted based on the rotation cycle that sugar-cane fields undergo every five years. Uncertainty was based on the prediction standard deviation of the factor value. Statistical analyses were performed using SPLUS 8.0 software.

Payback time. The substitution of the fossil fuels with sugar-cane ethanol has the potential to reduce GHG emissions. In this case, the payback time should be the time span that the conversion of a specific land into sugar cane would need to compensate emissions due to LUC with the offset associated with the replacement of fossil fuel by sugar-cane ethanol. To calculate the sugar-cane payback time, the average stock of soil carbon was derived for pastures, cerrado and annual cropping areas using the data in Supplementary Table 1. The LUC factors (Fig. 2) were applied to soil carbon stocks for each land use and depth range. The carbon debt (Mg CO_2) was calculated as the difference between the stocks found in sugar cane and the corresponding reference land use and the payback time was the ratio of C debt to the offset for sugar-cane ethanol, estimated at 9.8 Mg CO_2 ha^{-1} (ref. 1).

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Author contributions

F.F.C.M., C.E.P.C., C.C.C. and C.A.D. designed the study and conducted the analyses. S.M.F.M. and K.P. developed the model to determine the LUC factors for sugar cane. All the authors contributed to writing the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to F.F.C.M.

Competing financial interests

The authors declare no competing financial interests.