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Socio-environmental and land-use impacts of double-cropped maize ethanol in Brazil

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Agricultural intensification, and particularly double cropping, has been suggested as a practical strategy to reconcile biofuel feedstock production with other land-use priorities. Here we assess ethanol production under conditions representative of current practice in the west central region of Brazil: maize grown as a second crop with soybean on land that formerly grew a single soybean crop, and energy processed from a combined heat and power plant using plantation-grown eucalyptus chips. For maize ethanol thus produced we find large reductions in greenhouse gas emissions compared to gasoline, and considerable economic and employment benefits at both local and national levels. We also calculate reduced land-use emissions with maize ethanol production compared to the situation without it. Our study thus documents an example of how the complex linkages of bioenergy to food production and security, environment and economic development can be—and indeed appear to be—managed for positive outcomes using current technology.

Biofuels are probably needed in order to stabilize climate[1–3] and offer potential benefits in terms of rural economic development[4,5]. Aggressive expansion of biofuel production is a prominent feature of Brazil's Nationally Determined Contribution responsive to the Paris Agreement[6], and is targeted by the recently initiated Brazilian biofuel program, RenovaBio[7,8]. Assessments are widely disparate, however, with respect to the feasibility and desirability of using land for biofuel production without compromising food production, wildlife habitat, livelihoods of rural populations and ecosystem carbon stocks[9,10]. Recent studies reinforce the value of ecosystem services[11], and induced land-use change (LUC) arising from displacement of food production by biofuel feedstocks has contributed to this disparity[12]. Agricultural intensification and double cropping have been suggested as strategies that could reconcile biofuel feedstock production with other land-use priorities[13–17]. On-the-ground examples of biofuel production directly coupled to intensified land use are, however, scarce.

One such example, perhaps the largest to date, is unfolding in Brazil today in the production of ethanol from maize grown as a second crop with soybean on land that formerly grew a single soybean crop. This situation is quite different from the single-crop production of maize as practised in the United States, where winters are more severe. In addition to increasing production on existing agricultural land, production of maize as a second crop improves soil protection and nutrient recycling[18].

The development and deployment of double cropping has led to the rapid expansion of grain production in west central Brazil (Fig. 1), particularly in Mato Grosso State (MT). Between 2006/2007 and 2016/2017, total maize production increased from 4 million tons to 29 million tons in MT, resulting in it becoming by far the largest grain-producing state in Brazil[19]. Essentially all (99%) of this additional maize is produced as a double crop.

Expanded production has not, however, been accompanied by commensurate development of logistical systems, resulting in inadequate road conditions[20], accumulation of maize stocks and in local prices far below international norms[21]. Infrastructural improvements are under way but will take time and are still far from complete. Simultaneously, imports of ethanol are rising to meet increasing domestic fuel demand in Brazil, particularly in the northern and northeastern regions[22,23]. Future logistical improvements to expand maize access to markets would also benefit ethanol logistics.

In light of this situation, local producers—together with the state government—are currently developing a programme to transform the region's maize surplus into ethanol and value-added products[24]. Growth of ethanol production capacity in both Brazil and the United States has occurred in the past, largely during windows of time during which economic conditions were advantageous and payback periods were short, and suggests that such windows need last for only a few years to motivate investment[25]. A previous study indicated that profitability of maize ethanol in Brazil is robust with respect to changes in corn prices[24].

Production of ethanol from maize in Brazil was initially adopted in 'flex' plants, using infrastructure available at existing ethanol plants during the summer when sugarcane is not harvested. Early studies indicated that the environmental benefits of sugarcane ethanol would not be jeopardized by maize ethanol production, while economic viability is higher in regions with corn supply at low prices and high demand for animal feed.[26] With the current high volumes of maize production and relatively low farm gate prices, aggressive investments in maize ethanol have been made. The first stand-alone maize ethanol plant started operation in 2017 (refs. [27,28]) and, within its first year of operation, the company initiated doubling of annual production capacity from 250 to 500 million l yr^{-1} based on favourable economics. Further investment is expected.

Stand-alone facilities for ethanol production are expected to grow more rapidly than flex plants in MT. The provision of process energy in these facilities is based on integrated steam and electricity production using wood chips from rapidly growing eucalyptus plants as the primary fuel. For this representative scenario, we analysed

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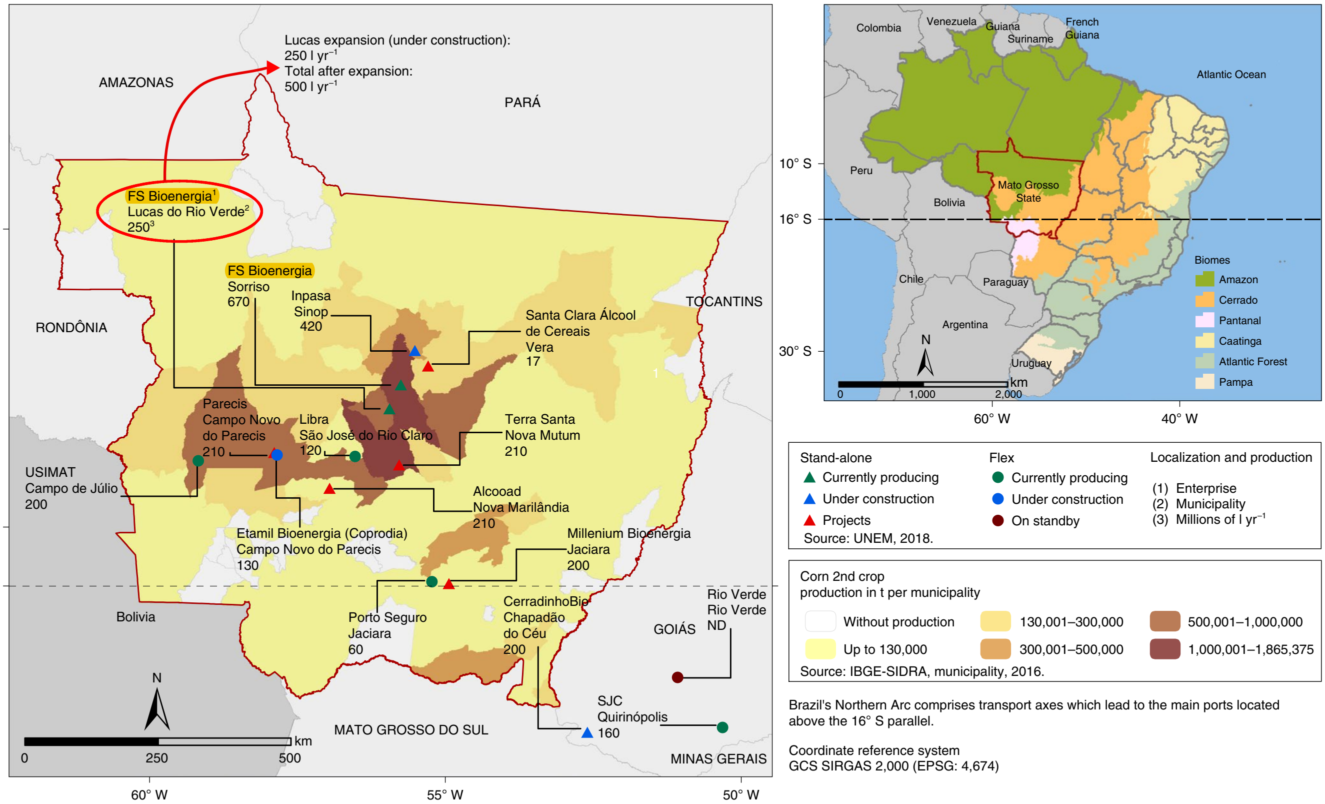

Fig. 1 | Sugarcane and corn mills enterprise. Production of corn ethanol (in million l yr^{-1}) and second-crop maize (t per municipality), and locations. ND, no data.

the impacts of maize ethanol expansion in Brazil with respect to socioeconomic indicators at the local and national levels, greenhouse gas (GHG) emissions, energy balance and land use.

Socioeconomic impacts

Based on an interregional input–output model[29–31] considering 500 million l of ethanol per year, we addressed total economic output, gross domestic product (GDP), employment and tax collection from substitution of imported fuels. Impacts are disaggregated with respect to MT and the rest of Brazil. The impacts of the construction and operation phases of ethanol production from maize in MT are presented in Table 1. During the 2-year construction period, approximately 8,500 direct and indirect jobs were generated in Brazil as a whole, of which 19% are in MT. This is accompanied by US$456 million in total economic output, an additional GDP of US$206 million and increased tax collection of US$25 million (adjusted throughout the current article using an exchange rate of 3.21 reals (R$) per dollar based on official statistics[32,33]). Of these national totals, MT realizes 12.6, 13.9 and 6.3% of total output, GDP and taxes, respectively. Despite the plant being located in MT, it is evident that many other Brazilian states benefit due to spillover effects.

Once the plant is operational, total additional annual output is US$791 million and annual added GDP is US$283 million, with about 80% of this total staying within MT. Increased tax collection, not to be confused with total tax collection, is US$23 million, with 56% remaining in MT. In contrast to the construction phase, the economic benefits of the operation phase occur primarily in the state where production occurs. Total direct and indirect job creation increases by approximately 4,500, with 65% of these jobs within the MT. Detailed results by economic sector, region and variable (output, GDP, employment) are presented in Supplementary Information.

Table 1 | Socioeconomic impacts related to a plant processing 500 million l yr^{-1}

Region	Total output (US$ million)	GDP (US$ million)	Employment	Taxes (US$ million)
Construction phase (aggregated over 2 years)				
MT	58	29	1,627	2
Rest of Brazil	398	177	6,846	23
Brazil	456	206	8,473	25
Operation phase (annual)				
MT	630	223	2,919	13
Rest of Brazil	161	60	1,597	10
Brazil	791	283	4,516	23

The economy-wide total output increase is 1.9-fold higher than the economic output of the maize ethanol plant. Maize and planted forests account for 27 and 4% of the increase in total output, respectively. Some national sectors were negatively impacted, mainly due to displacement of substitute products and co-products. The conventional feed sector in MT accounted for 46% of the output decrease, mainly due to the market introduction of distiller's dried grains with soluble (DDGS), a co-product resulting from maize ethanol production used in animal feed.

With respect to GDP, the maize sector in MT had the highest increase at US$100 million (35% of the total GDP increase). The sector next most positively impacted was the maize ethanol production facility, with US$88 million (31%). There is therefore a shift in

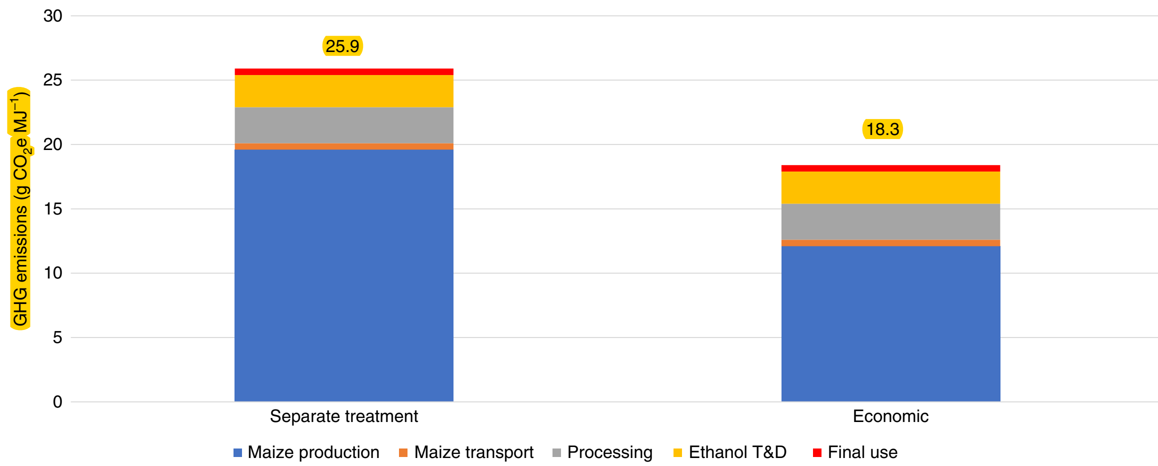

Fig. 2 | Life cycle GHG emissions of second crop maize ethanol. Emissions by allocation approach. T&D, transport and distribution.

ranking position compared to total output. Those two sectors, along with planted forests (MT), are responsible for 75% of the national increase in GDP. The conventional feed sector in MT was the most negatively impacted, with a total decrease of US$11 million in GDP, followed by other sectors displaced by maize ethanol co-products.

In terms of employment, the operation phase results in the net creation of 340 direct and 4,176 indirect jobs, with a strong spillover effect to other sectors. This effect is due to the high participation of labour-intensive upstream agricultural inputs. The maize sector generated 2,000 jobs, corresponding to 44.5% of total jobs generated. The planted forest sector contributed 308 additional jobs, 7% of the total. The maize and planted forest sectors, together with the maize ethanol production facility and road transportation sectors, represented approximately 66.5% of the increased employment at the national level. The conventional feed and cattle sectors (both in MT) were the most negatively impacted from an employment standpoint, with a 47% decrease corresponding to a loss of 800 jobs.

With respect to local taxes in MT, the maize ethanol plant and maize production contributed 36 and 24% of the total tax increase of US$14 million, respectively. The diesel and biodiesel industries, as well as the fertilizer and other petroleum-refining products for the rest of Brazil, represent together 20% of increased taxes at the national level, corresponding to US$4.7 million. Because substitution based on monetary value is assumed (see Methods), the US$22.7 million is in addition to the US$40.5 million sales tax payed by the ethanol mill in their final products and co-products. The sectors with greatest negative impacts on taxes follow the same trend as for the variables considered above.

Maize is the only crop planted on a significant scale as a double crop in MT today. Since construction of the first stand-alone facility in 2017, additional purchase of maize for ethanol production has absorbed all additional maize production in MT. Ethanol production is thus the most likely use for additional maize production capacity in MT for the near future[24]. Recognizing that it is possible that this situation might not persist in the medium-to-long term, we analysed the possibility of maize produced as a double crop and exported to international markets rather than being used to produce bioethanol. Either the expansion of the ethanol industry or the alternative export scenario (or both) could lead to expanded planting of maize as a second crop. Nine per cent more jobs would be generated if maize were sold for export as compared to its use for bioethanol production. However, total output, GDP and taxes would be lower for maize export compared to bioethanol production, by 47, 36 and 26%, respectively (see Supplementary Table 12). The higher number of jobs in the maize export scenario occurs because jobs in the feed sector are not displaced by DDGs, as occurs in the maize ethanol scenario. Total output, GDP and taxes are higher when maize is used for ethanol production because the products have higher added value. As presented in Supplementary Table 12, socioeconomic impacts are more positive for maize ethanol production compared to maize export in MT. However, the opposite is the case for the rest of Brazil.

Carbon footprint

In this section we present the results from two approaches to life cycle assessment: attributional and consequential.

Attributional life cycle assessment. Annual emissions from soybean–maize rotation were estimated at 2.7 t CO_2e ha^{-1}, of which 1.8 t CO_2e ha^{-1} resulted from maize cultivation, mainly in the form of N_2O and CO_2 derived from limestone and synthetic and organic nitrogen applied to crops.

Maize cultivation is by far the leading source of emissions in the ethanol life cycle. For emissions calculated via the 'separate treatment' approach (described in Methods), ethanol emissions resulted in 25.9 g CO_2e MJ^{-1}, 78% of which was due to maize cultivation and its transport (Fig. 2). Using the economic allocation approach, which seeks to better reflect the underlying rationale behind the soybean–maize system, emissions drop to 18.3 g CO_2eq MJ^{-1}.

Emissions from maize processing, on the other hand, are lower than for maize cultivation, with >60% of processing emissions attributable to utilities (steam and electricity) from the wood chip-fired co-generation plant. Sensitivity analysis indicated that uncertainties regarding eucalyptus production in the region have only minor effects on ethanol life cycle emissions (Supplementary Fig. 2), while maize cultivation parameters such as yield and nitrogen application have larger effects. Given the rapid expansion of second-crop maize in MT, along with farm-to-farm variation in cultivation practices, a wide range of maize environmental performance across farms can be expected. Furthermore, N_2O emissions from nitrogen fertilizers are also a relevant source of uncertainties, which must be addressed with continuous field experiments and are dependent on management practices. Even though it is still premature to adopt a specific emission factor for MT, empirical evidence suggests that IPCC's default factors (used in our reference case) may overestimate emissions for the case of Brazilian agriculture[34].

As with feedstock production, conversion to ethanol is also affected by the allocation method used in its treatment, DDGS and maize oil at the conversion stage. If energy allocation is adopted rather than economic allocation, emissions fall from 25.9 to

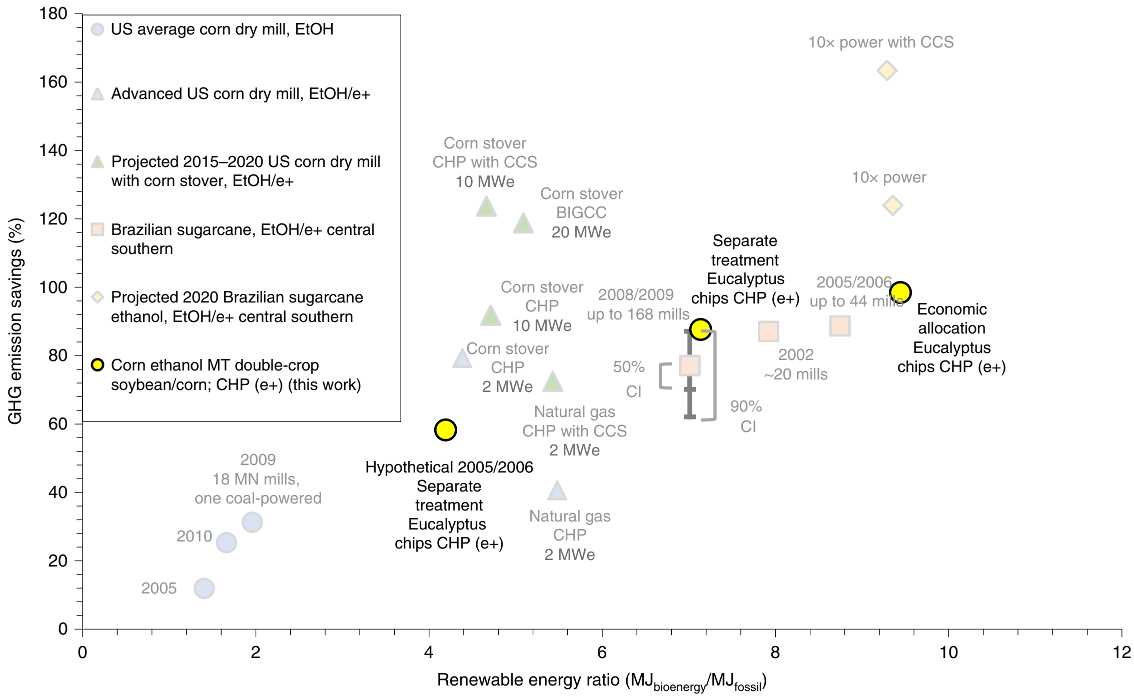

Fig. 3 | Environmental performance of ethanol (EtOH) from sugarcane and double-cropped maize ethanol. Elaborated based on refs. [40,69]. CI, confidence interval; CCS, carbon capture and storage; CHP, combined heat and power; BIGCC, biomass integrated gasification combined cycle; MN, Minnesota; e+, surplus electricity; MWe, megawatts electric.

22.8 g CO_2e MJ^{-1}. For mass-based allocation, emissions are reduced to 17.5 g CO_2e MJ^{-1}.

Compared to US maize ethanol[35–38], estimated GHG mitigation for maize ethanol production in Brazil is markedly higher. The main reason for this is that process energy is provided by eucalyptus chips in Brazil but is provided primarily by natural gas in the United States[39].

Using the analytical framework developed in another study[40] for comparison of maize and sugarcane ethanol in Brazil, we find that Brazilian maize ethanol under current conditions, as analysed here, has a mitigation capacity of approximately 90% compared to gasoline, with renewable energy ratios of 7.1 and 9.4, respectively for separate treatment and economic allocation for maize emissions estimation (Fig. 3). These figures are very close to the performance of sugarcane ethanol in Brazil[40]. US maize ethanol would achieve similarly high mitigation if wood chips were substituted for natural gas[41]. Additional data for maize ethanol production in the United States with process energy from either natural gas or biomass are presented in Supplementary Table 1, along with comparative data for sugarcane.

Maize yields are still considerably lower in Brazil than in the United States, given the different latitudes, soil types, cultivation practices and so on[42], but have increased by >50% during the past decade[43] due to better technology and cultivation practices. This development tends to have a positive effect on the environmental performance of maize ethanol. As illustrated in Fig. 3, assuming a hypothetical case for maize ethanol production in MT under 2005/2006 conditions[44], the renewable energy ratio (RER) would be 4.2 and the mitigation capacity ~60%. Given current conditions, notably yield, RER is 7.1 and mitigation capacity 88%.

Consequential life cycle assessment. From a consequential perspective, marginal emissions from maize ethanol expansion in Brazil would derive mainly from variation in agro-industry output (increase in maize and reduction in soybean production), maize processing and ethanol transport and distribution. However, those emissions are counterbalanced by significant credits from electricity surplus (given the premise of displacing generation from natural gas) and LUC, so that net emissions reach 4.5 g CO_2e MJ^{-1} (Fig. 4).

Four scenarios were analysed: S1 is the reference case with additional production of maize ethanol and co-production of both DDGS and vegetable oil, which requires additional maize and eucalyptus production. Scenario S2 is the same as S1 but excludes the expansion of eucalyptus areas, assuming that existing eucalyptus areas would be used. Scenarios S3 and S4 are the same as S1 but with different assumed values for the nutritional equivalence of DDGS. Further details may be found in Methods.

Sensitivity analyses was performed by changing one individual parameter compared to S1. Emissions could increase up to 9.8 g CO_2e MJ^{-1} if land conversion of pasture to eucalyptus (with higher carbon stocks) does not occur (scenario S2). It could be 7.6 g CO_2e MJ^{-1} in the case where DDGS have lower displacement ratios with respect to maize grain and soybean meal (scenario S3), but could also be close to zero in the case of scenario S4, for which case DDGS have a higher displacement ratio (see Methods).

LUC

Overall, production of maize ethanol has a direct effect in maize and eucalyptus areas, primarily in the west central Cerrado and North Amazon from the Brazilian land-use model (BLUM) regions (see Supplementary Fig. 1), where feedstock and biomass are sourced. Almost all expansion of maize area is as a second crop, but with indirect effects impacting other regions and agricultural activities (see Supplementary Information). Higher DDGS availability reduces the need for crop area for both soybean and maize used as animal feed. Similarly, but at a much lower scale, maize oil co-produced with ethanol reduces the need for other vegetable oil production. The lower soybean area for the scenario with maize ethanol compared to that without maize ethanol is due to reduced feedstock demand for feed. Therefore, lower conversion of pasture land for

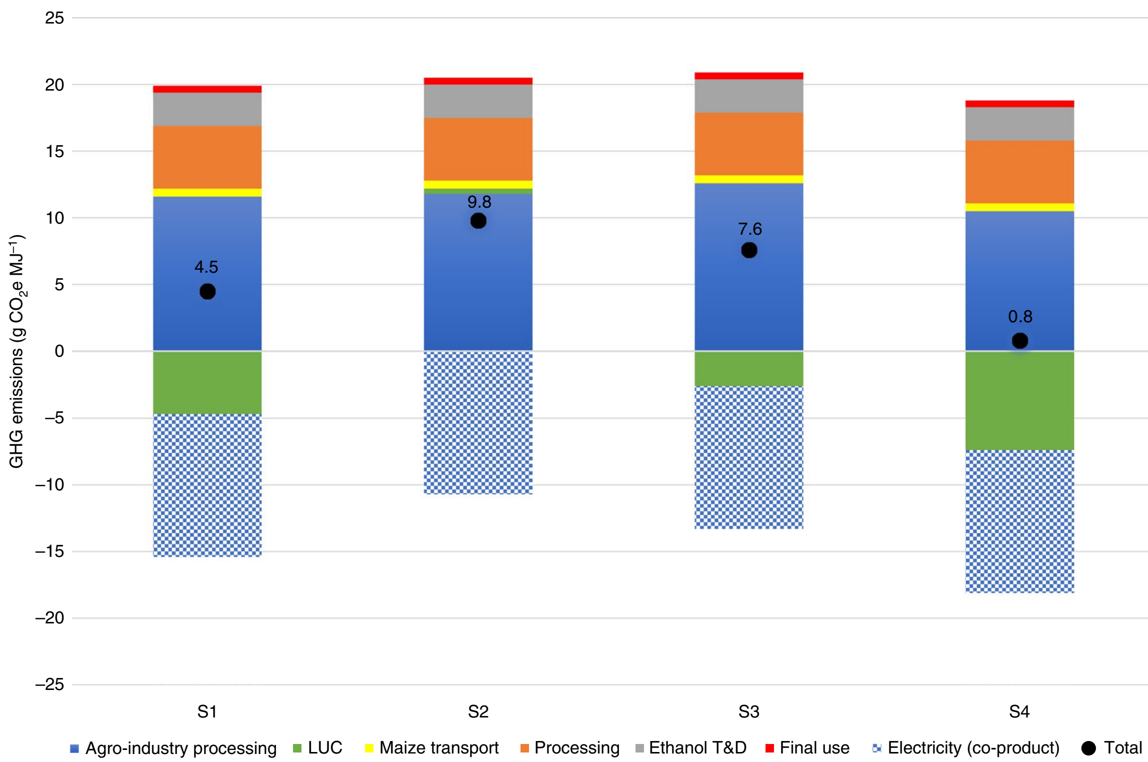

Fig. 4 | Sensitivity analysis of ethanol life cycle emissions (consequential approach). Data are shown for scenarios S1–S4.

Table 2 | LUC emissions (1,000 t CO_2e) of maize ethanol: scenario S1

Culture/region	South	Southeast	West central Cerrado	North Amazon	Northeast coast	Northeast Cerrado	Total
Annual to perennial	223	582	0	0	0	-2	803
Pasture to perennial	0	-4	-23	-1	13	0	-15
Pasture to annual	706	0	−2,190	-128	144	-25	-1,492
Pasture to eucalyptus	0	0	-2,368	-1,643	0	0	-4,011
Natural to annual	0	0	0	-3,713	195	0	-3,517
Natural to perennial	0	0	0	0	0	0	0
Natural to pasture	0	17	1,070	3,936	0	210	5,233
Total	930	595	-3,512	-1,549	353	183	-2,999

soybean production is observed in the west central area. Direct and indirect deforestation corresponds to 16% of maize and eucalyptus area expansion.

By coupling the results of area variation and emissions matrices, a total net removal of approximately 2,999,000 t CO_2e is obtained (bottom row, Table 2). Although 5,233,000 t CO_2e are emitted due to the conversion of natural vegetation to pasture (possible indirect effects of additional demand for maize), there is a significant CO_2e removal of 4,011,000 t due to land conversion from pasture to eucalyptus (with higher carbon stocks).

Decreasing the demand for cropland due to maize ethanol production leads to the maintenance of pasture and natural vegetation areas, which have higher carbon stocks when compared to annual crops. As presented in Table 2, negative emissions arise because annual area decreases and pasture area increases compared to baseline (see also Supplementary Tables 13 and 14).

Although the model includes indirect conversion of native vegetation, this effect does not preclude achieving negative overall emissions from induced LUC. Direct and indirect LUC hence resulted in a factor of -4.7 g CO_2e MJ^{-1} anhydrous ethanol for a 30-year amortization period in scenario S1.

For scenario S2, assuming no expansion of eucalyptus area, LUC results in a net emission of 0.4 g CO_2e MJ^{-1}, in response to the greater use of land for pasture and smaller cultivated forest areas when compared to S1. For S3, assuming the equivalence of 1/1 kg between maize/soybean meal and DDGS, LUC emissions were -2.6 g CO_2e MJ^{-1} because of the higher conversion of pasture areas to annual crop (particularly soybean).

For S4, which assumes a higher displacement ratio of 1/1.30 kg between maize/soybean meal and DDGS, LUC emissions were -7.4 g CO_2e MJ^{-1}, mainly due to the reduced planting of annual crops on pasture land. Consequently, total ethanol emissions varied from 9.8 to 0.8 g CO_2e MJ^{-1} between S2 and S4, for which the variation effect of agro-industry production was only marginal.

Discussion

Based on the current maize ethanol industry operating in west central Brazil, this study shows that avoided GHG emissions increase substantially and become roughly comparable to those of sugarcane when the dominant ethanol production technology used in the United States is adapted to conditions in Brazil. The two largest contributors to this increase are the use of biomass for energy process (all approaches) and maize production by double cropping (consequential approach).

The range of maize cultivation practices can significantly affect the environmental performance of ethanol, while sensitivity tends to be lower with respect to eucalyptus parameters. Utilization of eucalyptus in lieu of natural gas, and details of the supply chain, are important determinants of the sustainability of maize ethanol as practised in Brazil. A detailed study[45] found that short-rotation eucalyptus plantations do not have an adverse effect on local hydrology or water production and that eucalyptus forests appear to have greater water and nutrient use efficiency than other Brazilian forests and agricultural crops[45]. Confirming these observations, another recent study[46] found that eucalyptus forests feature efficient nutrient recycling, protect soil against erosion and contribute to biodiversity through provision of shelter for wildlife. On the other hand, on a life cycle basis some local impacts related to eucalyptus bioenergy (for example, eutrophication) can be higher than for alternatives based on fossil resources[46]. Yet another study[47] pointed out that the sustainability of biomass production where exotic species have been adapted to the seasonality of high rainfall, as with eucalyptus in Brazil, requires managing the trade-off between growth and recharge control to allow for more efficient use of resources.

The consequential approach brings new insights into land-use optimization. Although indirect conversion of natural vegetation is identified, this effect is more than counterbalanced (in terms of GHG emissions) by the expansion of planted forests and a smaller expansion of soybean area on pastures. Negative LUC emissions have not been reported previously for maize ethanol, although they have been anticipated for cellulosic biofuels. Our observation of such negative emissions underscores the importance of considering—and potentially optimizing—local circumstances in analysis and planning related to biofuels and GHG emissions.

The results of our analysis are similar to those reported previously for a Brazilian sugarcane/maize ethanol plant (attributional approach)[26], but very different from the 85 g CO_2e MJ^{-1} found in another study[48]. The differences between the results of that study and ours stem primarily from different estimates of LUC emissions, and secondarily from consideration of co-generated electricity. The previous study that calculated higher GHG emissions for maize ethanol production in Brazil used data for MT for the period 1993–2013 to calculate direct land-use change, and concluded that expansion of crops may have occurred in either areas of perennial crops or primary forests. This type of land conversion indeed generates high quantities of GHG emissions. However, second cropping does not require additional land beyond the status quo, but rather uses existing soybean land that is currently fallow for part of the year. Our results are aligned with international modelling efforts that recognize the importance of intensification[15–17].

Socioeconomic analysis identifies significant increases in total output, employment, GDP and tax collection. In the construction phase, much of the added value occurs outside MT; in the operation phase (which is the long-term legacy of investments), this is reversed. Our analysis considers the short-term socioeconomic impacts of substituting imported maize ethanol for locally produced ethanol. We do not consider potential structural changes in the economy that could occur over the longer term.

An alternative scenario, in which maize is exported (rather than converted to ethanol), would generate marginally more jobs but GDP, total output and taxes would be significantly lower. As with all scenarios considered in this paper, the comparison of maize conversion to ethanol and maize export assumes that subsidies are not in play. Carbon-pricing mechanisms—for example, RenovaBio—would favour ethanol production over export. Evaluation of economic feedbacks for longer-term analysis is recommended in future work.

In analysing GHG emissions, indirect LUC and economic impacts, we have endeavoured to address key factors determining the sustainability of biofuels. In terms of these factors we find that maize ethanol production, as it is practised in Brazil, is aligned with positive outcomes. Other dimensions of social and environmental sustainability should, however, be analysed in future studies to broaden and deepen our understanding. Examples include air pollutant emissions, impacts on biodiversity, landscape and watershed studies, and impacts on low-income populations. Such analyses can be expected not only to add more evaluative metrics, but also to inform benefit optimization going forward. Such optimization will be fostered by close stakeholder consultation and participation[49,50].

Methods

Production system. The analysis is based on a newly installed stand-alone maize ethanol plant in MT. Conversion of maize to ethanol is carried out according to the 'dry mill' process as developed in the United States[51,52], using eucalyptus chips in the energy process rather than natural gas, and with certain other differences. Process energy (steam and electricity) is supplied by an attached biomass co-generation plant.

The production system thus involves a melding of features from both US and Brazilian agricultural and biofuel sectors. Fermentation of maize to ethanol in Brazil is based primarily on technology developed in the United States involving batch processing of high-solids maize mash, which may be contrasted to the solids-free fermentation of cane juice with cell recycling used for sugarcane fermentation in Brazil.

Processing 1,000 kg of maize requires 464 kg of eucalyptus chips to meet the energy demand of the plant, which still allows 151 kWh of surplus electricity to be sold to the grid. Each 1,000 kg of maize produces 430 l of anhydrous ethanol, 363 kg of DDGS and 13 kg of raw maize oil.

Maize is assumed to be sourced from within a radius average of 50 km from the ethanol plant, whereas longer distances (690 km) are assumed for ethanol transport. DDGS, used to feed animals, is transported distances of up to 250 km. Maize oil is used for biodiesel production in an industrial complex near the ethanol plant.

Evaluation of socioeconomic impacts. The socioeconomic impacts (direct and indirect over the entire value chain) were evaluated using an estimated interregional input–output matrix[30,31], also used in other studies[53,54]. The 2011 matrix is disaggregated in 187 sectors and two regions—MT and the rest of Brazil. Input–output analysis represents a 'snapshot of the economy' that shows how sectors are interrelated. The results provide a detailed view of the productive structure of the Brazilian economy and identification of the different flows of goods and services production, and can be used to assess the degree of sectoral interconnection of the economy as well as the impacts on final product demand, GDP, employment, total output and taxes[55].

This part of the study focused on short-term impacts (that is, to 2020). We considered a maize ethanol plant producing 500 million l yr^{-1} and co-products, from 1.2 million t of second-crop maize. Socioeconomic impact assessment was divided into construction and operation (production) phases.

The displacement of products and co-products for socioeconomic analysis is based on equivalence in monetary expenditure. The basic assumption is that there is no greater possibility of arbitration between substitute goods taken at consumer prices. As a premise, each R$1 of ethanol and co-products of the plant displaces the same value (in R$) of the related substitute product. The displaced products considered were imported ethanol (without affecting production and final demand of Brazilian sugarcane ethanol), conventional feedstuff, electricity from natural gas and soybean oil.

Supplementary Table 2 gives a summary of the quantity, basic price and value for products and co-products. All values presented in this study are based on those in US$ (as of January 2018).

During the operation phase, the main inputs are maize, eucalyptus, industrial inputs (enzymes and chemicals) and employee compensation (340 direct jobs), profit-type income and capital consumption allowances in the plant. Considering average prices received by the mill, the production of 500 million l of ethanol and co-products generates a total annual value of US$428 million, of which US$317.5 million is ethanol, US$84 million is DDGS, US$14 million is bioelectricity and US$12.7 million is maize oil. This production leads to a final annual sales tax of about US$40.5 million

In the alternative scenario it is considered that the same amount of corn is produced and sent directly to international markets. In this case no displacement of other existing economic activity was considered.

Carbon footprint. Carbon footprint assesses the net GHG emissions of a product or service throughout its production and use, following the principles of life cycle assessment[56,57]. Here we used attributional analysis to evaluate GHG emissions associated with the production of maize ethanol in a dedicated plant (static system), and a consequential analysis to assess how GHG emissions would change in the face of an additional demand of maize ethanol in the medium term (2030), considering induced effects.

The attributional approach considered two options for the separate assessment of maize from the soybean–maize rotation system: 'separate treatment' and allocation by 'economic value'. In the former, flows associated with the cultivation of each crop were individually assigned to each culture despite the crop rotation practice. Thus, all resources used and emissions created after soybean harvesting were attributed to maize cultivation. In the allocation by economic value case, annual flows related to the cultivation of both crops were pooled and allocated in proportion to the income of each crop. Economic allocation was also used to treat the co-products from the distillery (DDGS and maize oil), while in the co-generation plant the allocation between electricity and steam was based on exergy.

The consequential approach, however, considered a 'shock' scenario—marginal change relative to a reference scenario—that includes both direct and indirect effects of the additional production of 1 billion l of maize ethanol in 2030. In this approach, it was assumed that new products introduced to the market would displace in the following proportions: 1 kWh of electricity surplus would displace 1 kWh of natural gas thermoelectricity (given the characteristics of the Brazilian power system[44]), 1 kg of DDGS would displace 0.81 kg of maize and 0.34 kg of soybean meal[58] and 1 kg of maize oil would displace 1 kg of soybean oil.

Common assumptions for both approaches include: (1) biogenic CO_2 emissions are synchronized; (2) all environmental burdens of eucalyptus cultivation were attributed to wood chips; (3) soil N_2O and CO_2 emissions (from fertilizers and agricultural residues) were estimated according to IPCC guidelines[59]; (4) diesel was assumed as B8 (8% volume blend with soy biodiesel); and (5) capital goods were disregarded. Emissions related to LUC were accounted for only in the consequential analysis (see details below).

For the foreground data, the study considered specific information from a newly installed stand-alone maize ethanol plant in MT, while agricultural data were based mainly on west central and MT characteristics and practices as reported in the literature[60] (see Supplementary Table 3). Other background data were extracted from the Ecoinvent database and the GREET model[61]. The modelling and connection of life cycle sub-processes were performed using SimaPro, GREET, Excel spreadsheets and BLUM. Results are expressed in g CO_2e MJ^{-1} of anhydrous ethanol, using GWP100 (AR5 from IPCC)[62] as characterization factors (except for land-use emission factors, which were modelled differently)[63].

To allow further comparisons to the literature[40], we also assessed the RER of maize ethanol production in Brazil according to equation (1):

$$\mathrm{RER} = \frac{\mathrm{Bioenergy}_{\mathrm{output}}}{\mathrm{Fossil\ Energy}_{\mathrm{input}} - \mathrm{Fossil\ Credits}_{\mathrm{non-energy\ co-products}}} \quad (1)$$

This indicator was calculated for a farm-to-gate scope, assuming the foreground and background systems described above.

Land use change. Emissions from LUC were considered only in the consequential approach. These include direct and indirect emissions from carbon stock changes (from biomass and soil—that is, deforestation and conversion of pastures in annual crops) and combustion/decomposition processes, but also removals of carbon from the atmosphere when the change occurs in the reverse direction (that is, reforestation or replacement by crops with greater carbon stocks). Emission factors are dependent on phytophysiognomies, soil, climate, changes in soil carbon stocks for each of the BLUM regions[63] and are complemented by data from a national inventory[64]. Final emission factors values are available in Supplementary Table 14. The BLUM model[65,66] was used to analyse economic–land-use interactions, considering a 30-year integration period. The economic model—with a comparative statistics approach—allows the induced land-use effects to be attributed to the marginal amount of biofuels produced.

Emissions were estimated from area conversions throughout Brazil disaggregated in six macro-regions (South, Southeast, west central Cerrado, North Amazon, Northeast Coast and Northeast Cerrado) and five types of land use (annual crops, sugarcane, pasture, native vegetation and planted forests). In addition to carbon stock changes, the study also considered life cycle emissions resulting from variation in agro-industry output as indicated by BLUM.

Four scenarios were analysed for LUC, as follows:

- Scenario S1 (reference case): additional production of 1 billion l of maize ethanol by 2030. This requires 2.3 million t of maize and 29,000 ha of new eucalyptus area (replacing pasture areas). Annual co-production of 844 million t of DDGS (equivalence 1/1.15), 351 GWh and 30,000 t of maize oil.
- Scenario S2: similar to Scenario S1, excluding area expansion for eucalyptus.
- Scenario S3: similar to Scenario S1, assuming that 1 kg of DDGS displaces 1 kg of maize and soybean meal (70% for maize and 30% for soybean meal).
- Scenario S4: similar to Scenario S1, assuming that 1 kg of DDGS displaces 1.30 kg of maize and soybean meal (70% for maize and 30% for soybean meal).

In summary, S1 considers the expansion of maize ethanol production in MT assuming additional market demand for maize, greater supply of DDGS and maize oil and additional area for eucalyptus. Agricultural markets are governed by prices and linked by scale and competition elasticities. Additional demand for maize increases prices, which has both competition and synergic effects on soybean production. At the same time, DDGS (as a co-product of corn ethanol) increases competition on the feed market, putting downward pressure on the price of both maize and soy. The net effect of changes in maize demand on the price is a small increase of about 0.9%. According to economic modelling, the competition effect of maize to soy prevails compared to synergic, and soybean area reduces.

The second scenario (S2) is equivalent to S1 but excludes the area expansion for eucalyptus. This sensitivity was considered because, despite the additional demand for eucalyptus, there is also the possibility of some use of the existing eucalyptus area without additional demand on it.

There is ample discussion in the literature regarding the nutritional substitution levels of maize and soybean by DDGS, focusing on the US market[67,68]. In Brazil, however, uncertainty increases once DDGS is considered as a novel product facing new marketing conditions, including variation in local cattle genetics and feedstock producers' commercial strategies. Scenarios S3 and S4 represent a sensitivity to the equivalence parameters of DDGS, considering alternative replacement ratios.

Data availability

The data that support the findings of this study are available from the corresponding author on request.

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Author contributions

J.E.A.S. performed life cycle assessment modelling. S.M.A. performed land-use modelling. M.P.C. performed the socioeconomic analysis. L.R.L. provided a critical review of the manuscript and background on maize ethanol production in the United States. J.J.M.G. provided the interregional matrix for the socioeconomic analysis. M.M.R.M. coordinated the study. All authors analysed the results and wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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