ENVIRONMENTAL LIFE CYCLE ASSESSMENT (LCA) OF SUGARCANE PRODUCTION AND PROCESSING IN AUSTRALIA

By

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Abstract

This paper reports the results of a detailed life cycle assessment (LCA) of sugarcane production and processing in Queensland. The work is part of an ongoing postgraduate research project examining the environmental implications of alternative sugarcane production systems for the Queensland sugar industry.

The results presented in the paper show the life-cycle impact of producing a tonne of raw cane sugar in Queensland, for a range of environmental impact categories – energy input, greenhouse gas emissions, eutrophication and water use. Results are presented for three scenarios – a 'State average' farming system as well as two fairly distinct cane growing regions, the Burdekin and the Wet Tropics. These results highlight the significant aspects associated with sugar production in Australia. They also show the range in variation present in the industry due to different growing conditions.

To put the environmental impact of cane sugar production into perspective, sugarcane is compared with other starch- and sugar-bearing crops – sugar beet and corn. Cane sugar is shown to have distinct advantages in relation to energy input, greenhouse gas emissions, and land utilization, but does not rate as well in relation to other the impacts assessed (eutrophication and water use). Three factors were found to have the strongest influence on the outcome – agricultural yield, nitrogen emissions, and the environmental 'credits' attributed to co-products.

The paper provides further insight into the environmental impacts of cane-sugar production in Australia, and suggests opportunities for improving the environmental profile of the cane industry in this country. These include maximizing the environmental 'credits' from co-products, optimizing nitrogen inputs, mitigating nitrogen losses, and continuing with water efficiency efforts.

Introduction

This paper presents the results of a detailed environmental life cycle assessment (LCA) of sugarcane production and processing in Australia. The aim of this work was two-fold. The first was to quantify the life cycle environmental impacts of raw sugar production to identify contributing factors. The second was to compare the environmental profile of sugarcane with other crops that produce sugars – sugar beet and corn.

LCA is a method for assessing the environmental impact of a product or service over its entire life cycle (Standards Australia, 1998). In essence, it is a process for generating environmental information about a product, accounting for all resources consumed, all wastes generated, and all emissions to the environment throughout its life cycle.

While LCA has been applied extensively to industrial products and processes, its application to agriculture has been quite recent. However, it is being used increasingly to assess the environmental sustainability of agricultural production systems. For sugarcane and its products, there are only a few published LCA studies from Brazil (Macedo *et al.*, 2004) and Mauritius (Ramjeawon, 2004). However it is known that there is increasing interest in other cane growing regions (Cuba, South Africa).

Method

LCA of raw sugar production from Australian sugarcane

The LCA of Australian cane-sugar production was based on production practices in Queensland. The system includes all processes from field preparation and planting through to the milling of the cane to produce raw sugar, as depicted in Fig. 1. Also included are the background processes for the production and delivery of fertilisers, pesticides, electricity, transport (operation and infrastructure), and farm machinery (tractors and harvesters). Capital goods associated with cane production have been included since they have been found to be significant in LCAs of agricultural systems (Audsley *et al.*, 1994). Milling infrastructure has not been included as the large throughput and long effective life of sugar mills make the impacts of their establishment and decommissioning insignificant.

Differences in cane growing practices have been considered, since variation in cropping practices has been found to have a considerable influence on LCA results for agro-industrial systems (Ferret *et al.*, 2004). To assess the influence of this, several cane growing scenarios were assessed. As well a 'State average' farming system, two cane growing regions with quite different growing practices were modelled.

- **Average scenario** uses area-weighted State averages for cane yields and inputs (fertiliser, agro-chemicals, water, fuel, etc.), and assumes that 66% of cane is harvested green and 34% is burnt prior to harvest. Harvested cane is assumed to be transported 17.5 km by dedicated cane rail plus 4.6 km by road to the mill for processing.
- **Wet Tropics** scenario, which is typified by relatively low nitrogen input (2.1 kg N/tonne cane), nil irrigation, green cane harvesting with trash retention, higher levels of ratooning (4-5 ratoons) and lower cane and sugar yields. Harvested cane is assumed to be transported 12.2 km by dedicated cane rail plus 17.6 km by road to the mill.
- **Burdekin** scenario, which is typified by higher cane and sugar yields, relatively high nitrogen input (2.4 kg N/tonne cane), high irrigation requirements, burnt cane harvesting

with no trash retention, but lower levels of ratooning (3-4 ratoons). Harvested cane is assumed to be transported 22 km by dedicated cane rail to the mill.

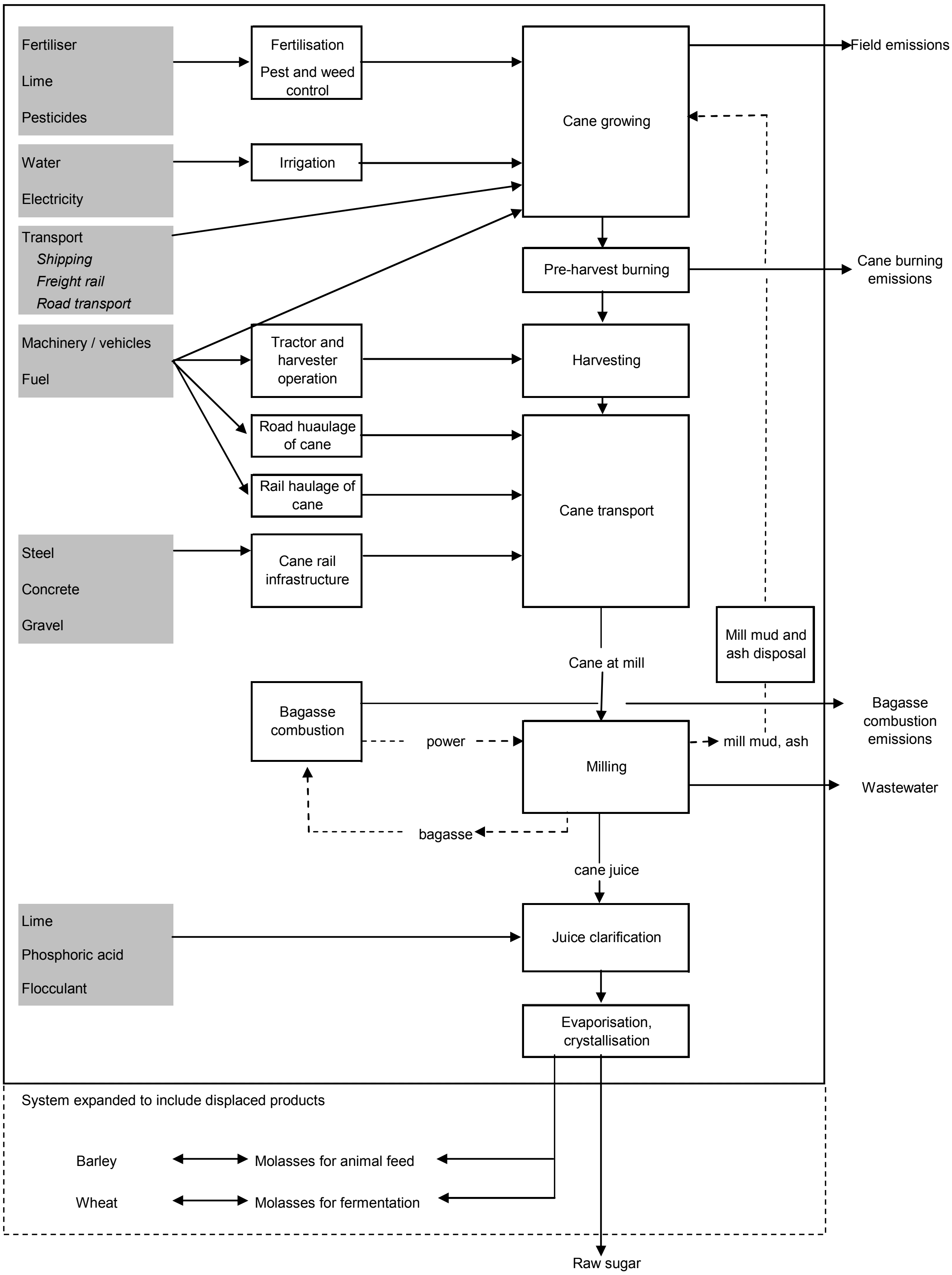

Fig. 1—System boundary for production of raw sugar from sugarcane

Milling is assumed to take place in existing mills with conventional energy efficiencies and no co-generation of power. Apart from the small quantities of fuel used for boiler start-up, all energy for milling is assumed to be met by bagasse. Material inputs are lime, phosphoric acid, and flocculants for juice clarification. Inputs to ancillary operations (lubricants, biocides, antifoaming agents, anti-scaling agents) were not included due to the low quantities involved. Mill mud and boiler ash are assumed to be applied back to cane fields, the transport for which was included within the system boundary.

Molasses is a co-product from the system. The co-production of molasses was accounted for using system expansion, whereby the system boundary was expanded to include the avoided production of substitutes for molasses (Ekvall and Weidema, 2004). The products displaced by molasses are assumed to be barley (in animal feed applications) and wheat (in fermentation applications). Details are shown in Table 1.

Table 1—Products displaced by molasses

Application		**Percent directed to this application** [c]	**Displaced product**	**Equivalency ratio (per unit of molasses)**
Animal feed	- pasture supplement	40%	Barley[a]	0.83 [a]
	- attractant or carrier for feed supplements	40%	Nil	
Fermentation	- for ethanol production	20%	Wheat[b]	0.68 [b]

a. Barley is assumed to be a proxy grain crop for animal feed. Barley has the same nutritional value in terms of energy as molasses on a dry matter (DM) basis (13MJ/kgDM). The equivalency ratio is based on a DM of 75% for molasses and 90% for barley (Agriculture NSW, 2004).
b. Wheat is assumed to be a fermentation proxy substrate. The equivalency ratio is based on a recoverable fermentable sugar content of 50% for molasses and 70% for wheat.
c. Naughten (2001).

Input and output data was obtained from industry surveys, published literature, personal communications with industry personnel and research undertaken by sugarcane and agricultural scientists (simulation studies, material accounting, and field measurements). Tables 2 and 3 list the data used in the analysis and Table 4 shows how the data for field emissions were derived.

Nitrogen (N) is lost from sugarcane fields via a number of routes (soil denitrification, urea volatilisation, leaching, and surface water runoff). Those N species recognised to contribute to potential environmental impacts have been accounted for in the LCA (see Table 4). N loss via surface water runoff has not been included, since it is highly dependent on management practices as well as environmental conditions making it difficult to represent generally. The complex interactions between the soil, the crop, and the surrounding environment make it difficult to account accurately for N emissions, making this the area of greatest uncertainty in the LCA. However it is known that N emissions vary between regions, with differences due mostly to climatic conditions and soil type (Thorburn *et al.*, 2004). Wetter areas tend to have higher rates of N loss via denitrification, leaching, and ammonia volatilisation. Trash blanketing also increases N emission rates via these routes, by providing additional nitrogen and a carbon source that promotes microbial activity.

Table 2—Inputs and outputs for the agricultural production of sugarcane (per hectare)

Inputs[a]	Unit	Wet Tropics	Burdekin	State average
Diesel (tractors / harvesters)	*MJ*	6,899	10,338	8,067
Electricity (irrigation)	*kWh*	0	1,531	1,830
Water	ML	0	12.3	5.2
Planting material	*kg*	945	1,361	1,031
Additional crop production area for planting material	*ha*	0.012	0.012	0.012
Fertilisers and agro-chemicals				
Urea (as N)	*kg*	140	223	167
DAP (as P)	*kg*	19	21	19
Potassium chloride (as K)	*kg*	66	66	65
Ammonium sulphate (as S)	*kg*	12	12	12
Lime	*kg*	613	884	669
Pesticide (active ingredient)	*kg*	3.8	1.8	3
Transport of inputs				
Shipping	*t.km*	4,609	6,694	5,282
Articulated truck	*t.km*	216	283	234
Rigid truck	*t.km*	23	32	25
Transport of crop				
Rail	*t.km*	961	2,464	1,484
Road	*t.km*	1,390	0	391

Outputs[a]	Unit	Wet Tropics	Burdekin	State average
Harvested crop	*t*	79	112	85
Sucrose content in harvested crop	*t*	10	17	12
Field emissions to air[b]				
Nitrous oxide (N_2O) via denitrification	*kg*	13.0	19.7	17.0
Nitrogen oxide (NO_x) via denitrification	*kg*	45.3	17.7	28.4
Ammonia (NH_3) via urea volatilisation	*kg*	3.4	1.5	4.5
Field emissions to water[b]				
Nitrate (NO_3) leaching	*kg*	71.9	15.7	46.8
Phosphorus (P) runoff	*kg*	2.4	2.7	2.4
Pesticide (active ingredient) runoff	*kg*	0.06	0.03	0.04
Emissions from pre-harvest burning				
Methane (CH_4)	*kg*	NA	10.0	3.4
Nitrous oxide (N_2O)	*kg*	NA	0.6	0.2
Nitrogen oxides (NOx)	*kg*	NA	37.1	12.6
Sulphur oxides (SOx)	*kg*	NA	4.6	1.6
Non-methanic VOC	*kg*	NA	22.8	7.8

a. Figures are based over an entire crop cycle, which may be 4-6 years, depending on the number of ratoon crops.
b. See Table 4 for details of how these were derived.
NA Not applicable.

Table 3—Inputs and outputs for processing sugarcane into raw sugar (per tonne sugar)

Inputs	Unit	Typical sugar mill
Harvested crop	*t*	7.0
Energy		
Coal[a]	*MJ*	70
Chemicals		
Lime (CaO)	*kg*	4
Phosphoric acid	*kg*	0.3
Flocculant	*kg*	0.001

Products displaced by molasses	Unit	Typical sugar mill
Barley	*kg*	61
Wheat	*kg*	25

Outputs	Unit	Typical sugar mill
Raw sugar	t	1.0
Co-products		
Molasses	*kg*	183
By-products		
Mill mud	*kg*	365
Ash	*kg*	51
Air emissions		
Particulate (PM10)	*kg*	0.8
Methane (CH_4)	*kg*	0.2
Nitrous oxide (N_2O)	*kg*	0.1
Nitrogen oxides (NOx)	*kg*	1.5
Sulphur oxides (SOx)	*kg*	0.6
Non-methanic VOC	*kg*	0.002
Emissions to water		
Biological oxygen demand	*kg*	0.001
Suspended matter	*kg*	0.002

a. Various supplementary fuels are used for boiler start-up. Coal has been used as a proxy.

Table 4—Field emission factors

Species emitted	Emission factor			
	Unit	Wet Tropics	Burdekin	State average
Emissions to air				
Total N via soil denitrification[a]	% of applied N	20.2	8.1	13.3
Nitrous oxide[b]	% of applied N (as N_2O-N)	6.1	5.7	6.7
Nitrogen oxides[b]	% of applied N (as NOx-N)	10.1	2.4	5.3
Ammonia via urea volatilisation[c]	% of applied urea N (as NH_3-N)	2.5	0.6	2.6
Emissions to water				
Nitrate via leaching[a]	% of applied N (as NO_3-N)	11.9	1.6	6.5
Phosphorus via runoff[d,f]	% of applied P (as P)	12.8	12.8	12.8
Pesticide (active ingredient) via runoff[e,f]	% of active ingredient applied	1.5	1.5	1.5

a. N emission rates via soil denitrification and leaching were derived from the work of Thorburn *et al.* (2004) using the APSIM-Sugarcane crop simulation model.

b. Partitioning of N lost via denitrification were derived from Denmead *et al.* (2005). They suggested N_2O:NO_x:N_2 ratios of around 30%:50%:20% for wet soils and around 70%:30%:0% for drier soils, which were assumed to approximate wet trash blanketed soil and the drier cultivated soils respectively.

c. Urea is prone to volatilisation when surface-applied. Urea is assumed to be surface applied for only 25% of cane land, except in the Herbert where broadcasting is assumed to be the main method (pers. comm. BSES extension officers). 50% of surface applied urea is assumed to be dissolved into soil due to rainfall and not prone to volatilisation. Volatilisation rates were estimated/speculated to be around 20% of the urea-N for trash blanketed soils (Freney *et al.*, 1994) and around 5% for un-blanketed soils (Thorburn *et al.*, 2005).

d. Losses of phosphorus were based on the work of Bloesch *et al.* (1997).

e. Losses of pesticide (active ingredients) were based on the work of Hamilton and Haydon (1996).

f. It has not been possible to distinguish between trash-blanketed and trash-free soils for phosphorus and pesticide losses, so a standard loss rate has been assumed for all scenarios.

It is important to note that the nitrous oxide (N_2O-N) emission rates estimated for this study (around 6% of applied N) are higher than the generic figure commonly applied to arable crops (1.25% of applied N) (Australian Greenhouse Office, 2003). Higher potential N_2O emissions for sugarcane are due to it being grown in conditions conducive to high rates of dentrification (high N availability, high soil moisture, high temperatures, and the presence of organic matter) (Denmead *et al.*, 2005).

Comparison of sugarcane with corn and sugar beet

LCA results for sugarcane were compared with other sugar-producing crops - corn and sugar beet. The comparison was made on the basis that each crop produces a functionally equivalent product – a sugar solution containing mono-saccharide of similar sugar purity – and focused on the agronomic and processing characteristics of the crops and not on factors related to where they are grown. The processes for extracting a sugar solution from each crop are different, but the output common to all is a clarified sugar solution, which was taken as the reference product. As a result, the system boundary used for the comparison is different to that used for the LCA of raw sugar production (see Fig. 2). The functional unit is sugar solution containing a tonne of mono-saccharide equivalent.

The corn analysis was based on data from the United States (Kim and Dale, 2004), and the sugar beet analysis was based on data from the United Kingdom (Mortimer *et al.*, 2004; Tzilivakis *et al.*, 2004).

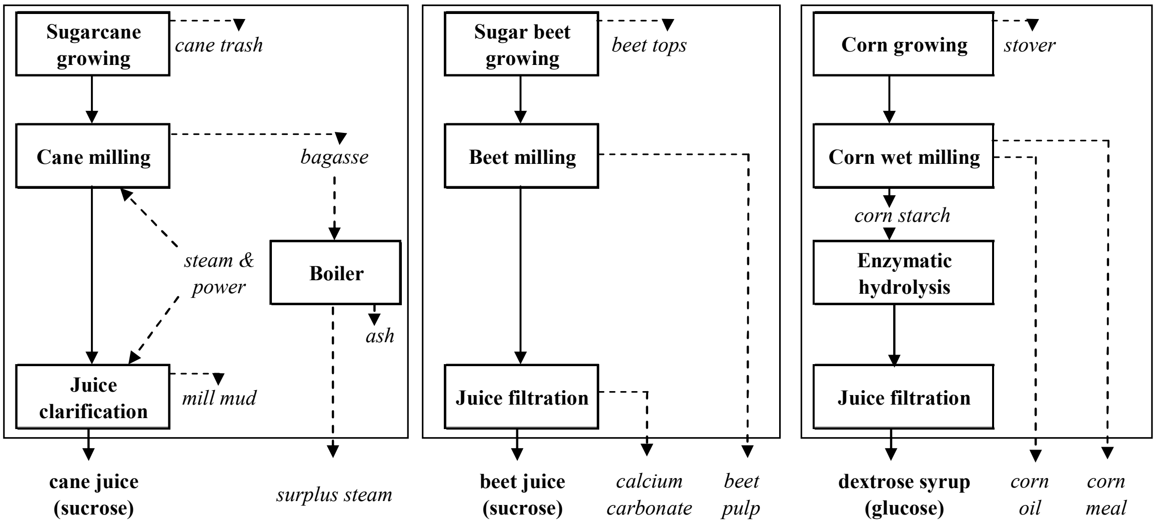

Fig. 2—Production of saccharide from sugarcane, corn, and sugar beet

For the sugarcane system, surplus low pressure steam from bagasse is considered a co-product from the system[1]. This surplus LP steam is assumed to be available for use elsewhere, substituting steam from natural gas. Co-products from corn wet milling are corn gluten feed, corn gluten meal, and corn oil. These products are assumed to substitute for soybean meal and barley in the Queensland animal feed market (pers. comm. Matt Callaghan, Ridley Agriproducts). Corn oil would directly substitute for soybean oil. The main co-product from sugar beet milling is beet pulp, which is assumed to substitute for barley in the animal feed market (pers. comm. Matt Callaghan, Ridley Agriproducts). Calcium carbonate is also produced which would directly substitute agricultural lime.

Results

Results are presented for energy input, greenhouse gas emission, eutrophication potential and water use. Two sets of results are given for each impact category. The first shows the results for a tonne of raw sugar from cane, which depicts the breakdown of activities contributing to the environmental impacts of cane-sugar production. The second shows how cane compares with corn and sugar beet, per tonne of monosaccharide.

Energy input

Fig. 3A shows the aspects of raw sugar production that contribute to overall energy input. Based on the average results, the most significant aspects are electricity for irrigation (41%), fertiliser production (26%), and on-farm fuel use for tractors and harvesters (22%). Capital goods (farm and harvesting machinery, cane railway rolling stock and infrastructure) account for between 5% and 10%. The remainder is associated with milling and transport. This breakdown is consistent with other LCA studies of crop production in Australia (Narayanaswamy *et al.*, 2004; Beer *et al.*, 2005).

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[1] All of the bagasse (9.2MJ/kg HHV) is assumed to be combusted at an efficiency of 62% producing around 2.3kg high pressure steam per kg bagasse (1700kPa, 260°C), which is used to drive the shredders and mills and for generating electrical power for the mill. After exhausting the mechanical and electrical turbines, 90% of the low pressure steam (100kPa, 120°C) is assumed to be recovered (2.0kg LP steam/kg bagasse). This steam, which would otherwise be used in a sugar mill to crystallise/evaporate the cane juice to raw sugar and molasses, is assumed to be available as surplus low-pressure steam.

The variation in overall energy input between the three scenarios is due to differences in irrigation. There is no or little irrigation in the Wet Tropics. For the Burdekin, while the volume of irrigation water is high, the furrow irrigation systems employed have relatively low energy demand. The state average scenario has the highest energy input since higher-pressure systems are employed more commonly across the state as a whole.

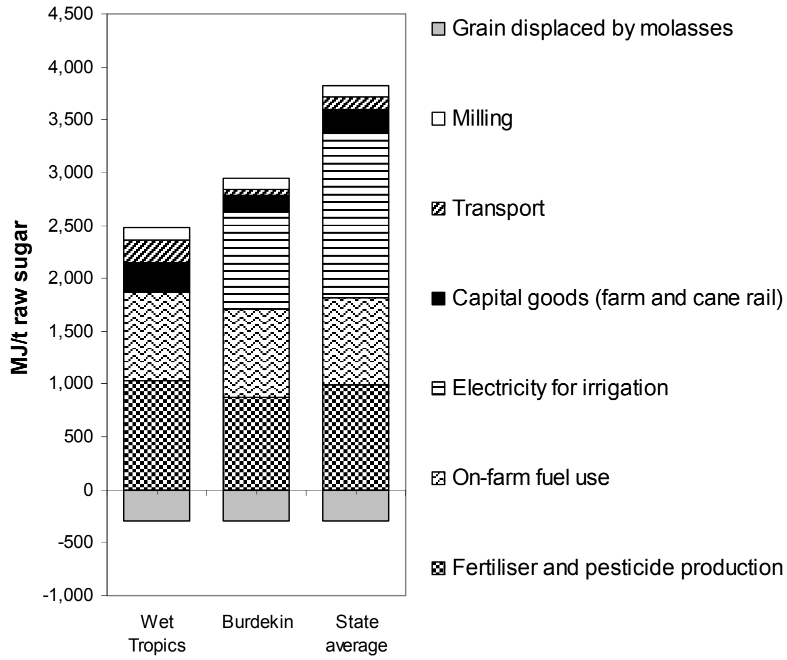

Fig. 3A—Energy input for cane sugar, showing contributing activities.

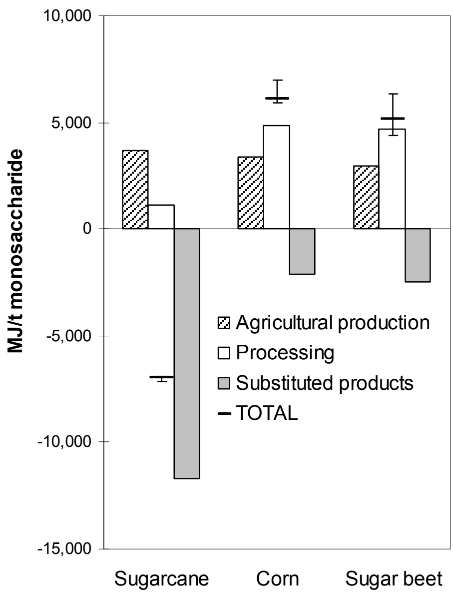

Fig. 3B—Comparative energy input for sugar from cane, corn and beet.

Compared with corn and sugar beet, sugarcane has a distinct energy advantage (Fig. 3B). Since bagasse is available as a fuel, sugarcane requires virtually no input of fossil fuel energy for processing. For the system assessed here, surplus energy is assumed to be available from the sugarcane system, giving an energy credit. In comparison, the corn and sugar beet systems rely on fossil fuel energy for processing and can only claim small energy credits for the barley and soybean production displaced through the use of co-products as animal feeds.

Greenhouse gas emissions

Fig. 4A shows the aspects of raw sugar production that contribute to greenhouse gas emissions. Based on the average results, nitrous oxide (N_2O) emissions from soil nitrification/denitrification processes are the dominant source (59%). The other significant sources are electricity for irrigation (20%), transport/machinery emissions (9%), fertiliser and pesticide production (5%) and bagasse combustion which releases some methane and N_2O (5%)[2].

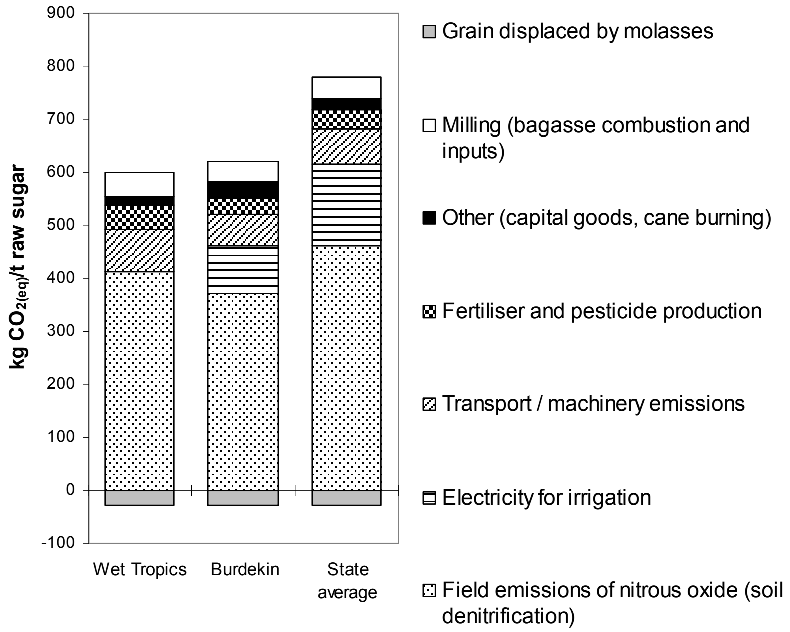

Fig. 4A—Greenhouse gas emissions for cane sugar, showing contributing activities.

The comparative results (Fig. 4B) show N_2O emissions to be significant for all three crops. The higher field emissions for corn are due to the lower saccharide yield per hectare for corn, which makes the in-field impacts per unit of product more significant. The lower field emissions for sugar beet are due to its slightly lower N input[3] and therefore lower potential for N_2O loss.

Sugarcane provides a greenhouse gas credit through the displacement of natural gas assumed to be displaced by burning the surplus bagasse. The greenhouse gas credit would be greater if more efficient crushing and bagasse combustion technology (co-generation) were in place. Corn and sugar beet generate credits through the displacement of barley and soybean production and processing, although not as high as those generated by the cane system.

Overall the results suggest that sugarcane has an advantage in relation to greenhouse gas emissions. However the uncertainty in the results is probably greater than is depicted in Fig. 4B, as variability in N_2O emissions for any of the crops has not been fully accounted for in the analysis.

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[2] The carbon dioxide released from biomass combustion has not been accounted for since it is regarded as a short-term release, assumed to be taken up by subsequent crops (IPCC, 2000).

[3] Sugar beet is a low-biomass crop with relatively lower N requirements.

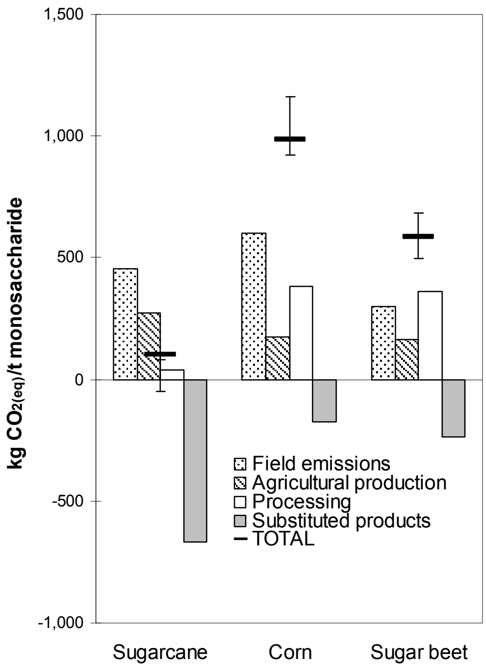

Fig. 4B—Comparative greenhouse gas emission for sugar from cane, corn and beet.

Eutrophication potential

Eutrophication potential results from the release to the environment of nutrients and other eutrophying substances, which have the potential to impact on water quality. Figure 5A shows the aspects of cane-sugar production that contribute to eutrophication potential. Based on the average results, the dominant source is emissions of nitrogen and phosphorous from cane fields, which combined account for 60%. The contributing species are ammonia from volatilization of urea, nitrogen oxides from denitrification processes in the soil, phosphorus loss via sediment movement in runoff, and nitrate leaching. The other sources are milling (25%), electricity and transport (10%) and pre-harvest burning of cane (4%).

The variation between the scenarios can be attributed to different environmental conditions (climate, soil type), which influence field emissions (Thorburn *et al.*, 2004). Wetter areas (as in the Wet Tropics scenario) tend to have higher losses of N via denitrification and leaching. Trash blanketing (as practised in the Wet Tropics and state average scenarios) also increases N emissions, by providing additional nitrogen and a carbon source, both of which promote microbial and metabolic processes in the soil. The Burdekin scenario has the lowest eutrophication result since it is a drier environment and cane is grown without a trash blanket.

The comparative results (Figures 5B) suggests that the sugar beet system has advantages in relation to eutrophication potential over the other crops, due mainly to the credits generated by avoided nutrient release from displaced soybean and barley production. The corn system also displaces other crop products with corn meal and oil, but the credits are not sufficient to offset the high impact of corn production due to its low saccharide yields per hectare. The sugarcane system can only claim relatively small credits from the displacement of natural gas combustion. Therefore the sugarcane system relies on mitigation of field emissions to reduce its overall eutrophication potentials.

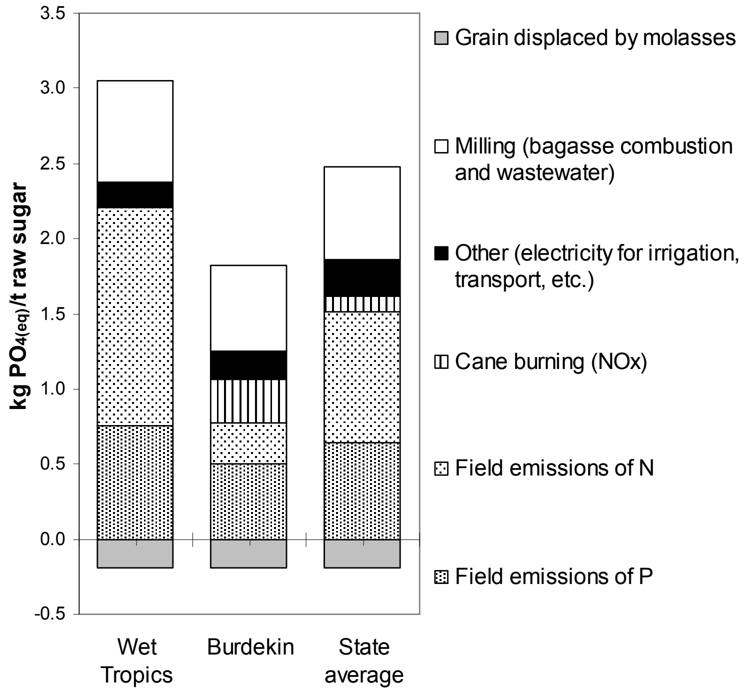

Fig. 5A—Eutrophication potential for cane sugar, showing contributing activities.

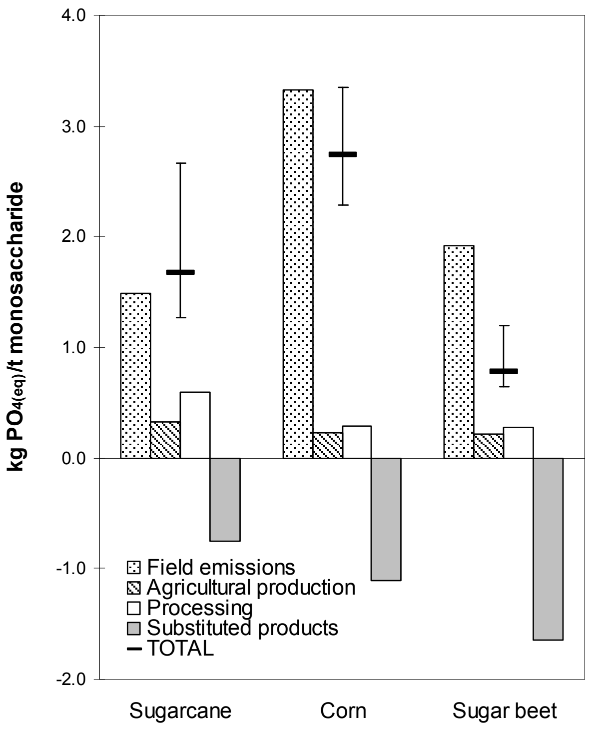

Fig. 5B—Comparative eutrophication potential for sugar from cane, corn and beet.

Water use

Not surprisingly, water use for cane sugar production is dominated by irrigation of sugarcane fields (Fig. 6A). Water consumed by background processes is negligible by comparison.

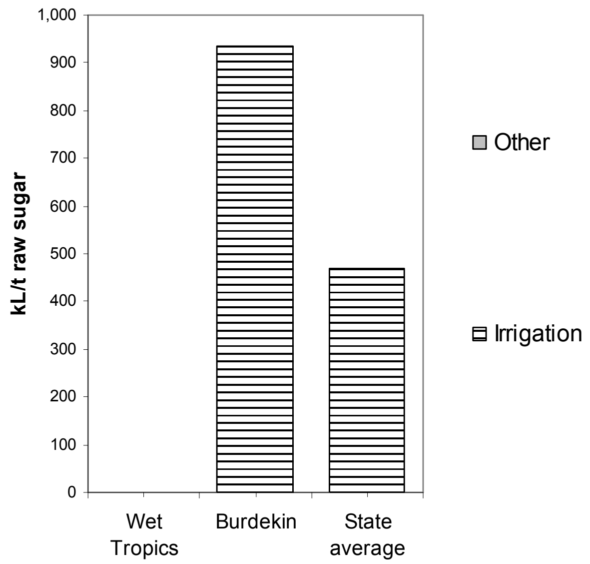

Fig. 6A—Water use for cane sugar, showing contributing activities.

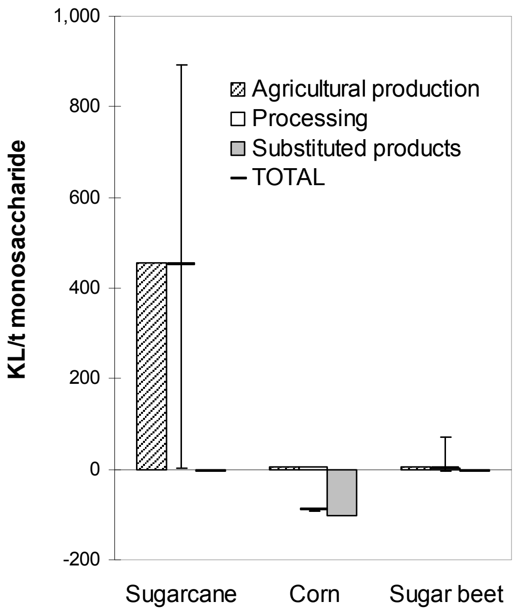

Fig.6B—Comparative water use for sugar from cane, corn and beet.

Water use for sugarcane production is much higher than for the other crops (Fig. 6B) due to the need to irrigate in many canegrowing areas. Around 60% of the sugarcane crop in Australia is irrigated (C4ES Pty Ltd, 2004), compared with only 16% of the US corn crop, and 7% of the UK sugar beet crop. This can be attributed partly to the climate in the areas where these crops are grown. However sugarcane responds particularly well to high water availability and has historically been grown either in areas with high rainfall or where water resources for irrigation are available. In many canegrowing areas, the availability of irrigation water could be considered a pre-condition for successful sugarcane production.

Land use

Comparisons of land use have been made based on the area of land use for crop production, but does not include land use associated with background processes, due to insufficient land use data. Based on the assumed yields for each crop[4], the land area required for the production of one tonne of sugar from sugarcane is 0.08ha, compared with 0.18ha for corn and 0.13ha for sugar beet. Sugarcane therefore creates a lower demand for agricultural land than the other crops due to its high sugar yield per hectare.

Discussion

When compared with other sugar-producing crops, sugarcane has advantages in relation to the depletion of non-renewable fossil fuels and emission of greenhouse gases, due to the availability of surplus bagasse, which can be used as a renewable fuel to displace fossil fuel resources. Sugarcane also requires less land than other crops to produce the same amount of recoverable saccharide.

Sugarcane does not rate as well in relation to eutrophication potential. Sugar beet appears to have an advantage in this respect, since the eutrophication impacts of its production are offset by the avoided production of other agricultural crops displaced when sugar beet pulp is used as an animal feed. The corn system can also claim environmental credits due to the displacement of other crop production with its co-products. However in this analysis, the credits were not sufficient to offset the high impacts of corn production due to its low saccharide yield relative to the other crops.

A disadvantage of sugarcane, compared with the other crops, is its potentially high use of fresh water resources. High water use is often required to achieve the high sugar yields required for economically viable production. Water use will be an important consideration, particularly in countries such as Australia.

The study has demonstrated the importance of agricultural field emissions for a number of impacts. Field emissions are strongly influenced by site-specific factors and the on-farm management and mitigation of field emissions is expected to be an important determinant of environmental impacts. This analysis has assumed conventional agricultural practices, and the influence of alternative growing practices has not been tested. More progressive cropping systems, such as those incorporating break crops (legumes, etc.), minimal tillage, and precision application of inputs, etc., will reduce the environmental impacts. This is an area for further investigation.

The LCA results show those aspects of sugarcane production and processing that make the greatest contribution to environmental impacts. This information can be used to guide environmental management efforts by the industry. The results would suggest that the strategic avenues for further improving the environmental profile of sugarcane production and processing include:

- Continued pursuit of high yields, which is an important determinant of the environmental impacts of agricultural products;
- Continued effort to achieve water use efficiencies;
- Precision application of N fertilisers to reduce the potential for losses to the environment;
- Energy-efficient irrigation systems;
- Maximising the utilisation of co-products to increase environmental credits.

[4] Assumed average yields for sugarcane are 85t/ha at 14% recoverable saccharide, for corn 9.1t/ha at 60% recoverable saccharide, and for sugar beet 50t/ha at 15% recoverable saccharide.

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