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Bio-production from Australian sugarcane: an environmental investigation of product diversification in an agro-industry☆

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ABSTRACT

This paper assesses the environmental impacts of producing bio-energy, bio-fuels and bio-materials from Australian sugarcane (*Saccharum officinarum*), and nominates the bio-production pathways offering the best environmental gains. A system-based, consequential approach was taken, which is different to past approaches that have commonly judged bio-production by comparing individual bio-products with their fossil-fuel counterparts. Possible diversified scenarios were developed, and the changes in environmental impacts from the system as a whole (per 100 t sugarcane processed) were assessed using life cycle assessment (LCA). Scenarios based on utilisation of co-products from existing sugarcane production (ethanol from molasses, and electricity and ethanol from surplus bagasse) were found to give modest reductions in non-renewable energy (NRE) use and global warming potential (GWP), and involve no or few trade-offs. Of these, ethanol and electricity from bagasse offer the best benefits. Scenarios necessitating expanded cane growing for dedicated production of ethanol and polylactide (PLA) plastics from cane juice were found to result in more substantial NRE and GWP savings, but involve the trade-offs associated with expanded agricultural production (land use, water use and potential water quality impacts). Of these, PLA production offers the better outcomes, amongst the scenarios. However, eco-efficient cane growing was found to be an equally important improvement strategy and should be implemented to enhance the benefits and mitigate some of the trade-off from bio-production.

1. Introduction

The need to stabilise the carbon dioxide concentration in the atmosphere to curb climate change is driving a transition away from fossil fuels (IPCC, 2007). Biomass is recognised as an important feedstock for renewable energy (fuel for transport and electricity) in greenhouse gas mitigation strategies (DEFRA. UK, 2007; IEA, 2009), and for producing materials such as organic chemicals, plastics, pharmaceuticals, etc. (Bringezu et al., 2007). The most significant source of biomass for future bio-production is predicted to come from agricultural crops, through increased use of agricultural residues and waste, sugar, starch and oil crops, and increasingly lignocellulosic crops (IEA, 2009; Smeets et al., 2007; Berndes et al., 2003; Hoogwijk et al., 2005).

For these industries, bio-production will be an important diversification opportunity as it potentially builds resilience by providing additional revenue streams, reduces exposure to fluctuating agricultural commodity prices, and promotes new rural industries (FAO, 2006). However, sustainable bio-production will require a better understanding of the risks posed by this important and growing sector (IEA, 2009).

The work presented in this paper contributes to this field of research by examining the environmental implications of product diversification in the Australian sugarcane industry. Sugarcane is recognised as Australia's largest source of useful biomass (O'Connell et al., 2007b), and can potentially play a crucial role in providing renewable stationary energy (CEC, 2008; ABARE, 2010) and transport fuels (O'Connell et al., 2007a), and in meeting the country's greenhouse gas mitigation targets. Product diversification is argued as important for the economic sustainability of the Australian sugarcane industry by providing additional income streams to reduce its exposure to volatile world sugar prices (Keating et al., 2002; Hildebrand, 2002; Milford, 2003). The

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Australian sugarcane industry is also faced with obligations to mitigate its environmental impacts, particularly in relation to protection of the sensitive Great Barrier Reef marine catchment, which neighbours much of Australia's cane growing areas (Wrigley, 2007). Diversification may offer a means of reducing the industry's overall impacts by producing bio-products that displace other fossil-fuel derived products, thereby offsetting its own impacts. The environmental case for product diversification in this industry has not been considered to date, and is the focus of this work. The hypothesis is that positive environmental outcomes could result from industry diversification into bio-energy, bio-fuels and bio-materials, and this research aimed to test that hypothesis.

Sugarcane is recognized as an ideas crop for bio-production, as a wide range of bio-products can be derived from it (Manohar Rao 1997; Paturau, 1989; GEPLACEA, 1988; Singh and Solomon, 1995), and it is more environmentally efficient than other sugar-producing crops (Miller et al., 2007; von Blottnitz and Curran, 2007; Renouf et al., 2008). The sucrose contained in the juice of the cane is traditionally used to produce sugar for human consumption; however it is also a highly suitable substrate for producing a wide range of chemical products including fuels, plastics, solvents, acids, etc., as well as food products (Burk, 2010). The fibrous component of the crop, either left in the field as cane trash, or recovered as bagasse for fuel at sugar mills, can be combusted to provide energy (thermal or electrical), or used as a lignocellulosic feedstock for fuel and chemical production. It is beneficial to understand the environmental outcomes from different bio-production pathways from sugarcane to inform future decisions about product diversification from this important crop.

There is an established body of research that considers the environmental impacts of sugarcane products and systems using life cycle assessment (LCA) from many of the key sugarcane growing regions. Much of this prior work has quantified the impacts of sugarcane products (per unit of product) for the purpose of identifying environmental hotspots (Ramjeawon, 2008, 2004; Pereira and Ortega, 2010; O'Hara, 2010; Smeets et al., 2009), estimating the environmental benefits of sugarcane-derived bio-products (electricity, ethanol, plastics) relative to their fossil fuel-derived substitutes (Beeharry, 2001; Beer et al., 2000; Botha and von Blottnitz, 2006; Groot and Boren, 2010; Harding et al., 2007; Kadam, 2002; Khatiwada and Silveira, 2009, 2011; Macedo et al., 2008; Nguyen and Gheewala, 2008; Silalertruksa and Gheewala, 2009; Yuttitham et al., 2011), evaluating alternative pathways for producing electricity and ethanol from sugarcane (Buddadee et al., 2008; Campbell and Block, 2010; Kiatkittipong et al., 2009; Luo et al., 2009; Nguyen et al., 2010, 2009), comparing alternative uses for sugar milling by-products and wastes (Contreras, 2009), and examining methodological considerations (Hoefnagels et al., 2010; Renouf et al., 2010a).

This current work adds to the body of work on sugarcane systems by examining a range of product diversification opportunities relevant to the Australian sugar industry, including bio-materials as well as bio-energy and bio-fuels. It takes a consequential LCA approach to determine 1) the environmental benefits and trade-offs of converting the Australian sugar industry from one principally focused on sugar production, to one producing a more diverse range of bio-products, and 2) identifying the bio-production pathways that could provide the largest environmental benefits with the least trade-offs. By using consequential LCA, it aims to capture the wider implications of diversified sugarcane systems more comprehensively than has been possible in past studies of sugarcane systems.

2. Materials and methods

2.1. Overview of the method

A range of scenarios for producing bio-energy, bio-fuels and bio-materials from Australian sugarcane were first generated. The changes in environmental impacts (positive and negative) that result from their implementation, relative to the conventional sugar-producing model (reference case), were then predicted. The aspect assessed is the difference in the 'whole of system' impacts between the diversified scenarios and the reference case. The observed value therefore is the change in impacts due to modifying the Australian sugarcane production and processing system, per 100 tonne of sugarcane processed (the functional unit). Since sugarcane yields in Australia average around 100 t/ha, this unit is roughly interchangeable with a unit of 1 ha of sugarcane growing. So it is a useful unit to describe the impact of modifying the system on either a production or land use basis. The nature and scale of changes in selected environmental impacts due to the different product diversification scenarios were quantified using LCA and compared. Observations were then made about the relative benefits and trade-offs of the different bio-production pathways to suggest which option(s) offer better environmental outcomes overall.

The predicted impacts of diversification were also compared with the benefits expected from more progressive cane growing. The Australian sugar industry is pursuing progressive cane growing practices aimed at reducing environmental impacts, which are described here as eco-efficient cane growing. By comparing the impacts of product diversification (hypothesized to be beneficial) with the benefits of eco-efficient cane growing, the comparative worth of diversification as an improvement strategy for the industry could be judged.

2.2. Definition of the reference case

The reference case, against which the diversified scenarios were compared, is based on conventional sugarcane production and processing in the state of Queensland, which accounted for 98% of total Australian sugar production over the period of the study (2004–2008). Conventional sugarcane growing in Australia is based on advanced crop production practices, including extensive use of machinery for land preparation, planting, crop cultivation and harvesting, the use of synthetic fertilisers (with some sugar mill residues) for plant nutrition, and limited application of crop protection chemicals to control weeds and pests. Much of Queensland's cane production relies on irrigation to supplement natural rainfall. Harvested sugarcane is transported to the State's 23 sugar mills mostly by a dedicated cane rail system, but with some road transport. The reader is referred to (Renouf et al. 2010b) for a more detailed description of the cane production phase.

The harvested sugarcane is processed in sugar mills to produce raw sugar. The cane is first crushed in roller mills to separate the sucrose-containing juice from the fibre (bagasse). Then the cane juice is purified, concentrated, and crystallized to produce raw sugar. There are very few external inputs to this process as energy required for mill operations (steam and electricity) is derived from the combustion of bagasse in sugar mill boilers, and process water is recovered from the evaporation of the cane juice. The only other inputs are minor quantities of process chemicals used in juice clarification and ancillary operations (cooling towers, maintenance, etc.). Molasses is a co-product which contains the residual sugars that cannot be recovered economically by further processing, and is currently used domestically for animal feed. The other by-products, mill mud (the organic matter remaining after juice clarification) and boiler ash (the residue from bagasse combustion), are returned to the cane fields. Bagasse is usually generated in quantities surplus to mill requirements. For the reference case, it is assumed that all bagasse is combusted inefficiently as a means of disposal without conservation of surplus bagasse for electricity generation, which is a common situation for traditional mills without co-generation capacity. The reader is referred to (Renouf et al. 2010a) for a more detailed description of the cane processing phase.

2.3. Definition of diversified industry scenarios

No prior analysis of product diversification opportunities for the Australian sugarcane industry was available to aid the development of scenarios for this research. Therefore a set of potentially viable diversified industry scenarios was developed by the authors based on a literature review of products that can be derived from sugarcane (Manohar Rao and 1st ed., 1997; Paturau and 3rd edition, 1989; GEPLACEA, 1988; Singh and Solomon, 1995) and consultation with industry. The criteria used to select the scenarios for assessment was as follows:

- That the set includes products representative of different product categories, i.e. energy, fuels and materials;
- That the set includes products that result from:
  a) continued raw sugar production from existing cane production, but with utilisation of mill co-products, and
  b) producing products other than sugar from cane juice, which would necessitate expanded cane production to provide feedstock for their dedicated production;
- That the production pathways be viable for the Australian sugarcane industry in the medium-term (up to 2020), i.e. the technology is available or developing, there is known interest from the industry and/or government, and markets exist for the products in Australia;
- That data were available for assessment.

The selected products and production pathways that met the criteria were:

1. *Electricity* (from surplus bagasse by combustion and co-generation);
2. *Ethanol* (from molasses by fermentation);
3. *Ethanol* (from surplus bagasse by pre-hydrolysis followed by fermentation);
4. *Ethanol* (from cane juice by fermentation);
5. *Polylactide (PLA) plastic* (from cane juice by fermentation to lactic acid followed by polymerisation).

Definitions of the diversified industry scenarios that deliver these products are provided in Table 1, and estimated quantities of products from each are given in Table 2. Process flow diagrams showing how the diversified scenarios differ from the reference case are provided in Fig. 1. They differ mostly in relation to whether the new products are derived from existing or expanded cane growing capacity, and how the cane is processed in the mill to produce them. The scenarios are hypothetical; developed to test the environmental implications of diversification generally. The practical and economic feasibility of the scenarios has not been tested as part of this research. For instance, the practicality of implementing scenarios requiring expansion of cane growing may in fact be limited by land and water availability in some cane growing regions.

Energy needs (thermal and electrical) for all diversified scenarios were assumed to be met by bagasse combustion in upgraded boilers, with higher efficiencies than in the reference case and with co-generation of steam and electricity. Therefore the bagasse is utilised more efficiently in the diversified scenarios, and surplus bagasse (in excess of that required for mill operations and downstream processes) was estimated to be available in varying degrees for the generation and export of electricity to the State electricity grid. Modelling of energy flows and balances to estimate the electricity surplus was undertaken by Sugar Research and Innovation at Queensland University of Technology (Hobson, P., unpublished data).

Scenarios 2 to 5 all generate wastewaters from fermentation processes (dunder/stillage). In all cases the dunder is assumed to be spread onto cane lands surrounding the mill to make use of its nutrient content. Other less contaminated wastewaters from ancillary operations were assumed to be treated and disposed of under licence, which is current industry practice.

2.4. Definition of the eco-efficient cane growing scenario

This scenario was generated as an alternative environmental improvement strategy, against which to compare the (supposed) benefits of product diversification. It approximates the best cane growing practices being introduced by growers. It is the same as the reference case except that cane growing is more efficient in relation to the key variables known to influence impacts (Renouf et al., 2010b). This means that the data used for eco-efficient cane growing are different from that used for the reference case as follows: Diesel fuel use was assumed to be 50 MJ/t cane (instead of 88 MJ/t cane); water was assumed to be 25 kL/t cane (instead of 37 kL/t cane); pre-harvest burning was assumed to not occur (instead of 39% burnt cane harvesting); N use efficiency was assumed to be 1 kgN/t cane (instead of 2 kgN/t cane); and there was

Table 1
Definition of selected diversified industry scenarios.

Scenarios based on continued raw sugar production from existing cane production, but with utilisation of mill co-products		
Scenario 1:	Electricity surplus bagasse	Upgraded boiler efficiency and co-generation capacity in the mill, so that surplus bagasse can be directed to electricity generation, which is exported to the State electricity grid.
Scenario 2:	Ethanol from molasses	All molasses is directed to ethanol fermentation for use in blended vehicle fuels (E10). The ethanol process is based on conventional fermentation technology expected to be applied in Queensland.
Scenario 3:	Ethanol from surplus bagasse	A portion of the bagasse produced at crushing (40%) is diverted to cellulosic ethanol production for use in blended vehicle fuels (E10). The ethanol process was based on a design for a cellulosic ethanol plant in the US employing dilute acid pre-hydrolysis, followed by fermentation (Aden et al., 2002).
Scenarios based on dedicated bio-production resulting in expanded cane production		
Scenario 4:	Ethanol from cane juice	All cane juice directed to ethanol fermentation for blended fuels (E10). The ethanol process was based on theoretical operating parameters for conventional fermentation technology expected to be applied in Queensland.
Scenario 5:	Polylactide polymer (PLA) from cane juice	All cane juice directed to lactic acid fermentation and subsequent polylactide polymer (PLA) production. The PLA production process was based on that of Cargill Dow in the US (Vink et al., 2003).

Table 2
Quantities of products from reference and diversified industry scenarios (per 100 t cane processed), and increased or decreased production of other products.

		Unit	Reference case	Utilisation of mill co-products from processing of existing sugarcane			Dedicated bio-production resulting in expanded cane production	
				Scenario 1 (electricity ex bagasse)	Scenario 2 (ethanol ex molasses)	Scenario 3 (ethanol ex bagasse)	Scenario 4 (ethanol ex cane juice)	Scenario 5 (PLA ex cane juice)
Products from the sugarcane system								
Main products	Raw sugar	t	14.3	14.3	14.3	14.3		
	Ethanol	L			755	2195	9391	
	PLA plastic	t						10.2
Co-products	Molasses	t	2.8	2.8		2.8		
	Electricity[a]	MWh		4.7	3.8	2.5	13.1	4.4
By-products	Dunder[b]	m^3			3	8	24	24
	Gypsum[c]	t				0.39		0.19
Products from other product systems								
Increased production	Sorghum[d]	t			1.2			
Decreased production	Electricity[e]	MWh		4.7	3.8	2.5	13.1	4.4
	Petrol[f]	L			542	1574	6735	
	Potassium chloride[b]	t			0.01	0.04	0.14	0.14
	PE plastic[g]	t						10.2

[a] Based on energy balance modelling by Assoc. Prof. Phil Hobson, Sugar Research and Innovation at Queensland University of Technology (unpublished data).
[b] Dunder from fermentation processes was assumed to be applied to cane fields as per current convention. This was assumed to displace irrigation water and potassium chloride fertiliser, due to its useful potassium content (5.69 kg KCl/m^3 dunder (Renouf et al., 2010a)).
[c] Gypsum is produced when acidic process streams are neutralised with lime. As there is little/no market for synthetic gypsum in Australia there were assumed to be no displacement effects. It is assumed to be stockpiled and disposed instead.
[d] Additional grain sorghum is assumed to be produced to replace the molasses diverted away from livestock feed applications to ethanol production. This substitution was assumed to occur for only 40% of molasses use; that used in fattening and holding applications. In its applications as an attractant and carrier for additives, substitution was assumed not to occur (pers. comm. with feed industry representatives). Substitution factor was based on this and the relative calorific values of molasses and sorghum (83 kg sorghum/kg molasses).
[e] Bagasse-electricity assumed to substitute black coal electricity (1:1).
[f] Ethanol assumed to substitute unleaded petrol (ULP) (0.72 L ULP/L ethanol (Renouf et al., 2010a)).
[g] PLA plastic assumed to displace polyethylene (PE) plastic in packaging applications (1:1).

assumed to be no urea volatilisation due to sub-surface application (instead of losses of 2.6% applied urea-N).

2.5. LCA method

A consequential LCA approach was taken in this study, in which the consequences resulting from scenario implementation were examined. It is predictive modelling that assesses the impacts resulting from changes to the production system, and has been described by (Ekvall and Weidema 2004) and (Rebeitzer et al. 2004). Recent developments in the consequential LCA technique call for the examination of the marginal production systems, i.e. identification of the marginal producers and consumers influenced by changes in production systems (Andrae, 2009; Schmidt, 2008). However, in this work the consequences of the diversified scenarios were developed through consultation with industry and are therefore qualitative predictions representing average conditions, and not based on a detailed analysis of marginal production systems.

The consequential LCA approach used here accounts for changes that occur in the diversified sugarcane systems, as well as changes that occur in other production systems (see Fig. 1 and Table 2). The latter results from decreased or increased production of products that substitute sugarcane products, in order to maintain functional equivalency of the system overall. For instance, sugarcane bio-products are assumed to displace their fossil-fuel counterparts, resulting in decreased production of these displaced products. Assumed changes are described further in the next section. The entire life cycle of affected production processes are considered, from extraction of resources through to the use and final disposal of end products, including all material and energy inputs.

The impact categories assessed were those found to be significant in a previous assessment of Australian sugarcane systems (Renouf et al., 2010b) – water use, land use, non-renewable energy (NRE), global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), respiratory inorganics (RI) and respiratory organics (RO). Eco-toxicity impacts were also assessed, but have not been reported here due to lack of confidence in the method (Renouf et al., 2010b). Impact assessment methods were based on the Impact 2002+ model (Jolliet et al., 2003) using Simapro (V7.1) LCA software, but with the following modifications:

- EP 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.

The data sources for the analysis are summarised in Table 3.

2.6. Assumed consequences for each diversification scenario

The aspects that change in the sugarcane system are shown in bold outline in Fig. 1. For scenarios 1 to 3 the scale of cane growing and the cane growing practices remain unchanged as these scenarios only involve utilisation of co-products. For scenarios 4 and 5, expanded cane growing was assumed to occur to provide feedstock for dedicated ethanol or plastic production. GHG emissions associated with land use change for this expansion have not been accounted for in the assessment. This is because the scenarios modelled are hypothetical and general, and the nature of the land converted is not known, making it difficult to quantify GHG from land use change without definition of prior land use.

The changes assumed to occur in other affected production systems (i.e. increased or decreased production of other products)

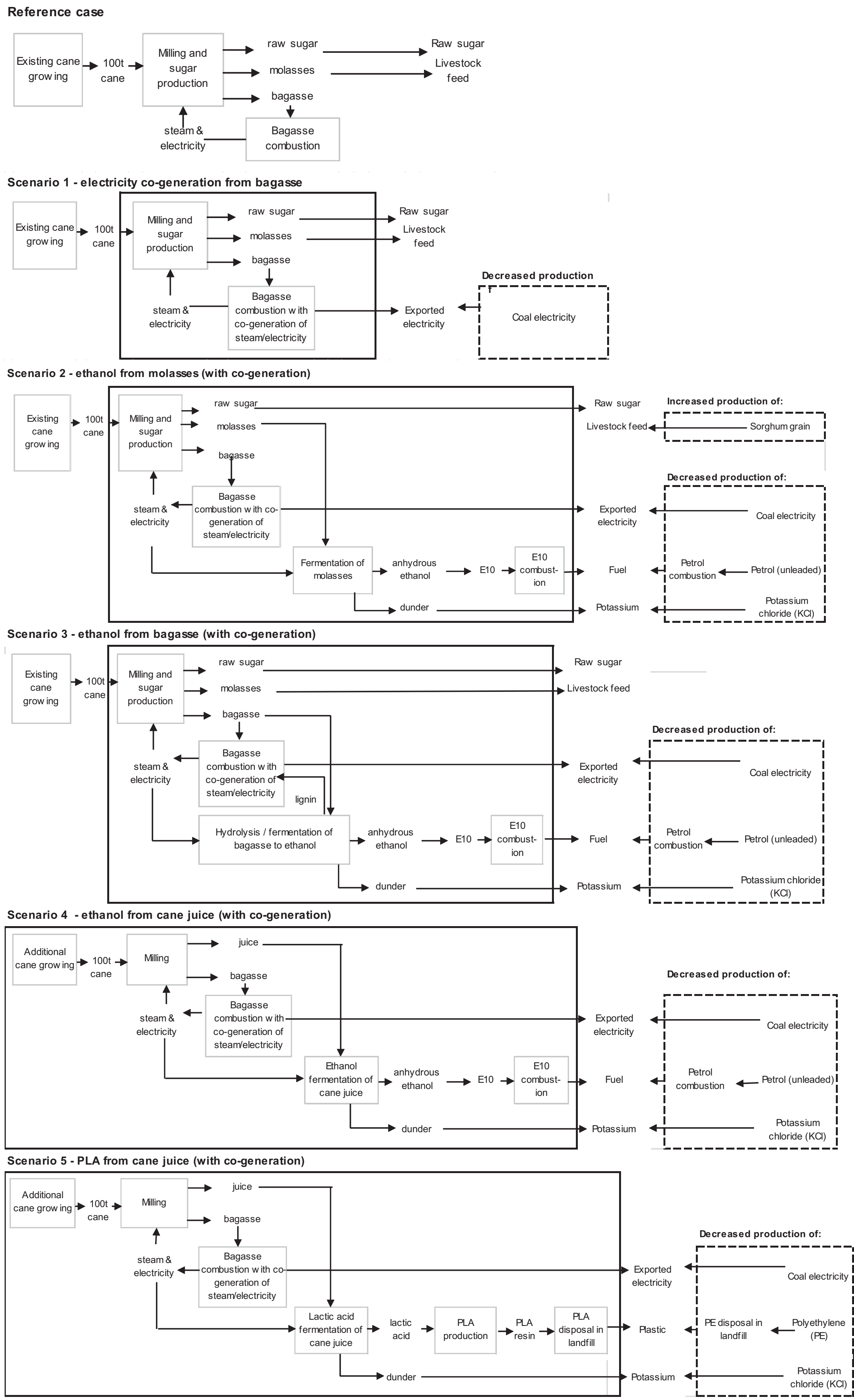

Fig. 1. Process flow diagrams for the reference case and diversified industry scenarios, showing the processes that change in the sugarcane system (bold outline) and in other product systems (dashed outline).

Table 3
Data sources.

Sugarcane growing and harvesting	(Renouf *et al.* 2010b), Tables 1 and 2; state average figures
Sugarcane milling and bagasse combustion	(Renouf *et al.* 2010a), Table 4
Bagasse combustion	(Renouf *et al.* 2010a), Table 4
Ethanol fermentation from sucrose (in molasses or cane juice)	(Renouf *et al.* 2010a), Table 4
Hydrolysis/fermentation of ethanol to bagasse	(Aden *et al.* 2002)
Lactic acid and PLA production from sucrose in cane juice	(Vink *et al.* 2003)
Fuel consumption and combustion emissions of fuels (E10 and ULP) in passenger vehicles	(APACE 1998), (Environment Australia 2002)
Life cycle inventory data for background processes (diesel, electricity, fertilisers, pesticides, chemicals, etc.)	(Life Cycle Strategies 2009)
Life cycle inventory data for displaced products (coal electricity, unleaded petrol, PE)	(Life Cycle Strategies 2009)

are shown in dashed outline in Fig. 1. The changed quantities of affected products under each scenario are shown in Table 2.

The generation and export of surplus electricity to the State electricity grid (in all diversified scenarios), is assumed to result in avoided generation of electricity from Queensland black coal, as this is the supply being displaced as alternative powers supplies come on line.

The consequence of ethanol production via the various routes (in scenarios 2–4) is assumed to be the avoided production of unleaded petrol (ULP), as well as differences in vehicle emissions when it subsequently displaces the use of ULP in passenger vehicles. When ethanol is produced from molasses (in scenario 2), molasses is assumed to be diverted away from animal feed. Therefore an additional consequence or this scenario is an increase in feed grain production to compensate for the absence of molasses in the animal feed market. In the first instance, molasses would be substituted with low-grade crop residues, but the supply chain would eventually be supplemented with grain. This was assumed to be sorghum as it is the most common feed grain grown in Queensland. Estimation of substitution rates is provided in the footnotes of Table 2.

For PLA production (in scenario 5), the consequences are assumed to be avoided production and use of polyethylene (PE) in single-use, disposable, packaging applications (Vink et al., 2003). Differences in landfill emissions from the end-of-life disposal of PLA and conventional plastics to landfill were also included. PLA was assumed to degrade to give 73 kg methane/t plastic (Life Cycle Strategies (2009), derived from US EPA (2006)), compared with PE which was assumed to not degrade (US EPA, 2006). Of this, 45% was assumed to be captured for electricity generation, resulting in further displacement of coal-derived electricity, 5% oxidized in the landfill cover, and the remaining 50% lost to atmosphere as a fugitive emission (Life Cycle Strategies (2009).

The dunder produced from fermentation processes (in scenarios 2–5) was assumed to displace potassium chloride (KCl) when land applied, due to its useful potassium content. However the resulting reduction in impacts due to KCl displacement was found to be very low and is not discussed further.

Since the assessment was concerned with changes in impacts not absolute impacts, some processes were excluded from the system boundary because they are not significantly different to processes occurring in the displaced production system. This is the case for the manufacturing of plastic products from resin (assumed to be similar for PLA and PE), and the transport, blending and distribution of fuel (assumed to be similar for ethanol and petrol). Further details of assumed displacement affects are provided in the footnotes below Table 2.

3. Results and discussion

The results in Table 4 show the change in impacts, per 100 t cane processed, for each scenario relative to the reference case. A negative final result (un-shaded cells in Table 4) indicates an environmental benefit, meaning that additional impacts in the sugarcane system are offset by the environmental credits from displaced products, resulting in an overall reduction in impact. A positive final result (shaded cells in Table 4) indicates an increase in impact. The reduced impacts for the eco-efficient cane growing scenario are also shown in Table 4 for comparison. Fig. 2 shows the contributional analysis indicating the contribution that each aspect makes to the changed impacts for the diversification scenarios. For brevity, the contribution analyses for water and land use are not shown in Fig. 2, as the vast majority of water and land use in scenarios assessed is associated with cane growing, with no significant contribution from other processes.

3.1. Results for scenarios that utilise the co-products of sugar milling

The production of electricity from surplus bagasse, ethanol from molasses and ethanol from surplus bagasse all give NRE conservation and reduced GWP, but at scales smaller than those from the dedicated bio-production scenarios. This is because only a small portion of the cane (that which finds its way into the co-products)

Table 4
Changes in impacts due to each diversified industry scenario (per 100 t cane processed), relative to the reference case.

	Unit	Utilisation of mill co-products from processing of existing sugarcane			Dedicated bio-production resulting in expanded cane production		Eco-efficient cane growing
		Scenario 1 (electricity. ex bagasse)	Scenario 2 (ethanol ex molasses)	Scenario 3 (ethanol ex. bagasse)	Scenario 4 (ethanol ex. cane juice)	Scenario 5 (PLA ex. cane juice)	
NRE	GJ	−45.3	−51.1	−75.2	−315.2	−738.7	−14.2
GWP	t $CO_{2(eq)}$	−4.1	−4.3	−5.7	−21.6	−20.1	−3.6
EP	kg $PO_{4(eq)}$	−2.0	1.4	−1.3	32.6	21.3	−11.7
AP	kg $SO_{2(eq)}$	−148	−74	−102	182	−368	−44.9
RO	kg $eth._{(eq)}$	0.0	0.0	0.0	5.3	−20.4	−6.2
RI	kg $PM_{2.5(eq)}$	−6.3	−4.0	−3.7	−2.6	−20.4	−9.2
Water use	kL	0.0	−1.7	0.0	3751	3767	−1235
Land use	ha	0.0	0.5	0.0	1.2	1.2	0.0

Negative results (in un-shaded cells) represent a decrease in impact (an environmental benefit). Positive results (in shaded cells) represent an increase in impact (an environmental trade-off).

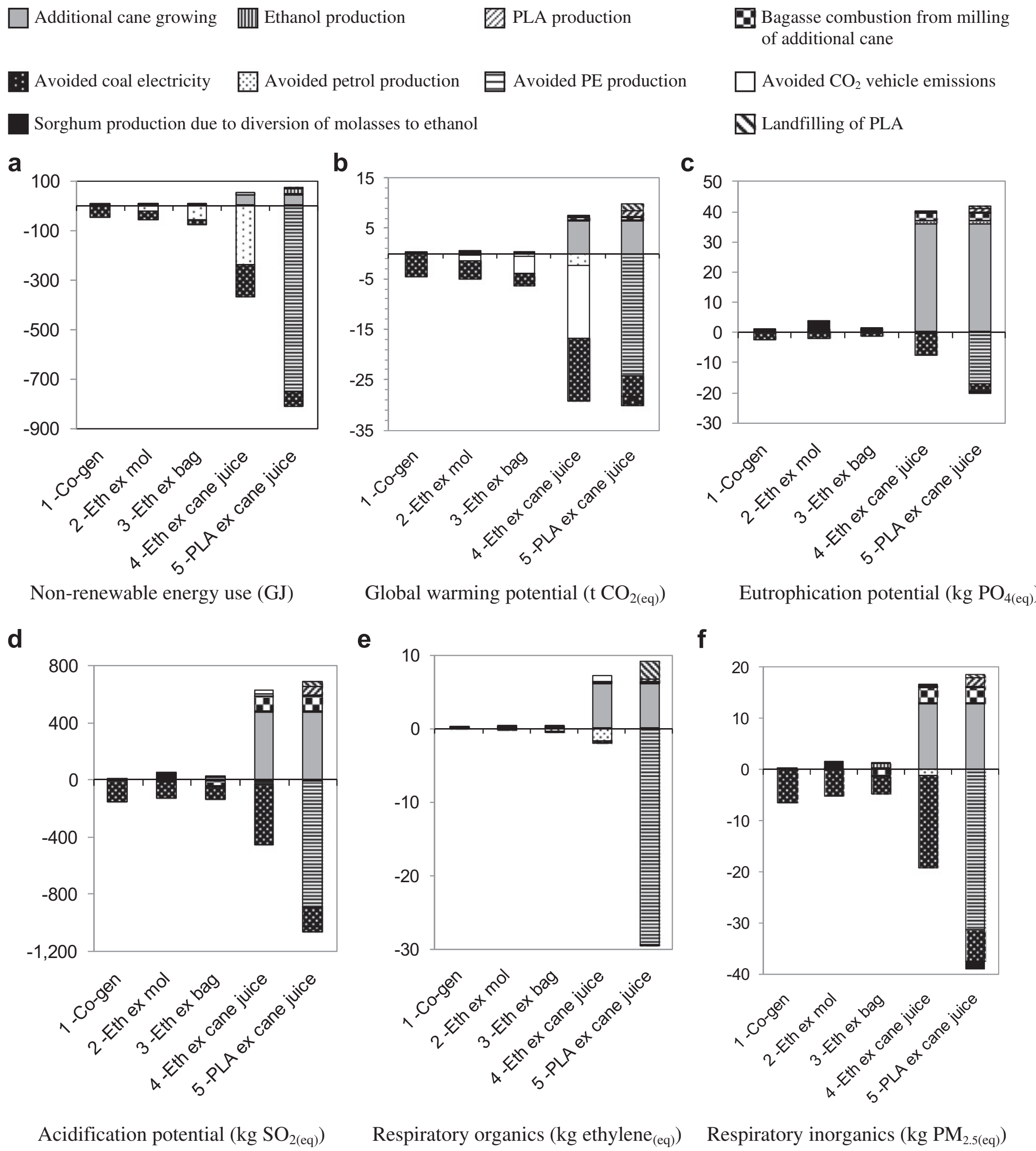

Fig. 2. Contributional analysis of the change in impacts (per 100 t cane processed), for each diversified industry scenario relative to the reference case.

is converted into products that displace fossil fuels. However the benefits come with few trade-offs, since the additional processes can utilise the energy from the cane and do not carry any additional significant impacts. The only potential trade-off is that associated with increased feed grain production assumed to occur when molasses is diverted from livestock feed to ethanol production (in scenario 2). It is difficult to predict the displacement effects of changing the quantities of molasses available in the animal feed market, so there is uncertainty in this.

3.2. Results for dedicated bio-production scenarios

For dedicated ethanol or plastic production, the NWE and GWP benefits per unit of cane processed are more significant because the whole crop is directed to the production of these products. The avoided NRE inputs and GWP more than offset the impacts derived from the expanded cane production and processing (Fig. 2a, b). For PLA production (scenario 5), NRE conservation is particularly large because of the fossil-fuel intensive nature of the polyethylene (PE) production assumed to be displaced (around 88 MJ/kg PE (Life Cycle Strategies, 2009).

However the benefits of dedicated bio-production come with the trade-offs associated with expanded cane growing required for these scenarios – land use (with possible impacts on biodiversity and social issues, which are not assessed in this work), water use, and eutrophication potential (EP) (see Table 4). Increased eco-toxicity impacts from herbicide use are also expected, but have not been fully assessed at this stage.

For dedicated ethanol production (scenario 4), the EP, AP and RO impacts of expanded cane growing are only partially offset by credits from avoided petrol and coal-electricity (see Fig. 2c–e). The result is a net increase in EP, AP and RO impacts (see Table 4).

For dedicated PLA production (scenario 5), the avoided emissions of various organic compounds from displaced PE production fully offset the AP, RO and RI impacts of expanded cane production, but EP impacts are only partially offset (see Fig. 2c–f). The result is a net increase in EP for PLA production.

The increased land use and water use due to expanded cane production for the dedicated bio-production scenarios cannot be offset by the avoided impacts from the displaced fossil-fuel products. Previous work (Renouf et al., 2010b) has suggested that land and water use may be the most significant aspect of Australian sugarcane growing due to its relatively high contribution to total national impact compared to other impacts. Therefore these factors may be the most significant trade-offs for these scenarios. However the limitations of the method used to assess the impacts of land and water use in this study need to be considered, and are discussed below.

3.3. Comparative benefits of eco-efficient cane growing

Table 4 also shows the reduction in impact that could be achieved from eco-efficient cane growing. These can be seen to be quite reasonable in scale, and also offer benefits across the full range of impact categories (EP, AP, RO, RI and water use). Of particular note, the GWP mitigation from eco-efficient cane growing is comparable to electricity co-generation and ethanol production from molasses, and it would probably be a more cost-effective route. Eco-efficient cane growing should be a priority, undertaken in combination with product diversification to further enhance the benefits and mitigate the trade-offs.

3.4. Which bio-products give the best benefits?

If the industry was limited to considering bio-products derived from existing sugarcane production, then the best environmental benefits with the least trade-offs come from diverting a portion of available surplus bagasse to cellulosic ethanol production, with the remainder used for powering the process. However the uncertainties in the data used for this scenario (based on available technology being in an early stage of development) needs to be considered. Further analysis of the scale of benefits from this scenario using more definitive data is justified. Utilisation of all available surplus bagasse for electricity generation is also a good option, as the benefits also come free of trade-offs, and the technology is well developed with certainty in the scale of benefits. (Botha and von Blottnitz 2006) and (Campbell and Block 2010) also conclude that electricity and ethanol from bagasse result in environmental benefits in the South African and Brazilian contexts. The utilization of molasses for ethanol production seems less appealing due to the potential for increased environmental impacts when molasses is diverted away from animal feeding. Animal feed may be the preferred use for molasses as it already displaces a product with relatively high impacts. However due to the previously noted uncertainty in predicting the displacement effects, more detailed analysis of this scenario is justified.

If the industry were able to consider expanding cane production for dedicated bio-production, then PLA plastic production would appear to worth considering as the avoided NRE and GWP from avoided PE production are very large and many of the trade-offs from expanded cane growing can also be offset. Again it is the nature of the displaced product that influences the resulting benefits, and avoided plastic production gives greater credits than avoided ethanol production.

These findings validate some of the broad conclusions that have been drawn from other research about the bio-production pathways that give the greatest environmental benefits (Dornburg et al., 2004; Lynd and Wang, 2004; Sheehan et al., 2004).

3.5. Limitations of the research

The water use and land use results are based on simple indicators of consumption and occupation, respectively. The results do not represent the impacts of water and land use in terms of potential to deplete the quantity and quality of these resources. If dedicated bio-production from sugarcane were to be assessed further, then more rigorous methods for verifying the real impacts of expanded land and water use would need to be employed.

Some of the assessed scenarios warrant further assessment of the consequences on producers and consumers influenced by changes in sugarcane production systems, to allow a more quantitative application of consequential LCA.

GHG emissions associated with changed land use practices were not considered, as the scenarios were general and prior land uses not known to enable quantification of GHG fluxes. Changes in soil carbon stocks and fluxes due to land use change are known to be important (Hoefnagels et al., 2010; Whitaker et al., 2010; Gibbs et al., 2008), and should be considered in future case-specific assessments of product diversification based on expanded sugarcane production.

A final limitation of the study is that the entire range of product diversification options was not assessed. There is scope for assessing other sugarcane bio-products and pathways which may give further insight into the optimal use of sugarcane to maximise environmental benefits. These could include the use of bagasse for pulp and paper production (Rainey et al., 2006) or building board, the use of sucrose for production of a wider range of products derived from fermentation products, and the production of plastics within genetically modified sugarcane (Brumbley et al., 2002).

4. Conclusions

In summary, this work has shown that all of the diversification scenarios assessed could achieve environmental benefits such as conservation of non-renewable energy resources (NRE) and reduced global warming potential (GWP), which arise from avoided production and use of fossil fuel-derived products. However the trade-offs need to be considered. Diversification based on utilisation of co-products from existing sugar milling practices offers modest NRE and GWP benefits, but with few or no trade-offs. The scale of benefits is similar to that which might be gained through adoption of eco-efficient cane growing practices. These options, if they were to be adopted in the industry, should be applied in combination with eco-efficient cane growing to maximise the benefits.

The dedicated bio-production options which necessitate expanded cane production offer larger NRE and GWP benefits, but there are trade-offs from increased agricultural production which cannot be offset by displaced fossil-fuel production and use – land use, water use, and water quality impacts. Eco-efficient cane growing could partially mitigate water quality and water use impacts, but cannot offset the need to use additional land use if dedicated production of fuels and plastics is contemplated. Assuming suitable land is available, the judgement that needs to be made for these scenarios is whether the benefits of conserving non-renewable energy resources and mitigating some global warming potential are valuable enough to justify the impacts from expanded agricultural production. The assessment of land use change impacts is not well catered for in the study. Both the direct and in-direct land use impacts of changing sugarcane production systems towards greater bio-production need to be considered at the local and regional scale using other techniques. This is an opportunity for further research, which would complement the LCA evaluation of diversification.

Despite the noted limitations of the method, the consequential, system-based approach taken in this work has been useful for evaluating product diversification in Australian sugarcane systems. It has captured many of the wider consequences of changing the sugarcane system, allowed for a holistic representation of the impacts of bio-production. These wider consequences are not always observable or consistently represented when using product LCA information, due to the ambiguity associated with the assignment of impacts to the multiple production of sugarcane processing (Renouf et al., 2010a). This approach could be applied to other agro-industrial system based on crops other than sugarcane.

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