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Life cycle assessment of Australian sugarcane products with a focus on cane processing

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Abstract
Purpose This work generates attributional life cycle assessment (LCA) results for products produced from Australian sugarcane—raw sugar, molasses, electricity (from bagasse combustion), and ethanol (from molasses). It focuses on cane processing in sugar mills and is a companion to the work presented in (Renouf et al. 2010), where the focus is on cane growing. This work also examines the preferred approach for assigning impacts to the multiple products from cane processing, and the influence that variability in cane growing has on the results.
Method Initially, global warming potentials were generated for a range of cane processing models, using economic allocation (EA), mass allocation (MA), and system expansion (SE). A preferred approach was identified and applied to generate results for a wider set of impact categories based on the Impact 2002+ method. Uncertainty in the results due to cane-growing variability was assessed using Monte Carlo analysis and compared with the results for substitute products to determine the significance of the variability.
Results While the generation of results using SE was appealing for assessing the determining product (raw sugar), it was found to be less valid for the co-products (molasses, electricity, and ethanol). Results could be generated more consistently across all products using allocation. MA was found to be best suited to sugarcane products, whereas EA posed some problems. The uncertainty due to variability in sugarcane growing was found to be significantly higher than that of substitute products.
Conclusions and recommendations LCA results for sugarcane products are influenced by (1) the nature of cane processing system, (2) variability in sugarcane growing, and (3) the approach taken for assigning impacts to the multiple products from sugarcane processing. The first two factors imply that results should be specific to the cane-growing region and the cane processing used to produce them. In relation to the latter issue, for generating attributional LCA results that are consistent across all sugarcane products, the recommended approach is to use mass allocation (with energy allocation for bagasse combustion and cogeneration).

Keywords Allocation · Electricity · Ethanol · Molasses · Sugar · System expansion · Variability

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1 Background, aim, and scope

The traditional function of sugarcane has been for producing sugar for human consumption. However it has also long been recognized as a producer of other energy and material products (Paturau 1989; Manohar Rao 1997). Sugar (sucrose), the dominant product, is crystallized from the cane juice that is extracted from cane when it is crushed. The remaining fiber (bagasse) is commonly combusted in mill boilers to produce steam and electricity for use in the sugar mill. If the bagasse is used efficiently, there can be surplus available for electricity generation. Ethanol can be produced by fermenting sucrose from the cane; either that contained in the cane juice, as is the common model in Brazil, or the residual fermentable sugars contained in molasses, a by-product of sugar manufacture, which is the case in Australia.

This work is concerned with the application of life cycle assessment (LCA) to quantify the environmental impacts of sugarcane products. In Australia, electricity generated from surplus bagasse and ethanol produced from molasses are becoming important products for the sugar industry as non-renewable energy sources which can contribute to meeting Australia's greenhouse gas (GHG) mitigation targets. Consequently, there is an interest in understanding the environmental performance of these products relative to the fossil-fuel products they substitute. In addition, a growing interest in the environmental impacts of food production in Australia has meant a need for LCA data for sugar and molasses, the former being a key ingredient in many food products, and the latter being an input into livestock feed formulations. Therefore, the primary aim of this work was to generate LCA results for Australian sugarcane products—raw sugar, molasses (used as an animal feed), electricity (from combustion of surplus bagasse), and anhydrous fuel ethanol (from molasses fermentation).

The LCA results presented are intended to be attributional, meaning that they represent the impacts of existing Australian sugarcane products (i.e., the status quo). A comprehensive LCA for Australian sugarcane production (up to the delivery of harvested cane to the sugar mill) is reported in the companion paper (Renouf et al. 2010), which has a focus on cane growing. In this current paper, the system boundary is expanded to the final products from Australian sugar mills, and has a focus on cane processing.

The recognition of sugarcane as an efficient source of renewable bioenergy and biofuels (Miller et al. 2007; von Blottnitz and Curran 2007) has lead to a growing body of published LCA studies of sugarcane products, which are summarized in Table 1. Only those that quantify the impacts of sugarcane products (either per unit of product or per unit of function that the products deliver) are listed, as this is the LCA application of interest in this work. However, other studies have examined the sugarcane system rather than the products to evaluate production alternatives (Beeharry 2001; Kadam 2002; Botha and von Blottnitz 2006; Macedo et al. 2008; Contreras 2009) or to compare with other production systems (Smeets et al. 2009). Ethanol has been assessed the most, in particular ethanol produced directly from cane juice, as undertaken in Brazil (Wang et al. 2008; Luo et al. 2009a; Ometto et al. 2009; Hoefnagels et al. 2010). Ethanol from molasses has also been assessed based on production in Thailand (Nguyen and Gheewala 2008; Silalertruksa and Gheewala 2009), Nepal (Khatiwada and Silveira 2009), Brazil (Gopal and Kammen 2009), and Australia (Beer et al. 2000). The purpose of past ethanol studies has commonly been to compare it with petroleum fuel or other biofuels, but also for assessing alternative production routes.

Interestingly, there have been few published studies reporting LCA results for the more traditional and wide-

Table 1 Past LCA studies of sugarcane products

Product	Region	Purpose	Functional unit (reference flow)	Reference
Raw sugar	Australia	Identifying hot spots and improvements	Raw sugar at mill (t)	(Renouf 2006)
	Mauritius	Identifying hot spots and improvements	Raw sugar exported (t)	(Ramjeawon 2004)
Electricity	Mauritius	Identifying hot spots and improvements	Electricity exported (GWh)	(Ramjeawon 2008)
Ethanol (cane juice)	Brazil	Identifying hot spots and improvements	Ethanol use in car (km)	(Ometto et al. 2009)
	Brazil	Inventory data (using the GREET[a] model)		(Wang et al. 2008)
	Brazil	Comparing alternative production routes	Ethanol use in car (km)	(Luo et al. 2009a)
	Brazil	Comparing a range of biofuels	Ethanol at distributor (MJ)	(Hoefnagels et al. 2010)
Ethanol (bagasse)	Brazil	Comparing alternative production routes	Ethanol use in car (km)	(Luo et al. 2009a)
Ethanol (molasses)	Australia	Comparing biofuels with petroleum fuels	Fuel using heavy vehicles (km)	(Beer et al. 2000)
	Brazil	Inventory data (using the GREET[a] model)	Ethanol at distributor (MJ)	(Gopal and Kammen 2009)
	Thailand	Comparing ethanol with petroleum fuels	Ethanol at distillery (L)	(Nguyen and Gheewala 2008)
	Thailand	Comparing ethanol from molasses and cassava	Ethanol at distillery (L)	(Silalertruksa and Gheewala 2009)
	Nepal	Calculating energy yield ratio	Ethanol at distillery (L)	(Khatiwada and Silveira 2009)

[a] *GREET* Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model developed by Argonne National Laboratory

spread products from sugarcane—sugar, molasses and electricity. Also, few studies have considered the methodological aspects that influence results for sugarcane systems. An exception is the work by Hoefnagels et al. (2010), who assessed the impacts of methodology choice on biofuels, including ethanol from sugarcane in Brazil. An additional aim of this work was to consider some of the methodological aspects that influence results for the broader range of sugarcane products.

Co-production of multiple products is a feature of sugarcane processing. The approach taken to apportioning impacts influences results, as shown by Hoefnagels et al. (2010), Kaufman et al. (2010) and Luo et al. (2009b) for biofuels, and by Thomassen et al. (2008) and Ekvall and Andrae (2006) for other production systems. In attributional LCA, the most common approach has been allocation, where impacts are split between the multiple products based on physical or economic ratios. However, system expansion (SE) has also been used as an attributional approach, including in biofuel studies (Hoefnagels et al. 2010; Kaufman et al. 2010; Luo et al. 2009b). SE was proposed initially to avoid allocation (Ekvall and Weidema 2004) and is in essence is a consequential approach to dealing with co-production, whereby its impact reflect the marginal changes associate with increased demand for the product. However its use in the attributional characterization of impacts has been described by Kaufman et al. (2010) as a hybrid approach, where “consequential SE is applied to co-product production…in an otherwise attributional LCA”. In this current work, SE will be considered as a one means of apportioning impacts in sugarcane processing, along with economic allocation (EA) and mass allocation (MA).

The other aspect examined is the influence of variability in cane growing on the results for sugarcane products. The assessment of the cane-growing phase in Renouf et al. (2010) characterized variability in impacts due to different regional conditions and found it to be significant. Smeets et al. (2009) also identified considerable uncertainty in the GHG emissions for ethanol from sugarcane, in relation to nitrous oxide emissions in cane growing. The known variability for Australian cane growing was carried forward into this work to see how it influences the results for the end products of sugarcane processing.

In summary, this work has three objectives:

- to examine the influence that the approach for assigning impacts to multiple products has on the results for a range of sugarcane products under different cane processing models, and to suggest a preferred approach;
- to generate life cycle impact assessment (LCIA) results for Australian sugarcane products based on the preferred approach; and
- to examine the influence of variability in Australian cane growing on the LCA results for end products.

2 Method

2.1 System description

The analysis was based on sugar mills in the state of Queensland, which account for around 98% of national production, and so can be taken to represent Australian production in general. All of the existing 23 sugar mills in Australia produce raw sugar as the primary product, but with co-production of molasses, ethanol (from molasses), and electricity to various degrees. In this work, a co-product is regarded as a product that has a value, i.e., provides an economic income. The following three models of cane processing were considered based on the most common sugar-milling practices in place during the study period (2004–2008). The products from each of the models are summarized in Table 2 and the quantities of products generated from each model are detailed in Table 3.

Model 1: *Conventional sugar mill.* A sugar mill producing only raw sugar and C-grade molasses, with the latter being used in animal feed formulations. All of the fibrous residue from the sugarcane (bagasse) is burnt in mill boilers to produce steam and electricity solely to operate the mill.

Model 2: *Upgraded sugar mill with cogeneration.* A sugar mill (as for 1) but with upgraded boiler

Table 2 Summary of products from Australian sugar mills under different cane processing models

Processing model	Primary product	Co-products			By-products
Model 1	Raw sugar	Molasses (animal feed)			Mill mud and boiler ash
Model 2	Raw sugar	Molasses (animal feed)	Electricity (from surplus bagasse)		Mill mud and boiler ash
Model 3	Raw sugar	Ethanol (from molasses)	Electricity (from surplus bagasse)	Dunder	Mill mud and boiler ash

Table 3 Quantities of products from each cane processing model (from 100 t sugarcane), including allocation factors (for MA and EA) and displaced products (for SE)

		Unit	Cane processing models		
			1	2	3
Flows of bagasse within sugar mill					
	Bagasse to mill boiler[a]	t	28.0	17.0	17.0
	Surplus bagasse to cogeneration[a]	t	–	11.0	11.0
Quantities of products					
Sugar mill	Raw sugar[b]	t	14.3	14.3	14.3
	Molasses (to animal feed)[b]	t	2.8	2.8	–
	Molasses (to ethanol)[b]	t	–	–	2.8
	Electricity export[a]	MWh	–	4.6	4.2
	Electricity to ethanol[a]	MWh	–	–	0.2
	LP steam to ethanol[a]	GJ	–	–	10.0
Ethanol plant	Ethanol[c]	L	–	–	755
	Dunder[c]	m^3	–	–	3.0
Mass allocation factors					
Sugar mill	Raw sugar[d]	%	94.9	80.3	76.8
	Molasses[d]	%	5.1	5.1	6.3
	Electricity[d]	%	–	14.6	13.7
	LP Steam[d]	%	–	–	3.3
Ethanol plant	Ethanol[e]	%	–	–	56.0
	Dunder[e]	%	–	–	44.0
Economic allocation factors					
Sugar mill	Raw sugar[f]	%	96.0	89.0	87.7
	Molasses[f]	%	4.0	3.8	3.7
	Electricity[f]	%	–	7.2	6.6
	LP Steam[f]	%	–	–	2.0
Ethanol plant	Ethanol[g]	%	–	–	94.0
	Dunder[g]	%	–	–	6.0
Displaced products (for system expansion)					
Sugar mill	Sorghum[h]	t	1.2	1.2	–
	Electricity (coal)[i]	MWh	0.0	4.6	4.4
	LP steam—natural gas[j]	GJ	–	–	10.0
Ethanol plant	Potassium chloride[k]	kg	–	–	15.0

Assumptions and data sources:

[a] Based on energy balance modeling by Sugar Research and Innovation at Queensland University of Technology (unpublished data).

[b] Based on industry average averages (Anon 2006).

[c] Industry data for anhydrous ethanol production using conventional Praj and Dedini technologies (unpublished data), with assumed yields of 254 L/t molasses (Lavarack 2003).

[d] Based on mass of cane constituents directed to each product (not including water and wastes). For raw sugar, 50% of cane dry weight is sucrose, however some bagasse is also directed to sugar production as energy.

[e] Based on mass of molasses constituents directed to the product (not including water and wastes).

[f] Based on average economic values (2004–2008): raw sugar A$400/t (ABARE 2004–2008), molasses A$85/t (pers. comm. industry reps.), electricity A$100/MWh, which includes the value of Renewable Energy Certificates (pers. comm. industry reps.), and LP steam A$10/t (Lavarack et al. 2005).

[g] Based on average economic values (2004–2008): ethanol A$1.00/L (ABARE 2004–2008), dunder A$20/$m^3$ (pers. comm. industry reps.).

[h] Use of molasses in animal feed formulations is assumed to substitute sorghum feed grain (0.83 kg sorghum/kg molasses)

[i] Bagasse electricity is assumed to substitute electricity generated from Queensland black coal (1:1).

[j] Bagasse-derived steam is assumed to substitute natural gas-derived steam (1:1).

[k] Dunder, used as a soil conditioner, is assumed to substitute potassium chloride (KCl) due to its useful potassium content (5.69 kg KCl/m^3 dunder).

efficiency and cogeneration capacity, so that electricity can be exported to the grid from the combustion of surplus bagasse.

Model 3: *Upgraded sugar mill with cogeneration and ethanol production from molasses.* A sugar mill (as for 2) with a colocated distillery producing fuel ethanol from fermentation of molasses, and dunder (stillage) as a co-product.

For a description of the initial growing, harvesting transport of sugarcane up to the sugar mill, the reader is referred to Renouf et al. (2010). What follows focuses on the processing of cane in Australian sugar mills. Cane is first crushed to separate the sucrose-containing juice from the fiber (bagasse). The cane juice is purified, concentrated and crystallized to produce raw sugar. There are very few external inputs to the milling process as the energy derived from the combustion of bagasse and the water recovered from the evaporation of the cane juice usually meet all the energy and process water needs of the mills. Small amounts of fossil fuels (usually coal) may be used for boiler start-up, however this was not included. Other inputs are minor quantities of process chemicals used in juice clarification and ancillary operations (boilers, cooling towers, waste-water treatment etc.), the quantities of which are detailed in Table 4. Molasses is a co-product of sugar production which contains the residual sugars that cannot be further recovered. The grade of molasses referred to here is C-grade molasses. It is either used in animal feed formulations in model 1 and 2, or fermented to produce ethanol in model 3. The fermentation of molasses, which commonly occurs at a plant colocated with the mill, is assumed to be based on conventional technologies, and utilizes steam and electricity provided by the mill. Fermentation generates dunder as a co-product which is applied to cane fields. Since it contains useful quantities of potassium and attracts an income it is regarded as a co-product. In models 2 and 3, surplus bagasse (in excess to that required for mill operations and any downstream fermentation) is available due to improved efficiencies in the mill, and is used to generate electricity exported to the state grid. Mill mud and boiler ash are the inorganic residues remaining after juice clarification and bagasse combustion, respectively, and are applied back to cane fields. While they make a small contribution to soil fertility, they rarely displace fertilizer use in practice and have no economic value, thus are considered by-products rather than co-products.

The system boundaries included all processes from sugarcane growing through to the processing of final products, including background processes associated with inputs to sugarcane growing and milling (agrochemicals, fuel, electricity, transport, and process chemicals), on-farm capital goods, waste management, and disposal. The capital

Table 4 Production inputs and outputs for sugarcane milling, bagasse combustion and ethanol fermentation. Inputs of bagasse fuel into milling and fermentation not shown (refer instead to Table 3)

	Unit	
Sugar milling (per 100 t cane)		
Inputs		
Flocculant[a]	kg	0.012
Lime (calcined)[a]	kg	50.0
Phosphoric acid[a]	kg	4.0
Lubricant[a]	kg	0.5
Outputs		
COD (in wastewater)[b]	kg	23.0
Mill mud	kg	5.2
Transport/spreading of mill mud[c]	tkm	52.0
Bagasse combustion (per ton bagasse)		
Inputs		
Bagasse (8.7 GJ/t—LHV)	t	1.0
Outputs		
Methane[d]	g	85.6
Nitrous oxide[d]	g	37.7
Carbon monoxide[d]	kg	15.0
Sulfur dioxide[e]	g	300
Particulate (PM10)[e]	g	480
Ash	kg	25.0
Transport/spreading of ash[c]	tkm	250
Ethanol fermentation (per ton sucrose)		
Inputs		
Diammonium Phosphate (P)[f]	kg	1.0
Urea (N)[f]	kg	1.1
Nitric acid[f]	kg	0.4
Caustic soda[f]	kg	0.7
Sulfuric acid[f]	kg	1.5
Outputs		
Dunder[f]	m^3	1.5
Transport/spreading of dunder[c]	tkm	180

Data sources and assumptions:

[a] Consultation with production engineers at Queensland sugar mills.

[b] A best-estimate of average COD loads in wastewater discharged from Queensland sugar mills from Queensland Environmental Protection Agency's licensing data.

[c] Based on transportation to cane fields over a best-estimate average distance of 10 km.

[d] Emission factors derived from National Greenhouse Gas Inventory Committee (2007).

[e] Derived from measured air emissions reported in the National Pollutant Inventory (DEWHA 2008).

[f] Based on industry data for the production of anhydrous ethanol using conventional technologies (unpublished data).

goods of the sugar mill, ethanol plant, and cogeneration plant have not been included in the system boundary, as the large throughput and long lifetime make the impacts of their establishment and decommissioning per unit of product insignificant. The functional unit for each product assessed is its production up to the mill gate prior to distribution, based on the following reference flows:

Raw sugar	1 t raw sugar
Molasses	1 t molasses
Electricity	1 kWh electricity
Ethanol	1 MJ anhydrous fuel ethanol

2.2 Data sources

Data for the environmental exchanges occurring in sugarcane growing are described in Renouf et al. (2010), which represents state average figures for Queensland cane growing, as well as minimum and maximum conditions to test the influence of variability. Data for sugarcane processing is based on processes considered representative of Queensland sugar mills, derived through industry consultation. The most important aspects of cane processing that influences the results are the flows of bagasse to boilers and flows steam and electricity to the mill and downstream processes as they influence the amount of surplus electricity that can be generated. These were estimated by engineers from Sugar Research and Innovation at Queensland University of Technology by modeling typical mill conditions (unpublished data), and are detailed in Table 3. Data for other inputs and outputs associated with milling, bagasse combustion, and ethanol fermentation are detailed in Table 4. Background data for production of inputs was sourced from the Australian Life Cycle Inventory Database (Life Cycle Strategies 2007), or the ecoinvent database (Swiss Centre for Life Cycle Inventories 2009) where Australian data were not available. The inputs to milling, cogeneration and fermentation did not influence the results at the screening stage so variability associated with these aspects was not considered and the analyses are based on average figures only.

2.3 Generation of GWP results using allocation and systems expansion

Global warming potential (GWP) results were initially generated for each of the sugarcane products using MA, EA, and SE to show the influence that choice of method has on the results. GWP was characterized using factors from the International Panel on Climate Change for a 100 year time horizon (IPCC 2003). The results were evaluated to identify a preferred approach for representing the impacts of sugarcane products.

2.3.1 Allocation

Figure 1 shows the system diagrams for each of the cane-processing models using allocation, indicating the point at which impacts are allocated to multiple products. Processes occurring in the sugar mill was considered to be a single unit operation, as they are highly integrated around the use of steam and electricity from the combustion of bagasse in the mill boiler (Fig. 1a). The boundary of the sugar-milling process was drawn at the production of raw sugar and molasses. Where cogeneration is part of the processing model (in models 2 and 3), it was deemed to be part of sugar-milling process as they are also highly interdependent. In this situation, the boundary was extended to also include the production of surplus electricity (Fig. 1b). If cogeneration were to be regarded as a separate process, surplus bagasse would be a product from sugar milling. This was not considered appropriate since the use of bagasse is limited to sugar mills, and consequently it is not a traded commodity.

The fermentation of molasses to produce ethanol (Fig. 1c) is commonly integrated with sugar mills to take advantage of the supply of steam and power from the mill. It may seem appropriate therefore to model the ethanol plant as part of the sugar-milling process, so that they form a single biorefinery system. This would make the assessment is more straight forward as it avoids the need to allocate impacts to the intermediate products (the LP steam and electricity that are supplied from the mill to the ethanol plant). Such an approach has been taken in past studies of biorefineries and timber sawmills (Jungmeier et al. 2002; Cherubini and Jungmeier 2010). However sugar milling and molasses fermentation are not interdependent and molasses is a product in its own right with a market value that can be sold on to other facilities. Therefore the ethanol plant should be considered a separate unit operation (as shown in Fig. 1c). It is also more accurate to treat the ethanol plant as a separate process so that only the impacts assigned to the molasses and the steam and electricity used in fermentation carry through to ethanol. This approach also helps in situations where ethanol distilleries source molasses from multiple mills.

Impacts were allocated to the multiple products both on an economic and mass basis. The allocation factors derived for each processing model are detailed in Table 3. Economic allocation factors were based on the proportion that each product contributes to the total economic value of all products, using average economic values over the study period (2004–2008). Mass allocation factors were based on the mass of sugarcane constituents directed to each product. This involved tracing the flow of sucrose and bagasse (but

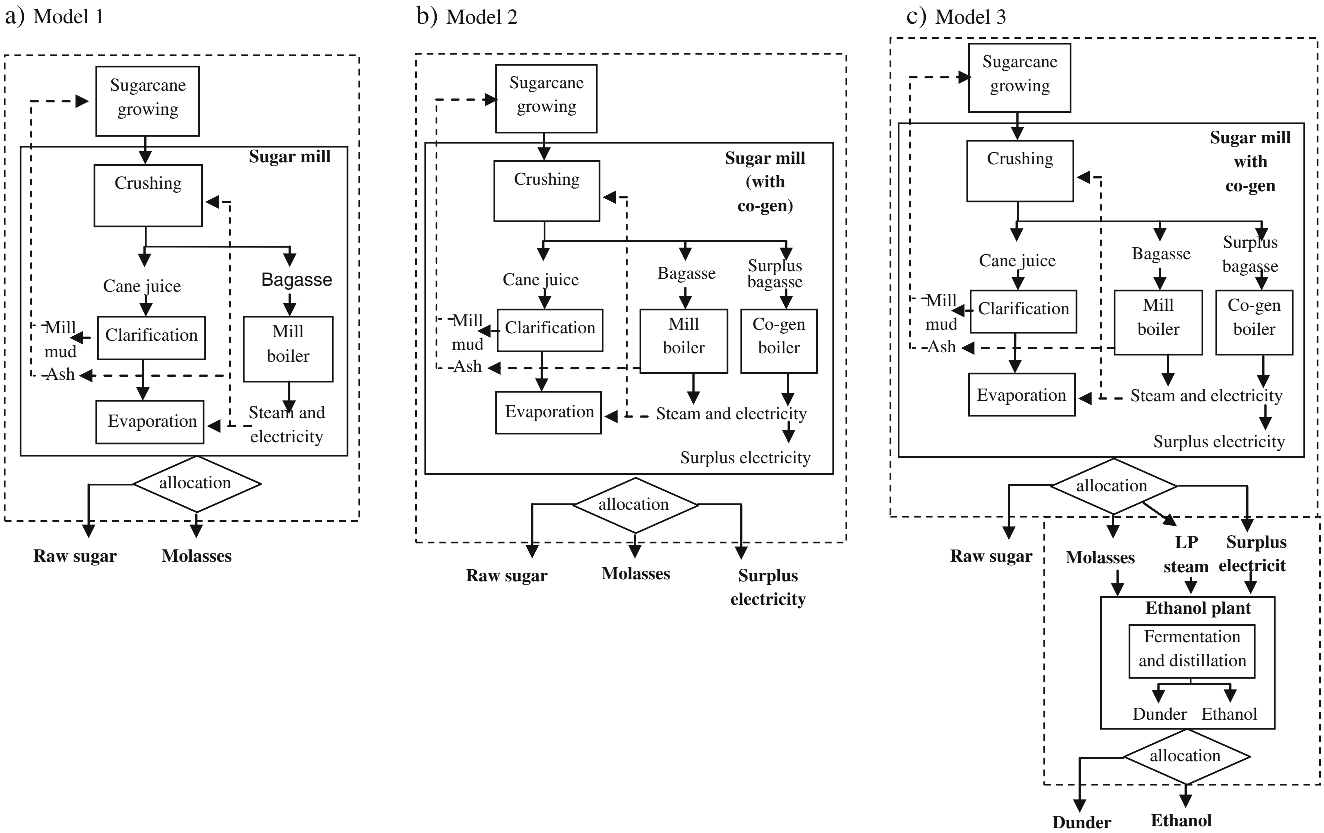

Fig. 1 System diagrams for sugarcane products from different cane processing models, based on allocation. System boundaries indicated by *dashed outlines*

not water and wastes) through the milling process to determine the quantities directed to each product. When bagasse is used as combustion to generate of steam and electricity, it was not straightforward to apportion the mass of bagasse between the steam and the electricity. Instead this was done based on the primary energy contents of the resulting electricity and steam (70% to electricity and 30% to LP steam).

2.3.2 System expansion

Figure 2 shows the system diagrams for each of the cane-processing models based on SE. For the sugar mill, all the impacts of cane processing (and the upstream cane growing) are assigned to the determining product, raw sugar. The system boundary is expanded to account for the products displaced by co-products, indicated by the shaded boxes in Fig. 2a–c. Molasses, when used in animal feed formulation, is assumed to displace grain sorghum. In the first instance, molasses would substitute low-grade crop residues, but the supply chain would eventually be supplemented with grain sorghum, as the most common feed grain crop grown in Queensland (verified by fodder industry contacts). Displacement of feed grain is assumed to occur for only 40% of molasses use; which is used in fattening and holding applications. In its applications as an attractant and carrier for additives, displacement is assumed not to occur. Based on this and relative calorific values of molasses and sorghum, the substitution factor was estimated to be 0.83 kg sorghum/kg molasses. Electricity, when exported to the state electricity grid or supplied to the ethanol plant, is assumed to displace electricity generated from Queensland black coal (1:1). Steam, when supplied from the mill to the ethanol plant (in model 3) is assumed to displace steam production from natural gas (1:1). For the ethanol plant, ethanol is the determining product and all impacts are assigned to ethanol. The co-produced dunder, when used as a soil conditioner, is assumed to displace potassium chloride (KCl) due to its useful potassium content (5.69 kgKCl/m^3 dunder).

The avoided impacts associated with the decreased production of the displaced products are credited to the determining product (raw sugar or ethanol), and the quantities assumed to be displaced are detailed in Table 3. Life cycle inventory data for the displaced coal-derived electricity was sourced from Australian Unit Process LCI Library (Life Cycle Strategies 2007), and data for the displaced sorghum production was sourced from QDPIF (nd).

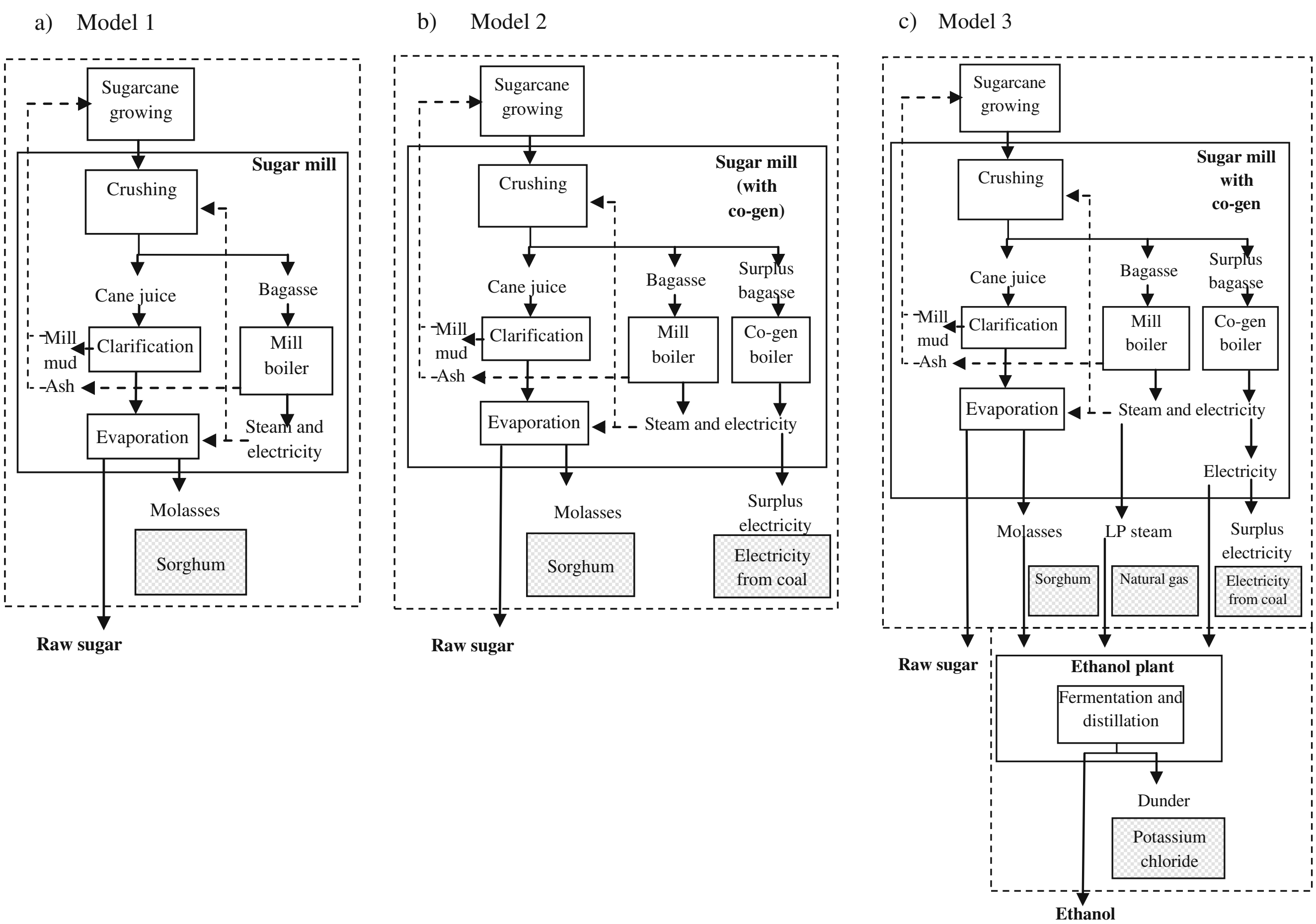

Fig. 2 System diagrams for sugarcane products from different cane processing models, based on system expansion. System boundaries are indicated by the dashed outlines, which have been expanded to include the avoided production of product displaced by co-products (in *shaded boxes*)

The above method enables the characterization of impacts for the determining products (raw sugar and ethanol). However characterizing the impacts of the co-products using SE is less obvious, and has not been clearly described previously. Beer et al. (2000) and Renouf (2006) in their previous assessments of ethanol from molasses considered the impacts of the molasses to be the impacts of substituting the molasses when it is directed away from animal feed to ethanol production, i.e., the additional production of a proxy feed grain. This is a consequential approach, as system expansion was originally intended to be. However it is concerned with the changes associated with an increased production of ethanol, which is different to assessing the status quo of existing ethanol production in an attributional fashion. Instead, applying SE attributionally would imply that no impacts are assigned to the co-products. The substitution effects have already been credited to the determining product so they cannot be assigned to the co-products. This is the approach that has been taken in this work. So when molasses, electricity and steam from the sugar mill are used for ethanol production (see Fig. 2c), they carry forward no embodied impacts, and the impacts of ethanol would be only those associated with the ethanol plant operations.

2.4 Life cycle impact assessment

The preferred allocation approach derived from the above analysis was applied to characterize the wider impacts of the sugarcane products. The impact categories assessed were those found to be significant for the assessment of the sugarcane production phase reported in Renouf et al. (2010) —water use, land use, non-renewable energy (NRE), global warming potential (GWP), terrestrial and aquatic acidification potential (AP(ter) and AP(eq)), eutrophication potential (EP), respiratory inorganics (RI), and respiratory organics (RO). Impact assessment methods were based on Impact 2002+ model (Jolliet et al. 2003) using Simapro (V7.1) LCA software, but with the following modifications:

- Global-warming potential was characterized using factors from the International Panel on Climate Change for a 100-year time horizon (IPCC 2003).

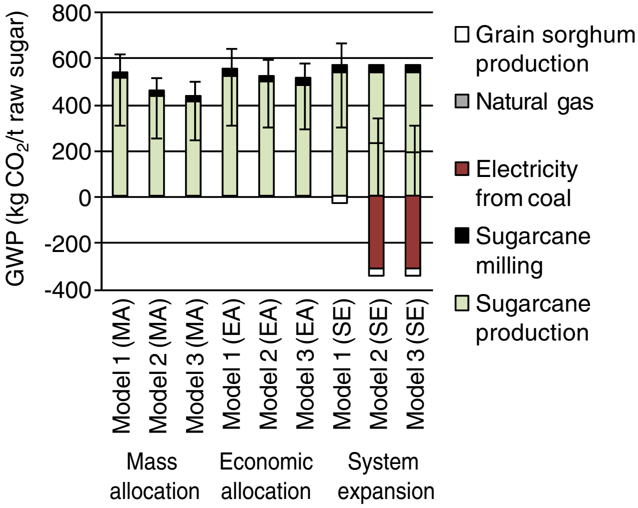

Fig. 3 GWP for raw sugar (per ton) from processing models 1–3 under different allocation approaches, and including ranges due to variability in cane growing

- Eutrophication potential was characterized assuming that receiving waters are limited by both N and P, due to the lack of information about the eutrophication susceptibility of Australian receiving waters.
- Land use was assessed using a basic indicator of land occupied, not land transformation.
- Water use was assessed using a basic indicator of water consumption.

Results have not been reported for human- and eco-toxicity impacts due to lack of confidence in the inventory data for pesticide losses from sugarcane fields and impact assessment methods available, as described in Renouf et al. (2010).

2.5 Influence of cane-growing variability on results for sugarcane products

The influence of cane-growing variability on the results was assessed by undertaking an uncertainty analysis of the GWP results using the minimum and maximum figures for cane-growing parameters reported in Renouf et al. (2010; see Tables 1 and 2). The variability present in Australian cane growing which influences GWP is mostly due to regional differences in nitrous oxide (N_2O) loss from denitrification of applied nitrogen fertilizers, and the energy intensity irrigation. Uncertainties were generated using the Monte Carlo function within Simapro (V7.1) over 500 runs to generate results falling within the 95% confidence limits. To assess the significance of the variability, the resulting uncertainty for the sugarcane products were compared with equivalent results for the products they substitute in Australia. Molasses was compared with grain sorghum grown in Queensland as a proxy grain crop that would substitute molasses in animal feed and ethanol feedstock applications. Electricity from bagasse was compared with electricity from Queensland black coal, natural gas, and wind. Ethanol was compared with unleaded petrol based on its fuel energy content (per MJ), but also based on its use in passenger vehicles as an 85% blend with unleaded petrol—E85 (per 100-km car travel). As there is no direct substitute product for sugar no comparison was made.

3 Results and discussion

3.1 Influence of different methods for assigning impacts

Figures 3, 4, 5, and 6 present the GWP results for the products from each cane processing model, based on the different methods for assigning impacts.

The allocation results for sugar (in Fig. 3) are influenced by the cane-processing model employed to produce the sugar. As more co-products are produced from the cane, the impacts allocated to sugar decrease. The MA and EA results are very similar for raw sugar produced under model 1 (where there is limited co-production), since the percentage allocations to sugar are heavily weighted towards raw sugar in either method (95% and 96%). However in processing models with greater co-production (models 2 and 3), the MA and EA results differ, with EA results being higher than MA results for sugar.

For the co-products—molasses (see Fig. 4), electricity (see Fig. 5), and ethanol from molasses (see Fig. 6)—the

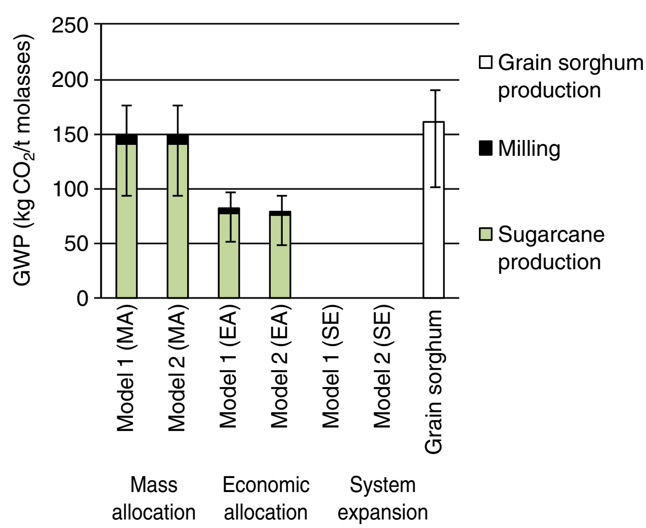

Fig. 4 GWP for molasses (per ton) from processing models 1 and 2, under different allocation approaches, and including ranges due to variability in cane growing

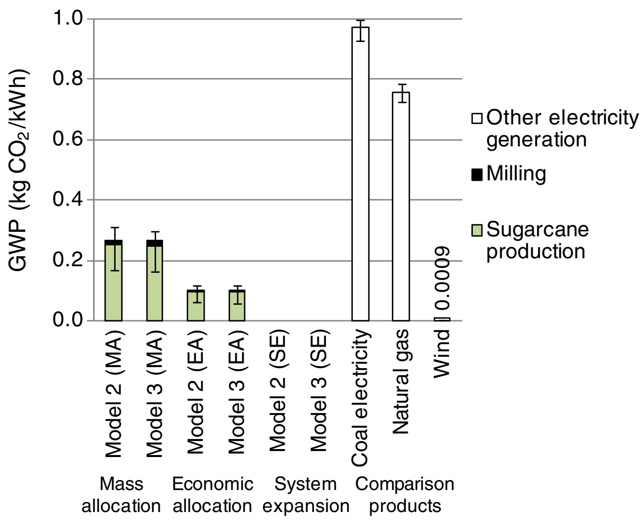

Fig. 5 GWP for electricity (per kWh) from processing models 2–4, under different allocation approaches, and including ranges due to variability in cane growing

GWP results are higher for MA than for EA since the mass contributions of bagasse and molasses toward that total mass of cane is higher than their economic contributions to the total value of the cane. In relation to the SE results, sugar was the only product for which SE could be confidently applied, as it is the determining product. For raw sugar produced under model 1 where there is limited co-production, the GWP results based on SE (in Fig. 3) are very similar to the allocation results. Where electricity is co-produced (in models 2 and 3), the avoided impacts of displaced coal-derived electricity credited to sugar are very significant, making the SE results considerably lower than the allocation results. This is consistent with the findings of Hoefnagels et al. (2010), who compared SE and allocation results for ethanol produced in Brazil, where ethanol is the determining product from sugarcane processing. SE was applied with less confidence to the co-products, due to the uncertainty in the mechanism for characterizing the impacts of the co-production using SE discussed in Section 2.3.2. The SE results for molasses (see Fig. 4) and electricity (see Fig. 5), show zero GWP due to the assumption that no impacts are assigned to the co-products. The SE results for ethanol (see Fig. 6) reflect only the impacts of ethanol plant operations.

3.2 Preferred approach for assigning impacts

SE is appealing for determining the product (sugar) because it considers the impacts occurring outside the sugarcane system in relation to co-product utilization, and thereby could be regarded to give a truer reflection of impacts. However, it is problematic for co-products and their derivatives. These benefits and limitations of SE have also been noted by Hoefnagels et al. (2010). Another limitation of SE for sugarcane products is that it relies on the determining product being clearly defined. Currently, sugarcane production is driven by demand for sugar (in

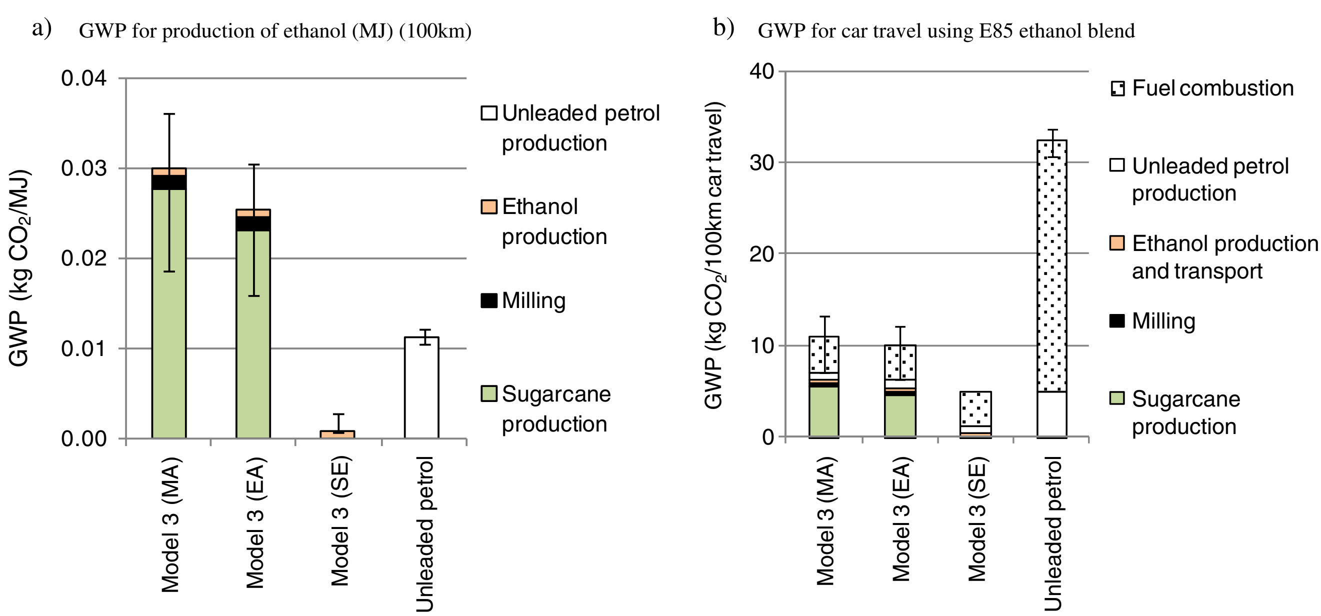

Fig. 6 GWP for (**a**) ethanol production (MJ) and (**b**) car travel using an E85 ethanol blend (100 km), based on ethanol produced from processing model 3, under different methods for assigning impacts, and including ranges due to variability in cane growing

the case of Australia) or for ethanol (in the case of Brazil), and so a single determining product can usually be identified. However with the growing interest in renewable energy products from sugarcane, future sugarcane production may be driven by concomitant demand for its multiple products. In such cases, a single determining product may be difficult to identify, making SE less useful.

Allocation can be applied more consistently across all of the sugarcane products—both the principal products and the co-products. Mass allocation is well suited to sugarcane products. The milling of sugarcane fractionates the cane into its constituent parts, with little left unutilized and few other inputs. So it is straightforward to assign impacts based on the mass proportion of constituents directed to each product, and can provide an adequate representation of the underlying physical relationships between the products, as required by the ISO Standard for LCA (International Standards Organisation 2006). Economic allocation poses some problems for sugarcane products. It is already prone to fluctuating prices, which for sugar products are very volatile. The recommendation made above to partition the downstream processing of milling co-products as separate unit operations means that economic values need to be defined for the intermediate thermal energy products from mills (LP steam, etc.), which is also problematic. Moreover, with the range of products derived from sugarcane biorefineries expected to expand, the partitioning of impacts based on economic returns will vary considerably depending on the range of products and their individual values. So overall, economic allocation is more prone to discrepancies and gives a weaker representation of the underlying physical relationships between the products.

The authors' preferred approach for attributional LCA of sugarcane products is to use MA combined with energy allocation for the energy products from bagasse combustion and cogeneration.

3.3 LCIA results based on preferred approach

Table 5 presents the LCIA results for the significant impact categories, using the preferred approach derived above. For molasses and bagasse-derived electricity only the results for model 2 are shown, as the MA results generated for the other processing models were very similar.

3.4 Influence of cane-growing variability

The variability due to different cane-growing practices for each product is depicted by the error bars in Figs. 3, 4, 5, and 6. It is as large as or larger than the variability due to allocation approaches. So it is a factor that also needs to be considered carefully when reporting LCA results. The overall potential for uncertainty in the results for sugarcane products is much larger than the uncertainty for the comparison products. For the comparisons made in this work, the uncertainty did not affect the ability to draw clear conclusions about the relative environmental performance of the products, since the difference in the GWP impacts was larger than the uncertainty in the results. However the large uncertainties may affect the ability to draw clear conclusions when comparing other products.

4 Conclusions and recommendations

This work adds to our understanding of the application of attributional LCA for sugarcane products, by examining some of the factors that influence LCA results for products

Table 5 Results for significant impact categories for Australian sugarcane products from all models, based on a mass allocation approach

Impact category	Unit	Raw sugar (per t)			Molasses (per t)	Electricity (per kWh)	Ethanol (per GJ)
		Model 1	Model 2	Model 3	Model 2	Model 2	Model 3
NRE	MJ primary	3,745	3,184	3,031	1,018	1.80	237
GWP	kg $CO_{2(eq)}$	546	463	442	148	0.26	31
AP (ter)	kg $SO_{2(eq)}$	41.7	35.3	33.7	11.3	0.020	2.30
AP (aq)	kg $SO_{2(eq)}$	6.8	5.8	5.5	1.9	0.003	0.38
EP	kg $PO_{4(eq)}$	2.8	2.4	2.3	0.8	0.001	0.15
RI	kg$PM_{2.5(eq)}$	1.1	1.0	0.9	0.3	0.001	0.06
RO	kg ethylene$_{(eq)}$	0.4	0.3	0.3	0.1	2E-4	0.02
Water use	kL	250	212	203	68	0.12	13.4
Land use	m^2.a	813	689	658	220	0.39	43.6

NRE non-renewable energy, *GWP* global warming potential, *AP (ter)* terrestrial acidification potential, *AP(aq)* aquatic acidification potential, *EP* eutrophication potential, *RI* respiratory inorganics, *RO* respiratory organics from Australian sugarcane. It has shown that LCA results for Australian sugarcane products are influenced by (1) the nature of cane processing system (i.e., the range of products produced from the cane), (2) variability in sugarcane growing, and (3) the approach taken for assigning impacts to the multiple products from sugarcane processing. This leads to the potential for large uncertainty, which can be significantly higher than that of comparable products.

The influence of the cane-processing system and cane-growing variability would suggest that representing sugarcane products on a generic or average basis should be avoided. Instead, results should be specific to the cane-growing region and the cane processing used to produce them.

The approach taken for assigning impacts to the multiple products from sugarcane processing was found to be an important consideration. When the product of interest is the raw sugar (the determining product), then MA, EA and SE could all be considered valid approaches. However when the product of interest is a co-product (molasses, electricity or ethanol), SE is less useful due to uncertainty in the mechanism for assigning impacts to co-products, and the potential future difficulties in defining the determining product if sugar mills become biorefineries with production driven by multiple products. To enable the consistent representation of impact across the full range of sugarcane products, the authors' preferred approach is MA combined with energy allocation for the energy products from bagasse combustion and cogeneration.

It should be noted that this applies for attribution LCA where the intent is to generate results for existing sugarcane products (i.e. representing the status quo). Where the aim is to determine the impacts of future production of sugarcane products (i.e. marginal production), then consequential LCA of each individual product as described by Ekvall and Weidema (2004) and further developed by Andrae (2009, Ch. 4.4) is more appropriate, including consideration of the impacts of the land use change as described by Hoefnagels et al. (2010).

This work has also generated novel data for the environmental impacts of Australian sugarcane products by using the approach recommended from this work.

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