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Life cycle assessment of sugarcane ethanol production in India in comparison to Brazil

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Abstract
Purpose India's biofuel programme relies on ethanol production from sugarcane molasses. However, there is limited insight on environmental impacts across the Indian ethanol production chain. This study closes this gap by assessing the environmental impacts of ethanol production from sugarcane molasses in Uttar Pradesh, India. A comparative analysis with south-central Brazilian sugarcane ethanol is also presented to compare the performance of sugarcane molasses-based ethanol with sugarcane juice-based ethanol.
Methods The production process is assessed by a cradle-to-gate life cycle assessment. The multifunctionality problem is solved by applying two variants of system expansion and economic allocation. Environmental impacts are assessed with Impact 2002+ and results are presented at the midpoint level for greenhouse gas emissions, non-renewable energy use, freshwater eutrophication and water use. Furthermore, results include impacts on human health and ecosystem quality at the damage level. Sensitivity analysis is also performed on key contributing parameters such as pesticides, stillage treatment and irrigation water use.
Results and discussion It is found that, compared to Brazilian ethanol, Indian ethanol causes lower or comparable greenhouse gas emissions (0.09–0.64 $kgCO_{2eq}/kg_{ethanolIN}$, 0.46–0.63 $kgCO_{2eq}/kg_{ethanolBR}$), non-renewable energy use (−0.3–6.3 $MJ/kg_{ethanolIN}$, 1–4 $MJ/kg_{ethanolBR}$), human health impacts ($3.6\cdot10^{-6}$ $DALY/kg_{ethanolIN}$, $4\cdot10^{-6}$ $DALY/kg_{ethanolBR}$) and ecosystem impairment (2.5 $PDF\cdot m^2\cdot year/kg_{ethanolIN}$, 3.3 $PDF\cdot m^2\cdot year/kg_{ethanolBR}$). One reason is that Indian ethanol is exclusively produced from molasses, a co-product of sugar production, resulting in allocation of the environmental burden. Additionally, Indian sugar mills and distilleries produce surplus electricity for which they receive credits for displacing grid electricity of relatively high CO_2 emission intensity. When economic allocation is applied, the greenhouse gas emissions for Indian and Brazilian ethanol are comparable. Non-renewable energy use is higher for Indian ethanol, primarily due to energy requirements for irrigation. For water use and related impacts, Indian ethanol scores worse due groundwater irrigation, despite the dampening effect of allocation. The variation on greenhouse gas emissions and non-renewable energy use of Indian mills is much larger for high and low performance than the respective systems in Brazil.
Conclusions Important measures can be taken across the production chain to improve the environmental performance of Indian ethanol production (e.g. avoiding the use of specific pesticides, avoiding the disposal of untreated stillage, transition to water efficient crops). However, to meet the targets of

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the Indian ethanol blending programme, displacement effects are likely to occur in countries which export ethanol. To assess such effects, a consequential study needs to be prepared.

Keywords India · Ethanol · Brazil · Life cycle assessment · Molasses · Sugarcane

Abbreviations

BOD	Biological oxygen demand
COD	Chemical oxygen demand
DAP	Diammonium phosphate
EA	Economic allocation
EBP	Ethanol blending programme
EQ	Ecosystem quality
GHG	Greenhouse gas
HH	Human health
ISO	International Standardization Organization
SE-C	System expansion conservative
SE-O	System expansion optimistic
SSP	Single super phosphate
TSP	Triple super phosphate
UP	Uttar Pradesh

1 Introduction

In 2008, India imported more than 70 % of its oil requirements and more than 15 % of its demand for high-quality coal. Among the three end-use sectors, transport accounted for around one third of the total final energy consumption (IEA 2011a). While the country's domestic energy production is expected to increase, the combination of other drivers (e.g. population growth and economic growth) is expected to push the energy demand for transport even further, thus creating a stronger dependency on foreign oil. Recognizing these dynamics, the Indian government launched a major programme for the production of biofuels in 2001 in order to introduce an alternative to petroleum-based fuels. Also, the programme intended to contribute to global greenhouse gas mitigation, reduce oil imports and generate employment (GoI 2003).

Due to the prominent position of the sugar industry in India and the established ethanol production by distilleries for potable liquor and industrial use (Table 1), the Indian government mandated in 2009 a 10 % blending target across 20 states and four union territories and proposed an indicative blending target of 20 % for ethanol and biodiesel by 2017 (GoI 2009). However, through the course of the Ethanol Blending Programme (EBP), this target has been partially met primarily due to fluctuating supply of sugarcane molasses and its impact on ethanol production costs. As a consequence, the Indian government revised the mandatory blending target to 5 % (USDA 2012). Biodiesel production for transport is not commercialised, as the potential for cultivation and utilisation of Jatropha plantations remains untapped (Gopinathan and Sudhakaran 2009). Therefore, the use of biofuels in transport relies on the success of the Indian EBP.

With the focus of the government and the industry on implementing the EBP, it becomes also important to address environmental concerns that characterise the ethanol production chain. For instance, Indian agricultural practices are characterised by excessive use of agrochemicals, especially nitrogen-based fertilisers (MoEF 2009a). Also, the Indian Central Pollution Control Board has classified the sugar and distillery industry among 17 industries with high-polluting potential (CPCB 2009). In addition, with sugarcane being a water-intensive crop, regional water stress is a significant resource constraint. Some studies report carbon emissions in the production of Indian ethanol and its use in the transport sector (e.g. Prakash et al. 2005). Other types of emissions (e.g. chemical oxygen demand; COD) have also been studied for specific steps of ethanol production (Tewari et al. 2007). However, in contrast to other countries that produce ethanol from sugarcane (e.g. Brazil, Australia, Thailand, Cuba, Mexico and Nepal), so far no comprehensive assessment has been carried out for molasses-based ethanol in India.

As molasses-based ethanol systems are characterised by multifunctionality due to co-production of sugar, molasses and bagasse or electricity in the sugar mill, the choice of allocation can be key in determining the results. Hoefnagels et al. (2010) demonstrated the latter for greenhouse gas and energy performance of biofuel production from 13 feedstock types, including Brazilian sugarcane ethanol. However, sugarcane molasses-based ethanol was not included where different allocation options are also possible. Nguyen and Hermansen (2012), in line with ISO (2006), show that system expansion is most appropriate to account for the multifunctionality problem of a sugar mill. In their study, molasses were assumed to displace feed, while in the system of this study, molasses have traditionally been used for ethanol production. On the contrary, Renouf et al. (2011) note that system expansion is more valid for the determining product (sugar) while results for all products can be generated more consistently using allocation. However, in their study, stillage was not digested anaerobically to cover energy demand of distilleries, thereby increasing the bagasse availability for additional power output as it is the case for most Indian distilleries. The multifunctionality problem of sugar mills and distilleries in India calls for an assessment of different approaches to account for impacts of molasses-based ethanol. It is the purpose of this study to provide an environmental assessment of Indian ethanol production, taking into account the system's intrinsic characteristics and their effects on allocation and to highlight potentials for improvement using life cycle assessment. To do so, we assess sugarcane ethanol production in Uttar Pradesh (UP), India.

Table 1 Bioethanol production and consumption in India, million litres (USDA 2012)

Year	Production	Total supply[a]	Consumption			
			Industrial use	Potable use	Transport	Total
2006	1,898	2,410	619	745	200	1,564
2007	2,398	3,160	650	800	200	1,650
2008	2,150	3,616	700	850	280	1,830
2009	1,073	3,025	700	880	100	1,680
2010	1,522	2,855	720	900	50	1,670
2011	1,681	2,766	700	850	365	1,915
2012	2,170	2,901	720	880	400	2,000
2013	2,239	2,955	740	910	450	2,100

[a] Includes beginning stocks and imports. Between 2006 and 2013, these account for 20–55 % and 1–9 % of total supply, respectively

Furthermore, it is unclear how the production of Indian sugarcane ethanol, which is exclusively based on sugarcane molasses, scores in environmental terms compared to production directly from sugarcane juice. To make this comparison, we also assess Brazilian sugarcane ethanol. Brazil has a long experience in sugarcane ethanol production, and therefore represents a good benchmark. For Brazilian sugarcane ethanol, we extend analysis of previous studies to include additional impact categories (Seabra et al. 2011), and we divert from other studies on inventory data and method to account for impacts of pesticides (e.g. Cavalett et al. 2013; Ometto et al. 2009).

For both systems, we assess two extreme cases by assuming high and low conversion efficiencies. In parallel, we address the influence of allocation by applying three different approaches. The results include greenhouse gas emissions, non-renewable energy use, eutrophication, human health and ecosystem quality. In the following, we describe ethanol production in India and Brazil, highlighting their differences. We then present the methodology and data used to compare the two products. Finally, we present our main findings and discuss the most influential parameters for the various environmental impact categories and the sources of uncertainty.

2 System description

2.1 Ethanol production in India

India is the world's second largest sugarcane producer after Brazil. In 2009, Indian sugarcane production was 292 Mtonnes (17 % of the total global production of 1,700 Mtonnes). Currently, sugarcane is being used to produce sugar, making India the world's second largest sugar producer and the world's largest sugar consumer (OECD 2011; USDA 2011). In 2009, India produced 21 Mtonnes of centrifugal sugar, which represents 13 % of total global production (USDA 2011). Not all sugarcane is crushed in conventional mills to produce crystalline sugar; a significant share is used for the production of unrefined, mixed with molasses, non-centrifuged sugars (Gur and Khandsari). In this study, only sugarcane processed by conventional mills is taken into account (75 % of total production).

In India, sugarcane grows in three distinct climatic-geographical regions: the subtropical northern region, the central-west subtropical peninsular region and the southeast tropical region. Across these regions, there are differences in production practices, yield, sugar content and production cycle (Gopinathan and Sudhakaran 2009). In most areas, a 1-year crop is followed by one ratoon crop (i.e. crop grown from the stubble of the harvested crop) (MoEF 2010). Cultivation practices are almost exclusively manual, with the exception of ploughing, which is mechanised in some states (Gopinathan and Sudhakaran 2009). This limits fossil inputs in sugarcane cultivation to agrochemicals and energy use for irrigation. Groundwater use is also significant since sugarcane is a water-intensive crop, especially when considering regional water scarcity in India. Additional inputs include manual labour and animal use. Unlike many other sugarcane-producing countries, pre- or post-harvest burning is not practiced in all regions. Sugarcane green tops are removed in the field and used as animal feed. Sugarcane is then transported to sugar mills by means of rickshaws, bullock carts and trucks (Kumar 2013).

In the sugar mill, sugarcane is washed and shredded, and then the juice is separated from the fibrous bagasse (MoEF 2010). Bagasse is predominantly utilised in co-generation facilities to cover energy requirements of the mill and to provide surplus electricity to the grid. Surplus bagasse is stored and used off-season to provide surplus electricity, and is sold as solid biofuel, for paper production or animal feed (ISMA 2011a). Crystalline sugar is produced by water evaporation after the juice has been heated, sulphitated, clarified and filtrated. The filtrate (called filter cake or mud, mixed with boiler ashes) is typically offered to sugarcane producers for free, who apply it back to the fields. After crystallisation of the clarified juice, residual sugars which cannot be recovered are separated by a centrifuge (MoEF 2010). This co-product, known as molasses, is collected and used by distilleries to produce ethanol (ISMA 2011a). Approximately 95 % of total molasses is directed to ethanol production. The remaining portion is mainly used as cattle feed (ISMA 2011a). Distilleries are either adjacent to sugar mills or are stand-alone facilities (MoEF 2009b). In the former case, molasses are directly supplied to the facility and the energy requirements are met by the co-generation system of the sugar mill. Otherwise, molasses need to be transported and the distilleries cover their energy demand through other sources (e.g. bagasse and biogas) (Prakash et al. 2005). After dilution and fermentation of molasses, the resulting broth contains 6–8 % (*v*/*v*) ethanol and is passed through an analyser column for distillation to approximately 40 % ethanol (*v*/*v*). The ethanol vapours are passed through a rectification column to produce hydrous ethanol of approximately 95 % (*v*/*v*) concentration (rectified spirit). For fuel-grade (anhydrous) ethanol, a dehydration step is required bringing the concentration to 99.5 % (*v*/*v*). The effluent that exits the analyser column, known as stillage, has a very high chemical and biological oxygen demand (BOD) and needs to be treated (MoEF 2009b). Over 90 % of Indian distilleries apply anaerobic treatment and recover biogas, which they use to cover own energy requirements (Tewari et al. 2007).

2.2 Ethanol production in Brazil

Brazil is the largest sugarcane producer of the world. In 2009, it produced 690 Mtonnes, which represents 41 % of global production (OECD 2011). Sugar and ethanol are the two main products of sugarcane processing. In 2009, total production exceeded 31 Mtonnes of sugar and 27.5 billion litres of ethanol (506 PJ; Lamers et al. 2011), making Brazil the world's second largest ethanol producer and consumer after USA. Brazil is also the world's leading ethanol exporter with exports peaking to 108 PJ in 2008 (Lamers et al. 2011). Most of the production is concentrated in south-central Brazil. In the harvesting seasons of 2004–2009, more than 85 % of sugarcane, 90 % of ethanol and 85 % of sugar output in Brazil was produced in this region (UNICA 2011). Brazil has a long regulatory and technological experience in ethanol production. In 1975, large-scale development of ethanol plants was promoted under the ProAlcool programme. Since then, ethanol plays an important role in the country's energy supply mix in the transport sector, accounting for 22 % in road transport fuels in 2010 (IEA 2012).

Sugarcane cultivation in Brazil offers high yields. It is harvested once per year in a 6-year cycle, during which five harvests (four of which are ratoon cultivations) and one field reforming cycle are performed (Macedo et al. 2008). However, there is some variation depending on local climate and cultivation practices. In the south-centre, 48 % of the sugarcane is harvested with machinery (Seabra et al. 2011), while 52 % is harvested manually. Until recently, sugarcane pre-burning was the dominating harvesting practice applied even on mechanically harvested areas. Based on state laws (No. 11.241/02) and the industry association's protocol of intention, mechanisation is expected to increase and sugarcane trash pre-burning practices are expected to phase out (by 2031 based on State decree or by 2017 based on the industry's protocol). Main inputs in Brazilian sugarcane production are agrochemicals, returned residues from ethanol production (filter cake, stillage and boiler ashes) and diesel used for land preparation, harvesting and ferti-irrigation. Contrary to production in UP, India, sugarcane crops in south-central Brazil are not irrigated as the production is based on rainwater.

In Brazil, ethanol is produced in stand-alone or adjacent distilleries to sugar mills. The most important difference compared to the Indian system is that sugarcane juice is directly used for ethanol production, next to 10 % of the Brazilian ethanol output, which originates from molasses (own calculations based on MME (2011) and UNICA (2011)). After harvested sugarcane has been transported to the mills by trucks, it is washed—if harvested by burning practices—and shredded so that juice can be extracted from bagasse. Apart from washing off the impurities, water is used to ensure higher sugar recovery. For physical treatment, the juice passes a series of screens before entering the fermentation tanks. The filter cake is collected and applied as fertiliser on sugarcane fields. After fermentation, the resulting broth enters the analyser and the rectification column to produce 95 % (*v*/*v*) hydrous ethanol. The stillage generated during ethanol production is sprayed on sugarcane fields as fertiliser. The majority of the bagasse is used in co-generation systems to cover all process energy requirements and to provide surplus electricity to the grid. Surplus bagasse is sold as solid biofuel. Brazil's car fleet includes 100 % alcohol- and flexible-fuelled vehicles which use hydrous ethanol.

3 Methods

3.1 System boundaries and functional unit

The main process steps included in the system boundaries are sugarcane production in UP (northern India) and south-central Brazil, sugarcane processing to sugar in UP, molasses processing to ethanol in UP and sugarcane processing to ethanol in south-central Brazil (Figs. 1 and 2). The system boundaries extend from cradle to gate, i.e. extraction of fuels and raw materials, production of material inputs and intermediate transport is included. The impact of infrastructure is excluded.

The functional unit is 1 kg of hydrous ethanol (92.6–93.8 % ethanol on a mass basis, the remainder is practically water) at the distillery gate. We exclude the use phase and

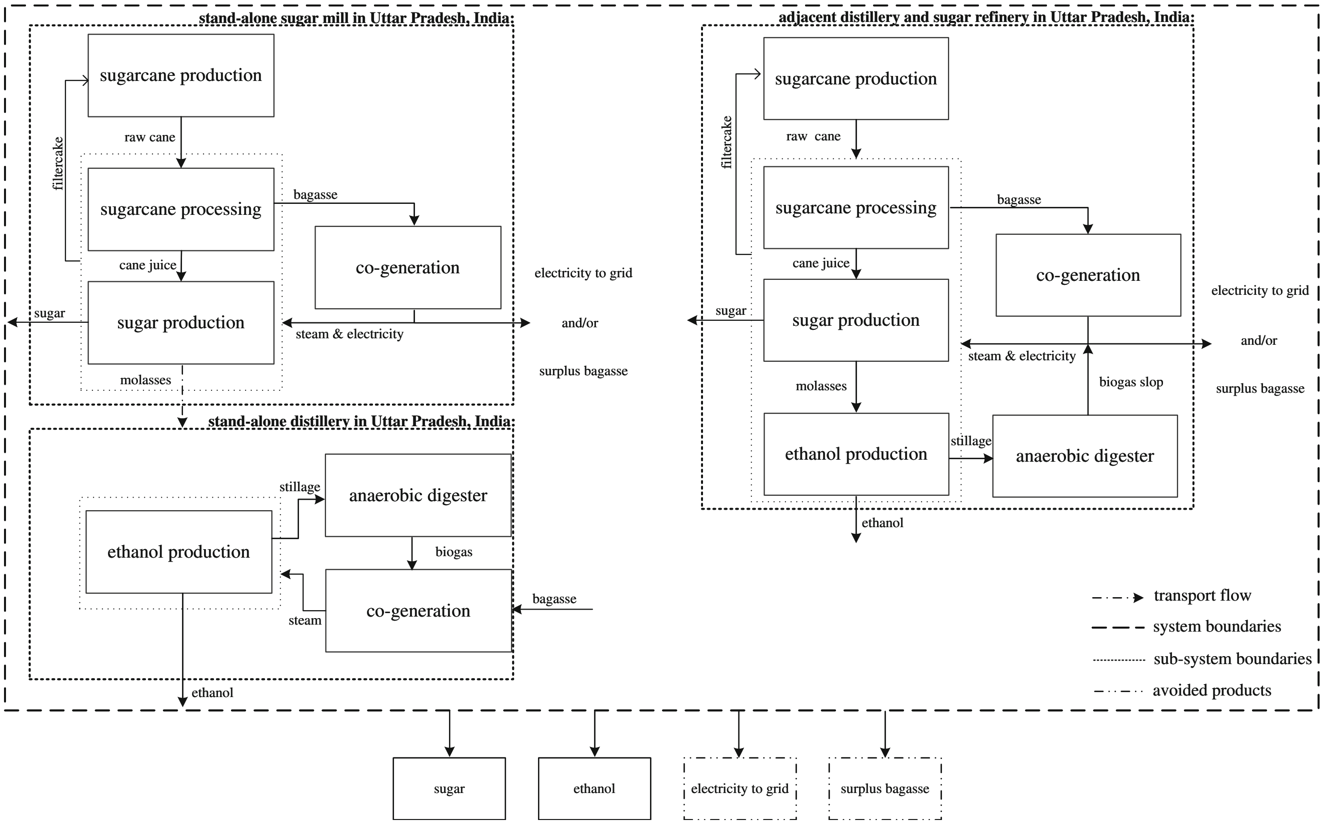


Fig. 1 Foreground process-chain of ethanol production in India. *Left* production at a stand-alone distillery, *right* production at a distillery attached to a sugar mill. In this study, a virtual average case is assessed on the basis of the products that exit the sector's boundaries within Uttar Pradesh, India

consequently the comparison with conventional gasoline, first, because we do not specify the transport and distribution of ethanol to gas stations; second, we do not study differences in fuel efficiency for ethanol-blends and gasoline; and third, we intend to account for ethanol applications also in the chemical industry, where hydrous ethanol serves as suitable feedstock.

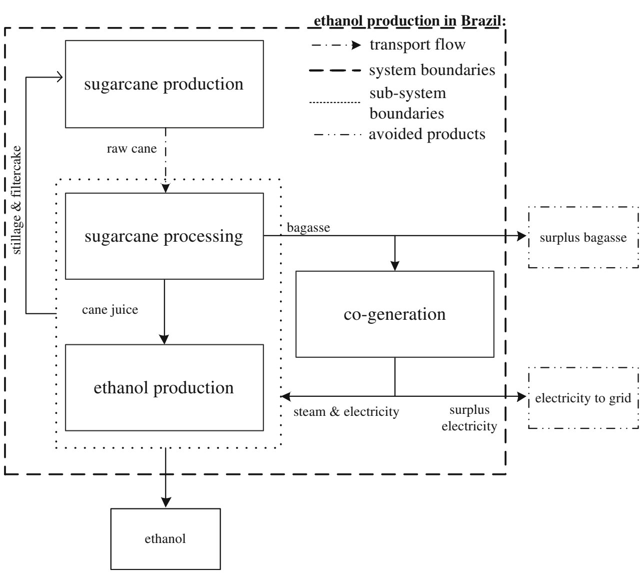


Fig. 2 Foreground process-chain of ethanol production in south-central Brazil

3.2 System range

In addition to assessing regional production in south-central Brazil and UP, India (average system performance), we present two extreme cases[1] (for greenhouse gas emissions and non-renewable energy use; extreme cases for impacts on human health and ecosystem quality are assessed by means of sensitivity analysis):

High system performance	For India, only attached mills and distilleries that produce surplus electricity are accounted. The sugarcane input is assigned based on the mills' crushing capacity, which ranges from 2 to 11 ktonnes sugarcane/day (DFPD 2013;

[1] The system's energy efficiency can be estimated either by accounting for the energy conversion efficiency (i.e. primary to secondary energy) and the process energy requirements (e.g. heat demand per unit of output) or by accounting for products (and co-products) per unit of total energy input, which is covered by bagasse. We assess a range based on conversion efficiency. However, efficiency improvements at the agricultural production phase (sugarcane productivity) are also important to assess the system's environmental and cost performance (van den Wall Bake et al. 2009).

	ISMA 2011b). It is assumed that excess electricity is produced from all the bagasse available at the mills and from biogas that was recovered after anaerobic treatment of stillage. For Brazil, we assume higher process and co-generation efficiencies which lead to a lower demand for process heat and higher surplus electricity per tonne of sugarcane processed (Seabra and Macedo 2011).
Low system performance	For India, we assume that no excess electricity is generated by mills. Mills use bagasse only to cover process heat requirement and sell any surplus biomass. Process electricity is supplied from the grid. Also, it is assumed that distilleries do not treat stillage anaerobically and cover heat demand by purchased bagasse and electricity demand from the grid. For Brazil, we assume all bagasse is consumed for own energy requirements, i.e. neither surplus electricity nor bagasse is provided by the mills.

The data used in this study are presented in Tables 2, 3, 4 and 5.

3.3 System expansion and allocation

In our study, we are confronted with multifunctional systems in several instances. In the Indian ethanol product system, sugarcane processing produces sugar, molasses, surplus electricity and surplus bagasse. In the Brazilian product system, sugarcane processing produces ethanol, surplus electricity and surplus bagasse. Other outputs produced within the system boundaries but have no market price (e.g. sugarcane trash, boiler ashes, filter cake) are assumed to be consumed within the system boundaries. The International Standardization Organization (ISO) recommends to solve multifunctionality problems by substitution (system expansion) and thus avoiding system partitioning (ISO 2006). The literature addressed the allocation problem of molasses-based ethanol production by applying different approaches to account for multifunctionality of sugar mills. Nguyen and Hermansen (2012) analyse stand-alone sugar mills and stand-alone distilleries and recommend system expansion to avoid allocation. In their consequential assessment, molasses are diverted from their use as feed and are assigned impacts of wheat production accounting for displacement effects. Renouf et al. (2011) applied system expansion to account for molasses-based ethanol for the system in situ, where sugar production is credited by avoided production of sorghum, which is used as feed. Consequently, sugar-mill co-products used for ethanol production have no impacts from sugarcane production. However, since, in India, molasses are used for ethanol production, system expansion cannot be applied following these approaches. In addition, applying substitution on surplus electricity output of Indian sugar mills may not be justified. The Indian electricity system is constrained since supply does not cover demand (CEA 2011). Therefore, it can be argued that, in the short-term, surplus electricity of sugar mills and distilleries stimulates additional consumption by marginal electricity consumers, while, in the long-term, it may contribute to reducing the demand of additional capacity, which is primarily fossil-based (CEA 2011).

Given the uncertainty that this system entails, we distinguish the following approaches[2]:

- As 'reference' approach, we assume that surplus electricity substitutes electricity of *low* CO_2 emission intensity. In UP, this is justified due to the regional proximity to the Uttaranchal grid and in Brazil due to the average national electricity mix. Both grids consist of high hydropower capacity (CSO 2012; IEA 2011a). For other co-products (sugar, molasses and bagasse), we apply economic allocation. We refer to this approach as 'SE-C', standing for "system expansion-conservative".
- As second approach, we assume that surplus electricity substitutes grid electricity of *high* CO_2 emission intensity. In India, this is the average national electricity mix, which is primarily based on coal (IEA 2011a). Similarly, in Brazil, it reduces fuel use in the operational margin, which is predominantly natural gas (Seabra et al. 2011).[3] For surplus bagasse, we expand the system to include direct heat production from bagasse with 79 % efficiency assuming that it displaces primary energy in fossil fuel-fired boilers. The fuels displaced depend on the fuels used for industrial heat production in each country. For India, we assume displacement of coal-based heat, supplied with 80 % efficiency.[4] For Brazil, we assume oil-based boiler

[2] System expansion is associated with consequential modelling. However, there are situations where it is applied to solve multifunctionality of foreground systems modelled by an attributional approach. These situations are encountered in product-related decision support studies that assess the life cycle of existing supply chains (EC 2010), similar to this study.

[3] In comparative life cycle assessment, the two systems should have aligned regional scope. This entails for India and Brazil that each SE approach should consider displacement of national average electricity (based on EC 2010) or marginal electricity production. Instead, in this study, we compare the systems on the basis of the credits assigned. This choice is made because the national average electricity fuel mix of the two countries differs significantly (fossil fuel-based and hydropower in India and Brazil, respectively). Considering the geographical context of the two systems and the EC (2010) guidelines, the SE-O approach for India should be compared to the SE-C approach for Brazil.

[4] Typically, coal boilers have higher efficiencies than biomass boilers. This study assumes similar efficiencies, which is likely for new biomass boilers that displace vintage coal-based boilers.

Table 2 Inputs for 1 tonne of sugarcane production in Uttar Pradesh, India (2009) and south-central Brazil (2008)

Input	Unit	Uttar Pradesh, India	South-central Brazil
Land occupation[a]	m^2a	169	147
Freshwater irrigation	m^3	59.5[b]	0
N-fertilisers	kgN	2.69	0.78
Ammonium sulphate		0.42	–
Ammonia		–	0.11
Ammonium nitrate		0.42	0.29
Diammonium phosphate (DAP)		0.37	–
Urea		1.23	0.37
Potassium nitrate		0.25	–
Monoammonium phosphate		–	0.08
P_2O_5-fertilisers	kgP_2O_5	1.31	0.25[c]
Diammonium phosphate (DAP)		0.62	–
Single superphosphate (SSP)		0.4	0.146
Triple superphosphate (TSP)		0.2	0.081
Phosphate rock		0.07	0.003
Monoammonium phosphate		–	0.022
K_2O-fertilisers	kgK_2O	0.82	0.98[d]
Potassium chloride		0.80	0.96
Potassium nitrate		$8.0 \cdot 10^{-3}$	0.01
Potassium sulphate		$8.0 \cdot 10^{-3}$	0.01
Pesticides	kg		
Herbicides, unspecified[e]		0.056	0.031
Triazine compounds[e]		0.011	0.006
Phenoxy compounds[e]		0.003	0.001
Glyphosate[e]		0.004	0.002
Diuron[e]		0.009	0.005
Insecticides, unspecified		0.050	0.003
Fungicides, unspecified		0.003	$1.0 \cdot 10^{-5}$
Other inputs	kg		
Sugarcane, as seed[f]		100	–
Lime		–	5.18[g]
Ash		2	2
Gypsum		–	2.30
Stillage		–	570
Filter cake		40[i]	31
Energy			
Diesel, transport of inputs	l	$4.1 \cdot 10^{-3}$	$5.6 \cdot 10^{-3}$
Diesel, field operations	l	–	3.62[j]
Diesel, irrigation[k]	l	0.54	–
Electricity, irrigation[k]	kWh	12	–

[a] India: based on 59.2 t_{cane}/ha (ISMA 2011a). Brazil: based on 86.7 $t_{cane}/ha_{harvested\ area}$ which represents 83 % of total area. The remaining area was not harvested due to reforming cycle or bad weather conditions

[b] Based on 14.6 kg_{cane}/m^3_{water} (Srivastava et al. 2009) for 92.3 % of area irrigated (DES 2010)

[c] Assuming 91 % of total P_2O_5 fertilisers (Seabra et al. 2011) are DAP, SSP, TSP as in Jungbluth et al. (2007)

[d] Assuming that total K_2O fertilisers are applied in the same ratio of potassium chloride, sulphate and nitrate as in Jungbluth et al. (2007)

[e] Brazil: types of pesticides calculated based on shares of specified and unspecified pesticides as in Jungbluth et al. (2007) based on total pesticides (herbicides, acaricides and other defensives) reported in Seabra et al. (2011). India: the same approach was applied. For Brazil, the active ingredients differ from other studies (e.g. Cavalett et al. 2013). However, given the uncertainties in pesticide use in both Brazil and India, the Ecoinvent inventory is preferred to provide a more conservative estimate

[f] India: includes losses or other non-productive uses (ISMA 2011a). Brazil: the inventory inputs of Seabra et al. (2011) account for seed requirement of sugarcane. Macedo et al. (2008) report seed efficiency of 6.9 ha sugarcane/ha seed

[g] Energy use in production of lime based on UNICA (2009)

[h] In this study, no impacts are associated to ash. Same quantity assumed for India and Brazil based on Seabra et al. (2011)

[i] Based on 4.5 % of sugarcane crushed in mills (ISMA 2012)

[j] Includes land preparation (reforming, tillage, ploughing), seeding, agrochemicals application, harvesting, ferti-irrigation. In Seabra et al. (2011), diesel consumption is given for the total area including transport of sugarcane to the mills and agrochemicals to the fields (274 l/ha). This value is adjusted per tonne sugarcane taking into account the productivity and total area and by subtracting the diesel requirement for transport of sugarcane to mills and agrochemicals to fields for an average truck efficiency of 55 tkm/l and distance of 42 km (round trip)

[k] India: groundwater pumping for UP (MoEF 2010). Average water depth is 36.7 m (Srivastava et al. 2009) and 20 % diesel and 80 % electric pumps (Shah 2009). Diesel requirement for groundwater pumping based on Kägi and Nemecek (2007), which is 0.059 l diesel/l water·depth (in meters) and diesel density of 0.832 kg/l. Brazil: sugarcane production is rainwater-dependent. Energy requirement for ferti-irrigation is accounted under diesel, field operations

Table 3 Sugarcane processing products and sector analysis in Uttar Pradesh, India for the 2009–2010 season. Calculated based on ISMA (2011a, b, c)

	Unit	Quantity
Processing products		
Sugarcane processed	Mtonnes	56.7
Sugar	Mtonnes	5.2
Molasses	Mtonnes	2.9
Ethanol	Mtonnes	0.51
Surplus electricity[a]	TWh	3.11
Bagasse (total)	Mtonnes	18.2
Biogas (total)[b]	TJ	2,785
Sector analysis		
Crushing capacity[c]	ktonnes/day	565
Crushing capacity of facilities which provide surplus electricity[c]	ktonnes/day	263
Ethanol capacity[d]	Mtonnes/year	0.9

[a] Of the total surplus, 84.5 % was produced during the sugarcane crushing season (103 days in 2009–2010), and the remaining was produced outside the sugarcane crushing season (ISMA 2011b). On-season energy output calculated based on on-season surplus capacity, multiplied by the number of days of the on-season period and 24 h in a day. Similarly for off-season

[b] Calculated based on 0.35 nm^3/kgCOD removed, with 72 % COD removal efficiency (typical for mesophilic treatment technologies), 100,000 mgCOD/$l_{stillage}$ and biogas energy content of 16.6 MJ/kg (Tewari et al. 2007). Ninety percent of distilleries apply anaerobic treatment (Satyawali and Balakrishnan 2008) and 12.5 $l_{stillage}$/$kg_{ethanol}$ is generated

[c] Based on DFPD (2013) and ISMA (2011a). A 77.5 % of the sugarcane crushing capacity is installed in stand-alone mills, and the remaining 22.5 % is installed in mills attached to distilleries (see Supporting information)

[d] Fifty percent of the total ethanol capacity is in stand-alone distilleries and 50 % is attached to sugar mills (NFCSF 2012). Based on ISMA (2011a), the capacity of the distilleries that provide surplus to the grid represents 26.5 % of the total. Since Indian stand-alone distilleries do not process sugarcane, only attached distilleries are associated with production of surplus electricity

efficiency of 92 %.[5] We apply economic allocation among the remaining co-products (sugar and molasses, applicable only for India). We refer to this approach as ‘SE-O’, standing for “system expansion-optimistic”.

- In the third approach, we apply economic allocation (referred to as ‘EA’) across all products. This approach is justified, first because it accounts for the competitiveness of the sector’s outputs based on economic criteria and second because it is consistently applied to all products, whereas in the other two approaches, a combination of system expansion and economic allocation is used. As electricity input, we use national average grid.

[5] Alternatively, for surplus bagasse in Brazil, we (a) assume that it is combusted to increase power output with 25 % efficiency (1.1 kWh/$kg_{bagasse,dry\ basis}$) and (b) assess pellet production, export to Europe and use in co-firing power plants where it displaces coal (Section 5.1). Background information is included in the Supporting information.

Table 4 Inputs and (co-) products for 1 tonne of sugarcane processing in Uttar Pradesh, India

	Unit	Quantity
Products	kg	
Sugar		91.4
Molasses		50.3
Bagasse[a]		6
Electricity[b]	kWh	54.2
Inputs	kg	
Sugarcane		1,000
Sulphur dioxide		1.5
Limestone		1.9
Sodium hydroxide		0.5
Superphosphate		0.1
Soda		0.03
Organic chemicals		0.01
Lubricating oil		0.6
Phosphoric acid		0.01
Water		30
Transport, sugarcane	tkm	12
Transport, inputs	tkm	0.6

[a] By subtracting surplus bagasse from total available amount, we estimate the quantity of bagasse used within the system boundaries to provide process energy requirements and excess electricity. Surplus bagasse is estimated based on total availability in sugar mills that do not produce excess electricity but supply bagasse to stand-alone distilleries to supplement their primary energy requirements. Process energy requirements are assumed to be met exclusively from bagasse and are 313 kWh/t_{sugar} and 16.9 GJ/t_{sugar} (Jungbluth et al. 2007) and 237 kWh/$t_{ethanol}$ and 11.5 GJ/$t_{ethanol}$ (Prakash et al. 2005). Bagasse requirement for steam and electricity generation based on Prakash et al. (2005). For distilleries, net primary energy requirement based on Prakash et al. (2005). Heating value of bagasse is 16 MJ/$kg_{dry\ basis}$

[b] Since power is produced both on and off season, we assume that all the available bagasse is consumed in the mills that produce surplus power and that no additional bagasse or other biomass source is supplied from other mills. Surplus electricity allocated between the two product systems on a primary energy basis; i.e. 98 % of the total surplus was produced by bagasse and 2 % by biogas. By dividing total surplus electricity by total sugarcane processed in UP sugar mills we calculate that 54.8 kWh/$t_{sugarcane}$ are produced (Table 5, Fig. S1 in the Supporting information). Biogas recovery estimated based on Tewari et al. (2007)

In Nguyen and Hermansen (2012) and Renouf et al. (2011), feedstock energy is clearly separated among the subsystems of sugar and ethanol production. However, the system of our study includes both attached and stand-alone facilities, and biogas produced from stillage treatment of the ethanol subsystem also contributes to reducing net primary energy from other sources. This also calls for a different approach than found in literature. Therefore, at an intermediate level, the system is broken down to the subsystems sugar and ethanol production and molasses are assumed as an intermediate product (Figs. 1 and 2). Surplus electricity that is produced from bagasse is assigned to the sugar product system and

Table 5 Inputs and co-products for 1,000 kg hydrous ethanol production in Uttar Pradesh, India and south-central Brazil

	Unit	Uttar Pradesh, India	South-central Brazil
Products			
Ethanol	kg	1,000	1,000
Bagasse	kg	–	130
Electricity	kWh	60	160
Inputs	kg		
Molasses		5,060	–
Sugarcane		–	14,960[a]
Lubricating oil		–	0.15
Lime		–	13.1
Sulphuric acid		0.41	9.3
Biocides		–	0.1
Organic chemicals		–	0.86
Magnesium sulphate		0.11	–
Urea		1.3	–
Phosphoric acid		0.14	–
Chlorine		0.38	–
Soda		0.06	–
Chromium oxide		0.1	–
Sodium hydroxide		0.6	–
Zinc		0.12	–
Formaldehyde		0.02	–
Water	m^3	11.4[b]	24.7
Transport, sugarcane (Brazil)	tkm	–	8.32[c]
Transport, molasses (India)	tkm	380[d]	197

[a] Based on hydrous ethanol yield of 84.7 l/t_{cane} and ethanol density of 0.789 kg/l

[b] Net water consumption based on Tewari et al. (2007), taking into account gross water requirement and freshwater returned to nature

[c] Based on total diesel consumption presented in Seabra et al. (2011) by subtracting diesel requirement of sugarcane harvesting operations

[d] Considering that approximately half of the total ethanol capacity is attached to sugar mills (NFCSF 2012). Only part of the molasses needs to be transported. The value includes transport of chemical inputs (0.58 $kgkm/kg_{ethanol}$). Not including transport of bagasse to stand-alone distilleries

surplus which is produced by biogas to the ethanol product system, based on primary energy. Depending on the allocation approach, surplus electricity is a critical parameter in determining the GHG emissions of ethanol production in UP. Therefore, results are also presented for a range based on the electricity surplus of high and low system performance (Section 3.2). In addition, it can be argued that since molasses do not exit the system boundaries, allocation approaches should consider only final products, namely sugar, ethanol, electricity and bagasse (Fig. 1). This entails that the system is treated as 'black box'. We solve the multifunctionality of the 'black box' based on (a) price of sugar, ethanol and bagasse with credits assigned for surplus electricity with *low* CO_2 emission intensity (SE-C); (b) price of sugar and ethanol with credits assigned for surplus electricity with *high* CO_2 emission intensity and substitution of coal-based heat generation from surplus bagasse (SE-O) and (c) price of all final products.

Allocation factors, prices and system credits of each approach are presented in Table 6.

3.4 Impact assessment method

The impact assessment method used is Impact 2002+ v2.10 (Jolliet et al. 2003). We present results for the midpoint indicators greenhouse gas (GHG) emissions, non-renewable energy use (NREU), freshwater eutrophication and water use. Furthermore, we present results on human health (HH) and ecosystem quality (EQ) at the damage level. For sugarcane production, we also present the contribution of midpoint impact assessment results to the endpoints HH and EQ. GHG emissions are calculated for global warming potential of 100 years (IPCC 2007). The characterisation factor for fossil and biogenic methane emissions is adapted to 27.75 and 25 $kgCO_{2eq}/kgCH_4$, respectively (Muñoz et al. 2013). We also provide an estimate on the influence of land use change emissions on the GHG profiles of ethanol, based on emission factors found in literature. We include the ozone depleting potential of nitrous oxides (N_2O), i.e. 0.017 $kgCFC\text{-}11_{eq}/kgN_2O$ (Ravishankara et al. 2009) because it is not considered in default characterisation factors of Impact 2002+. Lastly, impacts of aquatic acidification and freshwater eutrophication are linked with EQ, based on 8.82E-3 $PDF \cdot m^2 \cdot year/kgSO_{2eq}$ and 1.4 $PDF \cdot m^2 \cdot year/kgPO_4{}^3{}_{eq}$, respectively (Humbert et al. 2012).

4 Inventory data

We have selected the study regions based on data availability and representativeness. For India, the state of UP is selected, being the largest sugarcane-producing state accounting for 40 % of the country's total production in 2009–2010. Moreover, approximately 32 % of the country's total sugar production capacity and 34 % of the country's total ethanol production is located in UP (ISMA 2011a). The assessment of Brazilian ethanol production reflects practices of the south-central region, which is by far the most important cultivation area, i.e. 86 % of the total planted area (UNICA 2011).

For sugarcane production in UP, we use average sugarcane production yields from ISMA (2011c) and Kumar (2013), which are comparable with the average yields between 2001 and 2010. For agricultural inputs, we use data from Kumar (2013), who compiled inventories for UP. Compared to agricultural statistical information on fertiliser consumption (GoI 2013), data of Kumar (2013) indicate higher consumption for

Table 6 Products and multifunctionality allocation factors and credits based on the three different approaches

Products	Sugarcane processing (per t_{cane})	Price[b]	Multifunctionality allocation factors[c] and credits				
			SE-C Default	SE-O	EA	SE Black box	EA
Uttar Pradesh, India							
Sugar	91.4 kg	\$0.546/kg	91.5 (92, 89)%[a]	92 (92, 92)%	85 (79, 89)%	86.5 %	80.8 %
Molasses	50.3 kg	\$0.087/kg	8 (8, 8)%	8 (8, 8)%	7.5 (7, 8)%	–	–
Bagasse	6 (0.36)kg	\$0.043/kg	0.5 (0, 3)%	0.38 (0, 2)MJ/$kg_{ethanol}$	0.4 (0, 3)%	0.5 %	0.4 %
Electricity (bagasse)	54.2 (117, 0)kWh	\$0.076/kWh	0.44 (0.95, 0)kWh/$kg_{ethanol}$	0.44 (0.95, 0)kWh/$kg_{ethanol}$	7.1 (14, 0)%	54.8 kWh/t_{cane}	6.8 %
Electricity (biogas)	0.60 (2.5, 0)kWh	\$0.076/kWh	0.06 (0.25, 0)kWh/$kg_{ethanol}$	0.06 (0.25, 0)kWh/$kg_{ethanol}$	0.6 (2.5, 0)%		
Ethanol	9.9 kg	\$0.747/kg	100 (100, 100)%	100 (100, 100)%	99.4 (97.5, 100)%	13 %	12 %
South-central Brazil							
Ethanol	66.8 kg	\$0.64/kg	99.5 (99.5, 100)%	100 (100, 100)%	97.5 (93.5, 100)%		
Electricity	10.7 (32, 0) kWh	\$0.085/kWh	0.16 (0.48, 0)kWh/$kg_{ethanol}$	0.16 (0.48, 0)kWh/$kg_{ethanol}$	2 (6, 0)%		
Bagasse	8.6 kg	\$0.023/kg	0.5 (0.5, 0)%	0.9 (0.9, 0)MJ/$kg_{ethanol}$	0.5 (0.5, 0)%		

[a] Values in parentheses indicate parameters for the high and low performance cases (left and right value, respectively)

[b] Indian prices from Kumar (2013), ISMA (2011c) and personal communication with ISMA considering exchange rate US\$1=INRs45.8 (2010). Brazilian prices from Cavalett et al. (2011), where US\$1=R\$1.76 (2010). Price for hydrous ethanol obtained by converting the price of anhydrous ethanol based on average difference as estimated by UNICA (2011)

[c] Economic allocation factors. Price of sugar, molasses and ethanol in India largely depends on availability of sugarcane, which varies on an annual basis. However, the price ratio of co-products, used to calculate the economic allocation factors, is not expected to vary significantly

N and K_2O fertilisers (by 31 and 58 %, respectively) and lower for P_2O_5 fertilisers (by 28 %) per hectare. This difference is expected since the statistical information is not crop-specific while data in this study reflect sugarcane production. We include energy and groundwater requirement for irrigation based on MoEF (2010), Shah (2009) and Srivastava et al. (2009). We rely on survey-based irrigation data for the region (60 l/kg_{cane}), which also specify means of irrigation. Water footprint studies indicate higher consumption (140 l/kg_{cane}; Mekonnen and Hoekstra 2010) but do not specify means of irrigation. As sensitivity analysis, we assess impacts of a low and high water use. Apart from seasonal variation, spatial variation in yields, variation in inputs of agrochemicals, irrigation water consumption and practices is anticipated. However, there is limited information to support a further estimate on the range. For sugarcane production in south-central Brazil, we use industry-based data of the sugarcane technology centre, reported in Seabra et al. (2011). Parameters such as sugarcane productivity, unburned and mechanised area are representative for a large number of mills (up to 168), while the sample is smaller for diesel consumption, transport distances, and agrochemicals. When compared to aggregated regional data differences are expected. For example, in 2008, based on FAO statistics, Brazilian sugarcane yield was 79 t_{cane}/ha (FAOSTAT 2013), while based on data in this study, the yield in the south-central region was approximately 10 % higher (Table 2). We opt to use data from the sugarcane technology centre due to their traceability and reliability. Table 2 presents the inventory inputs of sugarcane production in India and Brazil.

For sugarcane processing in India, we use sector-wide data (Table 3) on production volumes (ISMA 2011a), sugarcane crushing capacity (DFPD 2013) and ethanol production capacity (ISMA 2011c). Table 4 presents the inventory inputs of sugarcane processing in UP, India.

Energy requirements of mills and distilleries that do not provide surplus power are estimated based on literature data on energy demand for sugar production (Jungbluth et al. 2007) and for distilleries (Prakash et al. 2005). Based on ISMA (2011a) and personal communication with the All India Distillers' Association energy requirements of stand-alone distilleries are met by biogas and biomass, which we assume to be bagasse (Gopinathan and Sudhakaran 2009; Khatiwada et al. 2012). In this manner, we estimate the net bagasse surplus assigned to sugar production as a co-product. Since in India bagasse flows are not monitored, results include a range for different net output assuming high and low system performance. Material inputs for sugar and ethanol production are from ISMA (2011c) and Kumar (2013). For south-central Brazil, we use industry-based data from Seabra et al. (2011). Compared to earlier studies (e.g. Macedo et al. 2008), these are the latest inventory data on Brazilian ethanol production. The inputs of ethanol production of the two product systems are presented in Table 5. Background data used in this study originate from Ecoinvent (2010) v2.2. For Indian average grid electricity production, we use data from the International Energy Agency (IEA 2010, 2011b; see Supporting information). Multifunctionality allocation factors, co-products and credits of the different approaches are presented in Table 6.

5 Results and discussion

5.1 Greenhouse gas emissions and non-renewable energy use

GHG emissions of Indian (IN) sugarcane production are higher than those of Brazilian (BR) sugarcane production (0.045 $kgCO_{2eq}/kg_{caneIN}$ as opposed to 0.036 $kgCO_{2eq}/kg_{caneBR}$ in SE-C; Fig. 3). The difference is due to high N_2O emissions from oxidation of nitrogen in N-fertilisers and CO_2 release from decomposition of urea[6] ('Emissions from soil'; Fig. 3) and CO_2 emissions from energy intensive production of N-fertilisers ('Emissions from production of agrochemicals'; Fig. 3). On the other hand, pre-harvesting burning and energy use related to mechanisation in Brazil reduce the difference of sugarcane emissions between the two countries. Note that the source of grid electricity in electric irrigation pumps in India is aligned with the source of electricity that credits are given for surplus electricity in the sugar product-system. Therefore, emissions of sugarcane under SE-O and economic allocation (EA) are 0.057 $kgCO_{2eq}/kg_{caneIN}$. The difference with SE-C (0.012 $kgCO_{2eq}/kg_{caneIN}$) is due emissions from electricity production for irrigation. The emissions of Brazilian sugarcane are the same under all approaches. Note that the assessment of Indian sugarcane excludes the impact of animal use and labour, while the assessment of Brazilian sugarcane includes the impact of machinery use.

For ethanol, we present results for GHG emissions and NREU (Fig. 4). For each allocation approach, the gross results for average system performance are broken down to contribution of sugarcane production, energy use for irrigation in India and agricultural operations in Brazil (subsumed as 'energy in agriculture'), molasses production (India), ethanol production and transport. The net impact of ethanol production after deducting the credits is represented by symbols, thereby distinguishing between high, low and average system performance (Section 3.2).

Net GHG emissions of Indian ethanol are lower when compared to Brazilian ethanol across the results for the system expansion approaches and average system performance (excluding high and low cases). This difference is due to the

[6] 1.325 % of nitrogen in N-fertilisers and 1.225 % of nitrogen in unburned trash is converted to N in N_2O (Macedo et al. 2008).

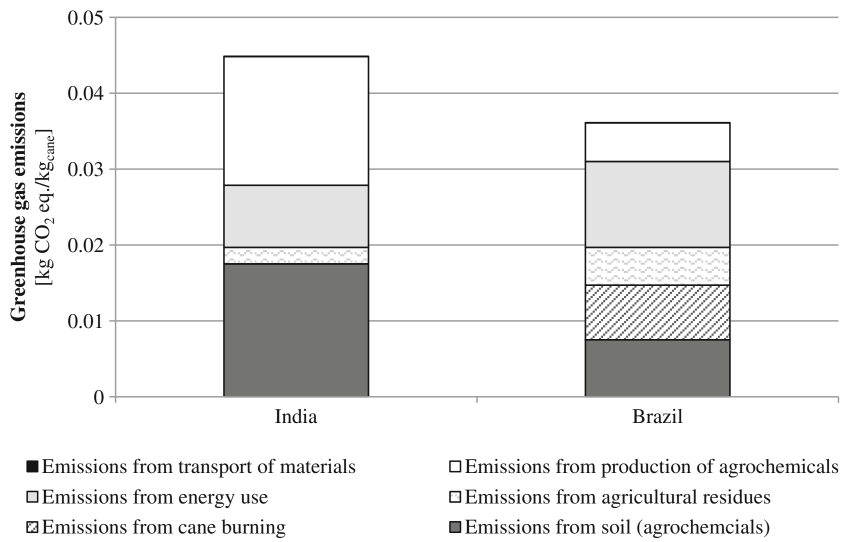


Fig. 3 Cradle-to-gate emissions of sugarcane production in India and Brazil, excluding animal use and human labour

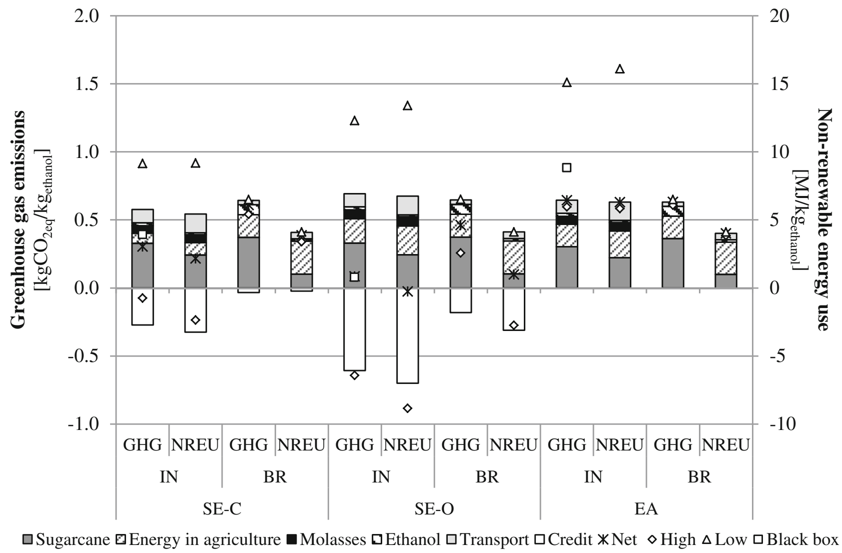
credits of the Indian system, which are by a factor 8 higher in SE-C (0.27 $kgCO_{2eq}/kg_{ethanolIN}$, 0.035 $kgCO_{2eq}/kg_{ethanolBR}$) and by a factor 3 higher in SE-O (0.61 $kgCO_{2eq}/kg_{ethanolIN}$, 0.18 $kgCO_{2eq}/kg_{ethanolBR}$) when compared to Brazil.[7] Credits are given based on the electricity output per tonne of sugarcane allocated to ethanol production, which as Table 6 shows, is higher for Indian ethanol (0.5 $kWh/kg_{ethanolIN}$ compared to 0.16 $kWh/kg_{ethanolBR}$) and the CO_2 emission intensity of the electricity that is displaced under each approach.[8] In addition, Indian ethanol is associated with a fraction of the impacts from the agricultural phase due to allocation between sugar and molasses[9] but also because impacts of animal use and labour are not included. Khatiwada and Silveira (2011) estimated that human labour contributes 3.5 % to GHG emissions of ethanol production in Nepal. Similar contribution in India would increase emissions to 0.31, 0.09 and 0.67 $kgCO_{2eq}/kg_{ethanolIN}$ under SE-C, SE-O and EA, respectively. Contribution to Brazilian ethanol would be lower because of high mechanisation and hence lower human labour in agriculture, which is accounted in results for Brazilian ethanol (Fig. 4). Assuming that surplus bagasse in Brazil is used to produce additional power then GHG emissions increase slightly to 0.5 $kgCO_{2eq}/kg_{ethanolBR}$ (SE-O). This is due to lower conversion efficiency of biomass to electricity but also due to lower emission factor of natural gas when compared to oil. If surplus bagasse were used for pellet production, displacing coal in European co-firing power plants, the emissions would remain unchanged (0.45 $kgCO_{2eq}/kg_{ethanolBR}$ instead of 0.46 $kgCO_{2eq}/kg_{ethanolBR}$ in SE-O). High credits for coal displacement are reduced due to high energy demand for drying wet bagasse and lower surplus electricity supplied to the grid due to electricity requirement of milling, pressing and handling. When EA is applied, results for GHG emissions are comparable, since both systems do not receive any credits. The range between the high and low performance cases is wider in India than in Brazil because in the low performance case, we assume that Indian mills use grid electricity but not Brazilian mills. Similarly, in the high performance case, it is assumed that Brazilian mills produce lower electricity surplus than Indian mills per kilogram of ethanol. The comparable results of the EA and the range between the high and low performance particularly for Indian ethanol indicate the importance of surplus power output and the effect that different methodological choices have. The 'black box' approach yields higher impacts in SE-C and EA as

[7] Distilleries in Uttar Pradesh also produce fuel-grade (anhydrous) ethanol. Due to aggregated reporting of hydrous and anhydrous ethanol by available statistics, the approach of this study might lead to an underestimation of co-products associated with hydrous ethanol. To assess the influence of our assumption (i.e. all production reported for Uttar Pradesh is hydrous ethanol), we correct the avoided energy requirement related to the conversion of hydrous to anhydrous ethanol based on the values in Prakash et al. (2005). The underestimation would be in the range of 1 % for surplus electricity and 3 % for surplus bagasse, which would only slightly affect the results of SE-O, i.e. GHG emissions and NREU would be lower by 0.007 $kgCO_{2eq}/kg_{ethanolIN}$ and 0.05 $MJ/kg_{ethanolIN}$, respectively.

[8] GHG emissions from Brazilian dams are controversial. Fearnside and Pueyo (2012) estimate higher emissions than those published by the national Brazilian electricity authority. The latter are also used in the Ecoinvent inventories (Dos Santos et al. 2006) and have been used in this study. Upward correction of these values in our analysis would entail that the CO_2 intensity of the national average Brazilian electricity mix was higher. By analogy, higher credits would be assigned to surplus electricity provided by the sugar mills, therefore reducing the relative difference between Indian and Brazilian ethanol.

[9] Due to allocation (Table 6), Indian ethanol is associated with the impacts of 8 $kg_{cane}/kg_{ethanoIN}$ (based on $\frac{19.9\ \text{kg sugarcane}}{\text{kg molasses}} \times \frac{5.06\ \text{kg molasses}}{\text{kg ethanol}} \times 0.08$), while Brazilian ethanol is associated with the impacts of 15 $kg_{cane}/kg_{ethanolBR}$. The difference in GHG emissions associated with the agricultural phase between the two product systems is 45 % in SE-C and 10 % in SE-O between Indian and Brazilian ethanol, respectively.

Fig. 4 Cradle-to-gate greenhouse gas emissions and non-renewable energy use of ethanol production in India and Brazil



shown in Fig. 4. For SE-C, this is explained because the system is not subdivided and the credits allocated to ethanol do not outweigh the allocated burdens. Following SE-O, the overall credits allocated to ethanol are higher in the 'black box' approach, which is illustrated by the slightly lower impacts when compared to the reference approach. The effect of the 'black box' approach is significant under EA because ethanol has higher price compared to the other co-products thus is assigned with higher burden share. Additional results are provided in the Supporting information.

Based on the emission factor of Cavalett et al. (2013), direct land use change reduces the emissions of Brazilian ethanol by approximately 2 % (−0.01 $kgCO_{2eq}/kg_{ethanolBR}$). Accounting for indirect land use change based on emission factors of the California Air Resource Board (CARB 2010) increases the emissions of Brazilian ethanol by 1.2 $kgCO_{2eq}/kg_{ethanolBR}$). Other studies propose much lower emission factors (e.g. review by Wicke et al. (2012)). For example, assuming the average land use change emission factor of Tipper et al. (2009), we estimate that emissions of Brazilian ethanol increase by 0.08 $kgCO_{2eq}/kg_{ethanolBR}$. Given the wide range and the absence of methodological consensus in accounting for additional emissions due to indirect land use change, these results should be interpreted with caution.

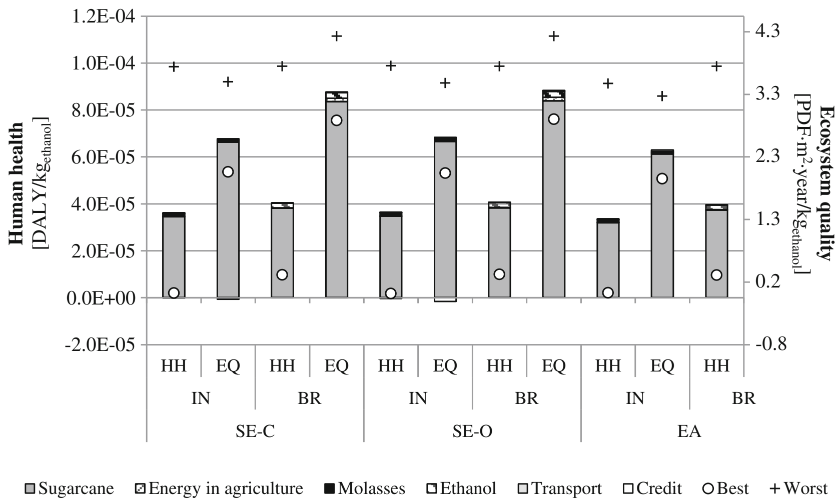
For India, to our knowledge, land use change emission factors for molasses-based ethanol do not exist. Due to the increasing ethanol demand (Table 1) and the high EBP targets in India, it can be anticipated that molasses used as an animal feed ingredient to be directed to ethanol production. This will increase the demand for feed crops, especially grain. Impacts of molasses diverted to ethanol production chain will be equivalent to impacts of feed crops in India or elsewhere. As Nguyen and Hermansen (2012) show, accounting for impacts of molasses diverted from feed with system expansion shows higher emissions when compared to economic allocation. Similarly, if ethanol is diverted from the potable liquor or chemical sector to transport, additional ethanol would have to be imported or produced domestically. Ethanol production in India is constrained by sugar demand; therefore, displacement of crops is likely to occur in ethanol-exporting countries like USA, South Africa, Thailand and Brazil (Gopinathan and Sudhakaran 2009). Marginal increase in ethanol demand for fuel in India will be associated with emissions of ethanol production in those countries. In view of the ambitious EBP, targets such impacts should be taken into account by a consequential approach to assess GHG emissions associated with the increase in demand.

5.2 Human health and ecosystem quality

Impacts of sugarcane ethanol production on HH and EQ are presented in Fig. 5. A range is included based on critical assumptions on pesticides, which are explained further on. The range is discussed only for SE-C since results are similar across all approaches, with the exception of results based on the 'black box' approach, which are 60 % higher. Indian sugarcane has higher impacts on HH than Brazilian sugarcane due to high use of pesticides and fertilisers (Fig. 6). Indian ethanol has comparable impacts with Brazilian ethanol, with only 10 % lower HH and 25 % lower EQ. This is partly associated with the allocation in the subsystem of sugar production (footnote 9). Contrary to GHG emissions and NREU, the credits do not influence the results.

Impacts on HH are to a large extent related with pesticide application on soil and more specifically with the arsenic-containing daconate. This input is included in the inventory because a large fraction of pesticides is unspecified (Table S1 in the Supporting information). While detailed data on

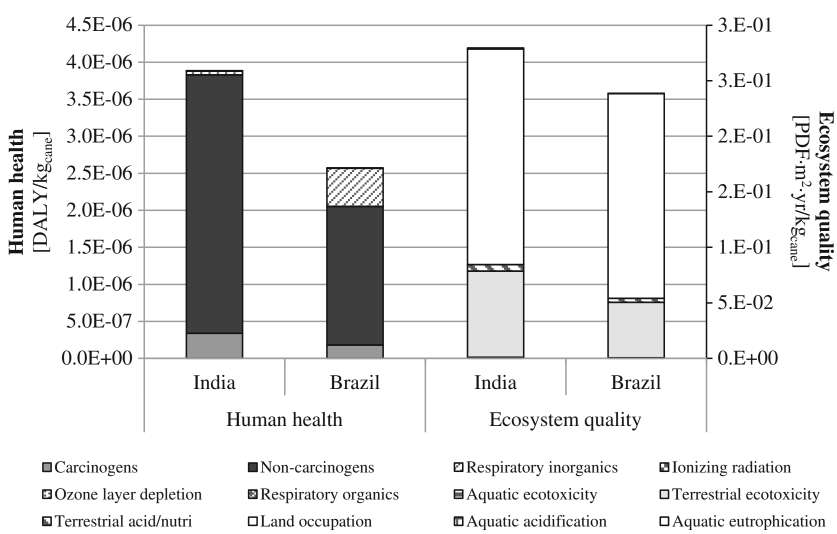
Fig. 5 Potential impacts of sugarcane ethanol production in India and Brazil on human health and ecosystem quality



consumption of chemicals in sugarcane production were not available, its usage is plausible since it is not banned according to the list of Persistent Organic Pollutants of Stockholm Convention (UNEP 2013). In Brazil, daconate is listed under the agrochemicals produced and applied in sugarcane production (MAPA 2012). According to Fig. 6, in India, the highest contribution to HH is due to carcinogenic and non-carcinogenic effects, which are related to daconate (99 %). The remaining impact is associated with respiratory inorganics from NH_3 and N_2O emissions related to fertilisers. By excluding daconate from the inventory, then impacts on HH remain lowest for India ('Best' in Fig. 5). If, on the other hand, all unspecified pesticides are assumed as daconate, there is a threefold increase on HH impacts ('Worst' in Fig. 5). For Brazil, carcinogenic and non-carcinogenic emissions are also associated with daconate and they contribute 80 % to HH. The remaining contribution originates from particulate matter emissions from pre-harvesting burning. Phasing out daconate reduces the impact on HH by 80–90 %. Eliminating pre-harvesting practices also reduces greenhouse gas emissions by 10 %. However, this estimation does not account the tradeoff with increased mechanisation. Last, for Brazilian ethanol, approximately 5 % of the impact on HH is associated with bagasse use in co-generation facilities. This effect is lower for Indian ethanol due to the effect of allocation. Note that other studies on Brazilian sugarcane (Cavalett et al. 2013), report lower quantities for pesticide application by a factor 5 (10 g/t_{cane}). This factor difference, in combination with different active ingredients assumed in this study (mainly arsenic and atrazine; see Supporting information) lead to significantly higher impacts for ethanol production due to pesticides. Even when the 'Best' scenario (no daconate application) is assessed, the impacts of pesticide application in sugarcane production are a factor 30 higher (on HH) and 15 % higher (on EQ) compared to Cavalett et al. (2013).

The method applied to estimate the fate of pesticides in different environmental compartments influences greatly the impact assessment results related with human and

Fig. 6 Potential impacts of sugarcane production in India and Brazil on human health and ecosystem quality



environmental toxicity. Our approach, in line with Ecoinvent, assumes that the agricultural field is part of the ecosphere, thus the full dose of pesticides is emitted to soil. For Australia, Renouf et al. (2010) account for a fraction of pesticides that runs off to other environmental compartments (1.5 % of the active ingredients). Similar run-off factors for Brazilian or Indian conditions are not available. If similar run-off factors were applied, the results on HH and EQ would be influenced, primarily due to the low run-off percentage. Differences in the contribution analysis are expected (Fig. 6). Other methods assume the agricultural field as part of the technosphere (e.g. PestLCI) and argue that only a fraction of the applied dose is emitted to the environmental compartments (Dijkman et al. 2012). Such methods could lead to lower impacts on ecotoxicity and human toxicity by two orders of magnitude (Ometto et al. 2009).

In sugarcane production, impact categories that contribute significantly to ecosystem damage are land occupation, terrestrial ecotoxicity, acidification and nutrification (Fig. 6). Per kilogram of sugarcane, land occupation in Brazil is lower by 15 % compared to India whereas per kilogram of ethanol, land occupation contributes more in Brazil due to the direct use of sugarcane juice for ethanol production (2.2 m^2org.arable/$kg_{ethanolBR}$ compared to 1.6 m^2org.arable/$kg_{ethanolIN}$). Due to data availability, for India, we accounted only for harvested land for productive use and seed, while for Brazil, we accounted also for non-harvested land, which is typically 17 % of the total area.[10] The impacts of terrestrial ecotoxicity are associated with daconate. Figure 5 ('Best') shows that if daconate is eliminated then the impact on EQ is reduced by 20 % in India and by 14 % in Brazil. Remaining impacts on terrestrial ecotoxicity are associated with heavy metals (e.g. copper and zinc). Impacts on terrestrial acidification and nutrification are associated with NO_x emissions from bagasse use in co-generation facilities and pre-harvesting burning practices.

On EQ, due to the high contribution of the impact categories mentioned above, freshwater eutrophication does not appear to be significant. Nevertheless, this impact category is particularly important for freshwater quality. We calculate emissions of approximately 0.5 and 0.2 gPO_4 for Indian and Brazilian ethanol, respectively. If instead we assume a 10 % *P* surface run-off factor, which is considered characteristic for Brazilian soils (Ometto et al. 2009), the impact of eutrophication increases by approximately a factor 3 in both countries (1.5 $gPO_4/kg_{ethanolIN}$ and 0.6 $gPO_4/kg_{ethanolBR}$). Nevertheless, this hardly increases the impact on EQ (only by 1 % for Indian ethanol). On the other hand, stillage treatment is significant for the Indian production system (MoEF 2009b; Satyawali and Balakrishnan 2008). This study assumes that stillage is treated anaerobically followed by a secondary treatment (Tewari et al. 2007). However, if distilleries do not apply treatment methods and dispose the effluents directly on soils or water streams, then eutrophication increases by approximately 2 orders of magnitude, primarily due to a high phosphorus (soil disposal) and phosphorus and COD content (water disposal). The impact on EQ increases by 25 % and 35 % for disposal on soils and water, respectively. If anaerobic conditions prevail, methane releases increase the GHG emissions of Indian ethanol. Based on 5.52 $kgCO_{2eq}/kgBOD_{stillage}$ (Nguyen et al. 2010) and 36,500 $mgBOD/l_{stillage}$ (Satyawali and Balakrishnan 2008), the net GHG emissions range from 2.6 to 3.1 $kgCO_{2eq}/kg_{ethanolIN}$ depending on the approach (compared to 0.09 to 0.64 $kgCO_{2eq}/kg_{ethanolIN}$; Fig. 4). CH_4 emissions from stillage disposal account for 80 to 95 % of the total emissions.

[10] In 2008, non-harvested land was as high as 28 % primarily due to bad weather conditions. In that year, compared to Indian ethanol, Brazilian ethanol would show higher EQ by 45 %, instead of 30 % as shown in Fig. 6.

5.3 Net water consumption and contribution to human health and ecosystem quality

Inventory results of net water consumption in ethanol production (Table 7) are calculated on the basis of freshwater extracted for irrigation and process water consumed for ethanol production (excluding the release back to the environment). Water consumption in Indian ethanol production is significantly higher than in Brazil. This is primarily due to groundwater extraction for irrigation, which is as high as 68 l/kg_{caneIN} (Srivastava et al. 2009), while some studies report higher consumption (100 l/kg_{caneIN}; IISR 2011). In south-central Brazil, sugarcane production is based on rainwater (UNICA 2007). Irrigation also has an effect on GHG emissions of Indian ethanol due to energy requirements for groundwater

Table 7 Net water consumption of ethanol production in Uttar Pradesh, India and south-central Brazil, in litres per $kilogram_{ethanol}$

	Uttar Pradesh, India	South-central Brazil	Source
Reference case	543	28	Srivastava et al. (2009), UNICA (2007)
Lower estimate	361[a]	19.5[b]	IISR (2011), UNICA (2007)
Higher estimate	1,150[c]	–	Mekonnen and Hoekstra (2010)

[a] Water use efficiency in India seldom exceeds 35–45 %. Demonstrated water saving techniques (skip furrow irrigation, critical growth stage irrigation, trash mulching and ring-pit planting) can enhance water use efficiency by 1.5 to 2.5 times. This value corresponds to the ring-pit planting method, taking into account increase in yield (IISR 2011)

[b] Calculated from 1.23 m^3/t_{cane}. Excluding mills with the highest specific water consumption (8 % of the sample)

pumping. The lower estimate indicates net reduction of 0.07 (−8 %), 0.06 (−73 %) and 0.06 (−9 %) $kgCO_{2eq}/kg_{ethanolIN}$ for SE-C, SE-O and EA, respectively. The net increase for the highest estimate is 0.02 (8 %), 0.2 (240 %) and 0.19 $kgCO_{2eq}/kg_{ethanolIN}$ (29 %) for SE-C, SE-O and EA, respectively.

Large difference between Brazil and India is illustrated when considering impacts of water use on HH and EQ. Using the characterisation factors presented in Pfister et al. (2009), we estimate an increase of Indian ethanol on HH by 4 % and on EQ by 11 %, compared to results in Fig. 6 (see Supporting information). The lower estimate for irrigation water increases the impacts on HH and EQ by 3and 7 % while the higher estimate increases the impact by 9and 23 %, respectively. For south-central Brazil, no increase on HH and EQ is estimated since it is not a water-stressed region.

Groundwater use for irrigation in India poses a serious constraint especially when considering expansion for meeting sugar and ethanol demand. It is imperative to promote practices which improve irrigation water use and efficiency. However, even if improvements take place, expansion of a water-intensive crop such as sugarcane only partly alleviates pressure on groundwater. As Table 7 shows, lower estimates on water use based on efficient water practices in UP are a factor 20 higher than Brazil. A transition to more water-efficient, drought-resistant crops could be a viable strategy to increase ethanol production without compromising scarce water resources (e.g. sweet sorghum, perennial grasses produced on marginal or degraded lands, other feedstocks for second-generation biofuels).

6 Conclusions and recommendations

The environmental performance of the Indian product system relies on the sector's capacity to provide surplus electricity to the grid. The electricity demand covered by the sugarcane processing sector reduces the demand for electricity generation by the power sector, and the ethanol system is credited depending on whether it displaces local or national electricity. However, since not all Indian mills and distilleries produce surplus (46 % of the Indian sugarcane processing capacity is associated with surplus electricity), the environmental profiles of ethanol in individual facilities differs significantly. This demonstrates the importance for the sector to modernise and increase its co-generation capacity in order to cover its own electricity requirements by utilising renewable resources (bagasse) and to export electricity to the grid. Mills and distilleries which rely on grid electricity have significantly higher emissions and non-renewable energy use when compared to the sector average (Fig. 4). Unless individual distilleries treat stillage in a manner that does not induce anaerobic conditions (e.g. storage ponds), the GHG emission performance is heavily affected. From an environmental perspective, it is preferable to capture CH_4 and produce biogas for the system to benefit from reduced primary energy from other sources. When the system does not receive credits (EA), the environmental profile of Indian ethanol is similar to Brazilian ethanol. Although GHG emissions and NREU of Indian sugarcane production are higher than in Brazil, the impact of ethanol is comparable due to the characteristic of the Indian sector, which produces ethanol exclusively by molasses. Therefore, only part of the environmental impacts associated with sugarcane production and processing is allocated to ethanol. Our study confirms the findings of Hoefnagels et al. (2010), that allocation is key in determining results, and extends it to ethanol production from sugarcane in different world regions. We show that different choices in system expansion (SE-C, SE-O) also impact the results. The influence is greater for Indian compared to Brazilian ethanol. Economic allocation yields higher GHG emissions compared to system expansion approaches. This conclusion is in line with results of Renouf et al. (2011). However, this finding contradicts results of Nguyen and Hermansen (2012), who estimate that system expansion leads to higher emissions than economic allocation. The main difference is that in the attributional study of Renouf et al. (2011), ethanol production is assigned only impacts of the conversion of molasses to ethanol, while in the consequential approach of Nguyen and Hermansen (2012), ethanol additionally carries the impact of displaced feed production. In our study, molasses do not displace feed because there is a long tradition of using molasses for ethanol in India; in applying allocation, molasses received impacts from sugarcane production but also part of the credits for surplus electricity based on economic allocation. For attributional modelling, we find that economic allocation provides most consistent results, since it is uniformly applied across the system co-products. Nevertheless, we recommend presenting results for all allocation approaches. For consequential modelling, increased ethanol demand in India stimulated by the EBP holds the risk of displacing molasses use for feed and diverting ethanol from the potable liquor and chemical sectors. In this event, impacts of Indian ethanol will be associated with impacts of crop production for feed, ethanol production in exporting countries or domestic Indian ethanol production from other feedstocks. A consequential study should be performed to account for marginal increase in ethanol demand for transport in order to assess the environmental performance of different marginal suppliers, including domestic first and second generation ethanol production.

Production of N-fertilisers and oxidation of nitrogen increase GHG emissions, and the high application of P-fertilisers and stillage disposal to soil or water bodies increase freshwater eutrophication. It is recommended to focus efforts on reducing fertiliser inputs of Indian sugarcane cultivation (e.g. to levels similar to Brazil), while maintaining or increasing sugarcane productivity. With regard to HH and EQ, it is important to monitor the amount and types of chemicals used. This is also relevant for Brazilian sugarcane production where chemicals such as daconate—if applied—and burning practices lead to high impacts. This can be supported by establishing chains of custody which focus on agrochemicals. Due to data and methodological uncertainties absolute results using other types of pesticides differ. Given that impacts of Indian sugarcane production are allocated to estimate the environmental profiles of Indian ethanol, the relative difference with Brazilian ethanol is small across all impact categories. Furthermore, as increase in biomass production may lead to a wide array of land-use related impacts such as habitat degradation and loss of ecosystem services, efforts should focus on developing impact assessment methods that quantify and characterise impacts at a higher disaggregation level than the EQ indicator used in this study.

This study did not address efficiency improvements in the agricultural phase. Literature showed that increase of yields in Brazilian sugarcane production was key behind cost reduction that Brazilian ethanol production met over the last three decades (van den Wall Bake et al. 2009). Therefore, efficiency improvements on agricultural production and their effects on the environmental performance of ethanol are likely to demonstrate new improvement potentials for both the Indian and Brazilian system.

Groundwater irrigation was shown to determine water use, GHG emissions (associated with energy for pumping) and EQ of Indian ethanol. In India, groundwater use poses a serious resource constraint, and it is important to decouple expansion of ethanol production from water-intensive crops such as sugarcane. Ethanol production from water-efficient crops such as sweet sorghum or agricultural residues used for second-generation ethanol is a step required to alleviate the pressure from the depleting groundwater resources. For current production of sugarcane, water efficiency measures are needed.

Although data for Brazilian ethanol call for higher quality in specific parameters (e.g. types of pesticides), they are characterised by completeness and robustness when compared to Indian ethanol production data. It is recommended to improve the quality and coverage of the latter to levels similar to Brazilian ethanol. For sugarcane production, statistics for resource input (fertilisers and pesticides) should become available at high spatially explicit levels to assess regional variability. Data for animal and human labour are also important for a complete assessment. Improved datasets need to include the sector's bagasse flows. Reporting should include bagasse consumption and surplus per mill and attached distillery, inter-sectoral flows, intra-sectoral flows (e.g. paper industry) and losses. In addition, similar to reporting of fossil-fuel use, material flows should also be monitored if other biomass sources are used. Until bottom-up data become available, we recommend subdividing the sector to account for energy recovery from distilleries in order to assign appropriate credits to ethanol. Due to regional variability of important parameters such as sugarcane productivity, mechanisation and irrigation, it is recommended that future studies assess the environmental performance of Indian ethanol at the national level, including effects of direct and indirect land use change.

Overall, it can be concluded that the Indian government's plan on introducing biofuels to the market does not cause higher environmental impacts than those of other sugarcane ethanol-production chains. However, this conclusion is limited to the production in UP. Also, the low yields, their dependency on groundwater irrigation, the constrained ethanol production based on sugarcane molasses and potential displacement effects, the high input of agrochemicals and the current electricity of sugar mills indicate unexploited opportunities for global players, governments and other stakeholders to support implementation of better practices and improve the GHG emission, NREU, HH and EQ performance of Indian ethanol production.

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