Customised life cycle assessment tool for sugarcane (CaneLCA) – a development in the evaluation of alternative agricultural practices

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ABSTRACT

Purpose To promote eco-efficient sugarcane products, there is a need for life cycle assessment (LCA) methods that enable rapid assessment of the environmental implications of alternative agricultural practices. In response, a customised LCA method for sugarcane growing was developed and operationalized in the CaneLCA tool. The aim of the paper was to describe the CaneLCA method in detail and to test the effectiveness of the parameterisation for evaluating the environmental impacts of cane growing practice alternatives.

Methods CaneLCA (Version 1.03) was developed over six years (2011-2017) in conjunction with the Australian sugarcane sector. The LCA process was customized for sugarcane growing by focusing on 'cradle to farm gate' operations and relevant impact categories and parameterising practice variables. To evaluate the effectiveness of the tool, we used it to assess case studies of actual practice changes at six farms in the Wet Tropics region of Australia, in terms of the scope of practice variables and environmental implications that can be accounted for.

Results and discussion The case study LCIA results generated by CaneLCA were consistent with those generated by past studies using LCA software. The parameterization of practice variables allowed for all the practice changes represented in the case studies to be assessed. It is suitable for evaluating such known practice alternatives; however evaluation of very innovative practice alternatives would require upgrades to the underlying algorithms and factors. Most of their environmental implications could be considered, except for effects on soil quality. This will be an area for future tool development to understand the full implications of agricultural practice change, along with the introduction of dynamic models to better estimate emissions.

Conclusions CaneLCA makes the LCA process more rapid for evaluating alternative sugarcane growing practices, thereby speeding up progress towards devising more eco-efficient sugarcane products. It provides a model that could be adapted for other sugarcane growing regions, and for other perennial cropping systems. The novelty of the method is the detailed parameterisation of practice variables so that a wide range of alternative practices can be evaluated.

1. Introduction

Environmental life cycle assessment (LCA) considers the environmental impacts across the life cycle of a product (Hellweg and Milà i Canals 2014; Rebitzer et al. 2004) from 'cradle-to-grave' or from 'cradle to farm or factory gate', depending on the focus of the investigation. It provides a comprehensive picture of the environmental impacts of a product supply chain, for identifying environmental hotspots and exploring environmental improvement opportunities. In this work we are interested in the use of LCA for evaluating alternative sugarcane growing practices. We refer to sugarcane as 'cane' hereafter for brevity. Past LCA studies of cane-based products (sugar but also bio-energy) have shown that the agricultural phase is a significant contributor to their life cycle environmental impacts (Renouf et al. 2011; Rocha et al. 2014; Silalertruksa et al. 2017). Hence, environmental improvements in the agricultural phase will be important for the environmental sustainability of cane products.

There has been some LCA evaluation of alternative cane growing practices, including more efficient fertiliser and water use, conversion from manual to mechanised operations, changes in tillage intensity, conversion from burnt-cane to green-cane harvesting, beneficial reuse of sugar mill by-products to cane fields, and the introduction of legume break crops (Fukushima and Chen 2009; Pryor et al. 2017; Sanchez Moore et al. 2017; Silalertruksa et al. 2017; van der Laan et al. 2015). Past work has commonly been based on hypothetical rather than actual data for growing practices, and has focused on individual practice change without considering the whole farming system. Consequently, the environmental performance implications of practice change in this sector have not been well explored to date.

Evaluating alternative practices using LCA for the purpose of informing environmental improvement efforts requires methods that can model practice variables in detail (Basset-Mens et al. 2007). This occurs during the development of the inventory of inputs and outputs. Conventional LCA methods using specialised software allow for parameterisation of variables in the inventory development (Cooper et al. 2012). However, the variables that can be parameterised relate to the quantities of raw material and process inputs, and it is more difficult to parameterise the nature of the practices that lead to the quantities of inputs. Therefore we aimed to customise an LCA method for cane growing, which is parameterised it in terms of practice variables, so that LCA results for alternative practices can be more easily and rapidly evaluated.

This method has been operationalized in the CaneLCA tool, which was developed over six years (2011 to 2017) in collaboration with the Australian sugarcane sector. Its design and development involved an industry steering committee, pilot testing of Version 1.01 by industry users (Renouf and Allsopp 2013) and desk-top testing of hypothetical practice alternatives using Version 1.02 (Renouf et al. 2014). This paper relates to the latest version of the tool (Version 1.03)[1].

The novelty of CaneLCA compared with other LCA tools customized for agriculture is the parameterization of practice variables to generate inventories of inputs and outputs so that practice alternatives can be evaluated and compared. The aim of the paper was to describe the methods used in the CaneLCA tool (Version 1.03), which have not been previously described, and to test its effectiveness of the parameterisation for evaluating alternative cane growing practices.

2. Material and methods

The two components of the method are described here; the methods used in the CaneLCA tool, and the method for testing its effectiveness (Fig. 1).

Insert Fig. 1

The methods used in CaneLCA are based on the International Standard ISO14044 (ISO 2006), and informed by an earlier LCA of Australian cane production (Renouf et al. 2010). It was customized and parameterized for sugarcane growing by focusing on the ‘cradle-to-farm gate’ stage, the most significant environmental impact categories in the Australian context, and the most significant practice variables. Sections 2.1 to 2.4 describe how each of the main elements of the LCA method were implemented in CaneLCA (goal and scope definition, inventory of inputs and emissions, and impact assessment).

As the customised methods does not require the computing power of LCA software, it was developed as a Microsoft Excel workbook, the components of which are described in Fig. 2. The user enters information about the cane growing practice parameters, which are translated into an inventory of inputs and outputs (using in-built algorithms and emission factors), and then into life cycle impact assessment (LCIA) results (using in-build embodied impact factors and impact characterization factors). The outputs from the tool are an inventory of inputs and outputs, and environmental life cycle impact (LCIA) results for selected mid-point impact categories, which are also presented as eco-efficiency performance indicators.

Insert Fig. 2

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[1] CaneLCA is available from the UniQuest eShop (http://eshop.uniquest.com.au/canelca)

The effectiveness of CaneLCA for evaluating practice alternatives was tested by using it to evaluate actual cases of alternative practices that have been implemented in the Wet Tropics cane-growing region of northeast Australia. Retrospectively evaluating actual practice change rather than hypothetical scenarios allowed for the whole-of-farming system implications of those practice changes to be considered. Effectiveness was considered in terms of whether the degree of parameterization was sufficient to enable the environmental implications of the practice alternatives to be evaluated (Renouf et al. 2018). The evaluated case studies and the evaluation criteria are described in Sections 2.5 and 2.6.

2.1 Goal and scope definition

2.1.1 Goal

The goal was to provide a rapid means of conducting attributional LCA of cane growing for the purpose of evaluating alternative practices, and for use by non-LCA practitioners. Intended users include agricultural extension advisors and the farmers they support who are interested in farm-level management practices, researchers who want to explore new production systems and natural resource managers who are interested in land management practices more generally.

2.1.2 System definition

Sugarcane is a perennial crop, and the cane growing system can be defined by the various phases of the cane’s agronomic life cycle, which typically includes one year of plant cane, four years of ratoons (but ranging from three to six or more), and one year of fallow or break crop (Fig. 3). All of these phases (productive and non-productive) should be accounted for in an LCA as recommended by Brankatschk and Finkbeiner (2015) and Bessou et al (2016). We also included non-productive ‘headland’ areas (field peripheries, tracks between fields, and buffer or conservation strips), which are typically 5-10% of the total farm area. While headland areas do not contribute to production directly, they contribute to the environmental impacts of the overall farm, positively as well as negatively. Their inclusion provides the opportunity to account for the environmental benefits that these areas can contribute in terms of impact mitigation (and biodiversity in the future).

Bessou et al (2016) recommend including data for each year of the perennial crop cycle to account not only for the non-production phases, but also the variability in practices and yields that occurs over the productive phase. As practices for the multiple ratoon crops are generally the same, it was appropriate to evaluate them collectively as a single crop class to reduce the complexity. The cane yield for the ratoon crop class is an average of the individual ratoon crops, which declines over time. It was therefore possible to define the system in terms of the proportion of the farm area under each crop phase, which remains consistent over time. For example, one-sixth will be under plant, four-sixths will be under ratoon crops, and one-sixth under fallow or break crop, plus some additional headland areas (Fig.3).

The user defines practice parameters for each crop class and area, from which the tool calculates and aggregates the environmental exchanges (inputs / outputs) per year. These are divided by annual cane production to derive environmental exchanges per tonne of cane. Hence the results are cane-weighted averages. Individual crop classes can be assessed individually if necessary.

As harvested cane is usually the only product from the cane system there is no allocation of impacts. Break crops, where included, usually support cane production by improving soil health, breaking pest cycles, and in the case of legume break crops providing nitrogen to subsequent cane crops. In this case their impacts are fully assigned to cane production. The exception is when break crops are harvested as a cash crop, in which case a proportion the impacts of the break crops are assigned to cane production, based on a user-defined allocation factor.

Insert Fig. 3

2.1.3 System boundary and functional unit

The system boundary is 'cradle to farm gate', including on-farm (foreground) activities, and also off-farm (background) activities that are up-stream in the supply chain, i.e., those associated with producing and transporting farming inputs (fuel, electricity, fertilisers, pesticides, soil ameliorants, etc.) (Fig. 3). The functional unit is one tonne of harvested crop per year at the farm gate (transport siding).

The foreground and background processes included in the system boundary were those known to be significant for cane growing from a prior LCA of Australia cane production (Renouf et al. 2010). Some processes were not included due to them being insignificant, outside the scope, or for which data was not currently available. See details in Supplementary Material 1.

Agricultural soil was assumed to be part of the agricultural system and thus within the system boundary. The production of seed cane was accounted for by virtue of the fact that a portion of harvested ratoon cane is used as seed for the next year's plant crop, and deducted from the net production. As CaneLCA performs an attributional assessment, land use changes (direct or indirect) or marginal impacts on other production systems were not considered.

2.1.4 Spatial scale of evaluation

CaneLCA can be applied at different spatial scales depending on the purpose of the study: for an individual field or crop class; an individual farm made up of multiple crop classes; a farming enterprise or cooperative made up of multiple farms; or a region made up of multiple farming enterprises. The assessment scale is nominated by the user, by defining the area to be assessed and the crop classes within it. Production parameters need to be appropriate to the defined scale. For farm-scale assessment, the production parameters are farm averages for each crop class, for larger scale assessment (a region) they are regional-averages for each crop class, and for a finer scale (individual crop classes) they can be field-specific. For the case study evaluations, a farm-scale evaluation was conducted.

2.2 Inventory of inputs

The method used in CaneLCA for calculating inputs and outputs is a novel feature of the tool. The methods were parameterised so that practice variables that influence environmental impacts can be defined and modified to evaluate alternative practices. The practice variables and the practice parameters used to define and quantify them are detailed in Table 1. The practice parameters are the data entry requirements of the tool. This section describes how the inventory of inputs and outputs is derived from the practice parameters.

Quantities of inputs (i.e. agro-chemicals, energy, water, machinery and infrastructure) are calculated from practice information entered by the user, rather than records of the actual amounts. However the calculated amounts can be cross-checked against, and over-written by, actual records if available and more accurate.

Quantities of outputs to the environment, i.e., direct emissions to air and water from the farming operation (nitrogen, phosphorous, pesticides, sugar) are derived from the calculated estimates of inputs and assumed emission factors (Table A2). For emissions to soil, only those that subsequently leach to groundwater or surface waters were considered, due to agricultural soils being within the system boundary (the technosphere) and not the environment. The emission factors (EF) are the fraction of applied substances assumed to be potentially emitted to the environment. They are generic values which do not take into account site-specific climate and soil conditions, and assume the loss relative to application relationship is linear. Best available published EFs for the Australia cane production context were used wherever possible.

Insert Table 1

2.2.1 Machinery and implements in service

The amounts of machinery and implements (capital goods) were calculated for the purpose of estimating the impacts of their production. Capital goods production was accounted for as it make a more significant contribution to impacts in agriculture than in manufacturing systems due to lower utilisation rates (Nemecek and Erzinger 2005). It included tractors, implements, harvesters, and trucks. Farm vehicles and motorbikes were excluded as being relatively insignificant and not greatly influenced by practice change.

The amounts were estimated as amortised mass of machinery employed per tonne of cane. For tractors, harvesters and trucks, the mass is calculated from a measured correlation with the power rating (kW) after Wells (2001, Fig 5.3) (Eq. 1, A1). The mass of implements and trailers were assumed to be large (1,000 kg), medium (600 kg) or small (300 kg). For machinery used on a contract basis the mass accounts for the percentage of the machine's work that is in the service of the farm (user's estimate). The (allocated) mass (kg) for all types of machinery was amortised to cane production (per t cane) by dividing it by the amount of cane produced over its service life (Eq. 2, A1).

2.2.2 Fuel use for tractor / truck operations

Fuel use by tractors and trucks was calculated for the purpose of estimating the impacts of their exhaust emissions and the production of the fuel consumed. Fuel use for harvesting cane and other crops was calculated using a different method (see 2.3.3). Tractor (and truck) operating parameters (row width, speed, field efficiency) were first defined to estimate an operating rate (ha/hr) for the tractor / implement combination (Eq. 3, A1). Fuel use per ha of operation (L/ha) was then calculated from the operating rate (ha/hr), the specific fuel use at maximum load (L/hr), and a load factor estimated by the user (i.e. how hard the engine works as a proportion of full load) (Eq. 4, A1). Specific fuel use for tractors was estimated using a general rule of thumb proposed by agricultural engineers (Chen and Baillie (2007, p.13), citing Harris (2005)) which correlates fuel use (L/hr) to the power of the machine (Eq. 5, A1). The fuel used for the operation was then derived from the calculated fuel use per ha and the area treated (Eq. 6, A1).

2.2.3 Fuel use for harvester operation and haul out

Fuel use for the harvesting cane and other crops is usually undertaken by an external contractor and therefore operating parameters are difficult to collect. Therefore fuel use for the mechanical harvesting and haulout of cane (to the transport siding) was calculated using a parameterized model developed by Sandell and Prestwidge (2004), based on crop size, row width, speed and haulout distances and turnaround times. Fuel use for harvesting other crops using a combine harvester was calculated based on a correlation with crop size (Eq. 7, A1).

2.2.4 Irrigation infrastructure

Only irrigation infrastructure was accounted for. Farm building, roads and fences were not considered, as the impacts associated with their production are insignificant (Nemecek and Erzinger 2005). The amount of irrigation infrastructure in service was calculated for the purpose of estimating the embodied impacts of its production. The user enters the area serviced by the irrigation system(s), from which the infrastructure input per tonne cane is amortized over the productive life of the infrastructure. The materials used in the infrastructure were accounted for within the embodied impact factors used in the subsequent impacts calculations (2.5).

2.2.5 Nutrient inputs

Nutrient products include synthetic fertilisers, organic fertilisers (sugar mill by-products of mill mud, ash and vinasse, as well as compost, manure etc.), and soil ameliorants (lime, dolomite, gypsum). The quantities of synthetic fertilisers and soil ameliorants applied were calculated for estimating the impacts of their production and their transport to the farm. The production and transport of organic fertilisers were not accounted for as they are waste products from other processes, and so impacts are assigned to the generating processes rather than the processes that utilises them, consistent with the approach taken in other studies (van der Werf et al. 2009). Only the impacts of their spreading and the fate of the contained nutrients were accounted for.

The quantities of nutrients supplied by the nutrient products were calculated for estimating subsequent emissions (see Sections 2.3.1 and 2.4.2). The nutrients accounted for are nitrogen (N), phosphorus (P), potassium (K) and sulphur (S). For synthetic and organic fertilisers, the quantities applied and their constituent nutrients were estimated from information entered by the user about the area treated, application rates per hectare, and nutrient contents (%wt/wt) (Eq.8-9, A1). The quantities of the individual fertiliser ingredients were then estimated, assuming that urea (46%N), diammonium phosphate (DAP 20%P, 18%N), potassium chloride (KCl 50%K) and granulated ammonium sulphate (Granam 24%S, 21%N), are the dominant synthetic sources of N,P,K and S, respectively (Eq. 10-13, A1). For soil ameliorants (limestone, dolomite), only the total amount applied is calculated (Eq. 14, A1) for estimating the impacts of production and supply, and also the carbon dioxide emissions from their carbonation, where relevant (Section 2.3.6).

The amount of N provided by harvest residues retained in the field and legume break crops (both fixed and in their residues) was estimated using methods consistent with the International Panel on Climate Change (IPCC) methods (DEE 2016) (Eq. 15-16, A1).

2.2.6 Pesticide inputs

The quantities of pesticide products applied (herbicides, insecticides, and fungicides) were first calculated for the purpose of estimating the impacts of their production and supply (Eq. 17, A1). The quantities of individual active ingredients (AI) contained in the products were than calculated for the purpose of estimating subsequent emissions (Eq. 18, A1) (see Section 2.3.15) See Supplementary Material 3 for the list of AIs accounted for.

2.2.7 Water input

The amount of water used for irrigation (from dams, water courses, groundwater and irrigation schemes) was calculated for the purpose of estimating the impacts of water extraction and energy use for pumping. Water use (ML) can be calculated in two ways, either based on a known application rate (ML/ha) and the area irrigated (ha) (Eq. 21, A1) or the pumping rate (ML/hr) and pumping duration (hr/operation) (Eq. 22, A1). The amount of water pumped away from the farm (dewatering / drainage) can also be accounted for.

2.2.8 Energy inputs for pumping water

The energy (electricity or fuel) for pumping water to the farm, or off the farm, was calculated from the known correlation with the pumping head pressure (m) and the pumping efficiency (Chen and Baillie 2007, p.11) (Eq. 23-24, A1).

2.2.9 Transport effort for the supply of inputs

Transport effort (t.km) for supplying agro-chemical inputs from the manufacturer to the farm was calculated from the amounts of fertiliser, pesticide and soil ameliorant products applied, the distance from the assumed origin of production, and the relevant transport mode (see Supplementary Material 4) (Eq. 25-26, A1).

2.3 Inventory of emissions

2.3.1 Nitrogen emissions

Ammonia (NH_3) emissions to air from the volatilisation of ammonia-N were estimated from the amount of NH_4-N that is surfaced applied and the NH_3 emission factor (EF) (Eq. 27 Table A1). In this method volatilisation is assumed to only occur for surface application, in line with other methods that account for NH_4 not being prone to volatilisation after incorporation or infiltration (Nemecek and Schnetzer 2011). NH_3 EFs specific to Australia cane production for different conditions were used (Table A2) (Chapman et al. 1995) , which are similar to those recommended by Nemecek and Schnetzer (2005) and Brentrup (2000) (0.15-0.2 kgN/kg N applied) in the European context.

Nitrous oxide (N_2O) emissions to air via the *direct* denitrification of applied N were calculated using methods and factors consistent with IPCC (2006) (Eq. 28 Table A1). The amount of N applied (from fertilisers, mill by-products and crop residues) was multiplied by the relevant N_2O EF depending on the source of N (Table A2). The NO_2 EF for synthetic fertilisers and mill by-products was specific to Australian sugarcane (DEE 2016, S 5.6.2). According to IPCC guidelines, no NO_2 emissions were calculated from biological fixation of N by legumes, but those from legume residues were accounted for.

Nitrate (NO_3) emissions to water via groundwater leaching as well as surface water runoff were calculated using methods and factors consistent with IPCC (DEE 2016, S.5.6.10). After subtracting for NH_3-N lost via volatilisation and N_2O-N lost via denitrification, the remaining N was multiplied by the fraction of N assumed to be available for loss, and the NO_3 EF (Table A2), which is the same for all forms of N (synthetic, organic, legume) (Eq. 29, Table A1).

Nitrous oxide (N_2O) to air via *indirect* denitrification of redeposited NH_3-N (DEE 2016, S 5.6.9) and soluble NO_3-N emitted in runoff and leaching, was calculated using method and factors consistent with IPCC (DEE 2016, S 5.6.10) (Eq. 30, Table A1). The amounts of NH_3-N and NO_3-N emitted were multiplied by the appropriate N_2O EF (Table A2).

2.3.2 Phosphorus emissions

Phosphorus (P) emissions to water via surface water runoff were estimated from the amount of P applied (Eq. 31 Table A1) and the P EF (Table A2), which was derived from a phosphorus budget of the Australian cane sector (Bloesch et al. 1997).

2.3.3 Pesticide (active ingredients) emissions

Emissions of pesticide active ingredients (AI) to water via groundwater leaching and surface runoff were estimated from the amount of AI applied (Eq. 32 Table A1) and the AI EFs (Table A2). In the absence of factors that link empirical or modelled emissions of AI losses to the amount applied, the EF was based on a conservative best estimate. The EF is the same for all pesticide active ingredients, and the emissions are assumed to occur at the point of discharge to nearby waterways (freshwater).

2.3.4 Sugar emissions

Sugar emissions to water from harvesting were estimated using a known relationship with harvester operating parameters (Whiteing et al. 2017). Sugar loss occurs when cane is harvested green (i.e. not burnt prior to harvest), and is due to extruded sugar accumulating on harvest residues and available for loss to the environment via runoff if it rains. The amount of sugar extruded from the cane depends on the speed of the trash extraction fan on the harvester (Eq. 33 and 34, Table A1). The fraction of extruded sugar that is subsequently emitted to runoff depends on if it rains during or post-harvest (Eq. 35 Table A1). If harvesting is assumed to occur during dry weather there will be no losses. Otherwise the amount emitted is based on the percentage of harvest days that are wet and the sugar EF (Table A2).The amount of sugar lost was then converted to an equivalent chemical oxygen demand (COD) (Eq. 36 Table A1).

2.3.5 Combustion emissions from cane burning

Combustion emissions of methane (CH_4), non-methanic volatile organic compounds (NMVOC), nitrous oxide (N_2O) and nitrogen oxides (NO_x) from pre- or post-harvest burning of harvest residues were calculated using method and factors consistent with IPCC (DEE 2016, S 5.8.1) (Eq. 37-41, Table A1). They are based on the mass of dry matter burned, the carbon and nitrogen fractions of the dry matter, and the respective emission factor (Table A2).

2.3.6 Carbon fluxes

Carbon dioxide (CO_2) from the carbonation of limestone and dolomite was calculated using methods and factors consistent with IPCC (DEE 2016, S 4.3.4) (Eq. 42 Table A1). CO_2 emitted from cane burning was not accounted for as it is considered a short-term releases in accordance with IPCC (2006). CO_2 emitted from the breakdown of urea in the field was also not accounted for, because it was accounted for in the embodied impact factors for urea, used to calculate the impacts of urea production (see Section 2.5), as a by-product of the ammonia production stage of urea production.

2.4 Impact assessment and performance indicators

Life cycle impact assessment (LCIA) results were generated for the mid-point impacts categories found to be most significant for Australian cane production in past LCA studies (Renouf et al 2010). They are non-renewable energy use (NRE), greenhouse gas emissions (GHG), eutrophication potential (EUT), ecotoxicity potential (ETOX) and water scarcity (WS). Acidification potential and particulate matter formation can be significant impact categories due to emissions of combustion gases and particulates when can harvest residues are burnt (Ometto et al. 2009). However as cane burning is now not widely practiced in Australia, they were omitted as less relevant in this case.

Impact assessment methods most appropriate to the Australian context were applied based on the Best Practice Guide for Impact Assessment in Australia (Renouf et al. 2015), which is operationalized in the 'ALCA Best Practice Recommendations' method set within the AusLCI database (AusLCI 2017). Details of the methods are in Table 2, and their impact characterisation factors can be found in Supplementary Material 3.

Insert Table 2

To derive the LCIA results, the impacts associated with the inputs (background processes) and the (foreground) emissions are calculated using in-built factors. The impacts of the background processes were calculated by multiplying the calculated input quantities of by their respective embodied impact factors (EIF). EIFs were derived using Simapro LCA software for the most representative processes from the Australian Life Cycle Inventory (AusLCI) Unit Processes database V1.27 (AusLCI 2017) (see Supplementary Material 2), and the above-mentioned impact assessment methods. Where representative processes were not available in the database, a proxy was used (eg., tractor operation in place of harvester operation, and unspecified pesticide production in place of the individual active ingredients). The impacts of the emissions were calculated by multiplying the calculated emission quantities by the respective impact characterisation factors for the impact assessment methods (see Supplementary Material 3).

In the CaneLCA tool, the LCIA results are reported as eco-efficiency performance indicators, rather than as absolute values. The relative eco-efficiency performance indicators are the absolute LCIA results for each impact category divided by highest expected LCIA results for the sector (expressed as a %). The generation of relative results was possible due to the availability of a database of cane farming inputs and practices for the Queensland sector (n=100) (unpublished data of Canegrowers compiled by Milford and Pfeffer, (2002)), from which the range of environment impacts for the industry had been derived (Renouf et al. 2010). This approach was taken because i) relative eco-efficiency performance indicators emphasise the positivity of improving environmental performance rather than the negativity of reducing environmental impacts, ii) they are more meaningful for non-LCA practitioners than absolute values; and iii) results for all impact categories can be presented on the one graph with a common scale to make interpretation easier. Terms more meaningful to users to describe the impact categories are also used in the tool rather than the terms commonly used in LCA (Table 2). However in this paper the LCIA results from the case study analyses are reported as absolute results using the standard LCA terminology.

2.5 Case study evaluations of practice change

The environmental implications of practice changes implemented at six cane farms in Australia were assessed using CaneLCA. This provided the opportunity to test the effectiveness of the practice parameterisation in CaneLCA for evaluating practice alternatives, because they represented actual cases of changed practices. The case study farms are all located in the Wet Tropic region of north-east Queensland, ranging in size from 95 to 810 hectares, and each producing between 5 and 60 tonnes harvested cane per year. They provide of good sample of cane farms in this region.

The practice changes implemented at the case study farms were those recommended in the SmartCane best practice program (https://www.smartcane.com.au/home.aspx) to address environmental issues whilst maintaining productivity (Schroeder et al. 2008), and are consistent with international best practice programs (Bonsucro 2016). The following is a list of the main practice changes implemented at each of the case study farms.

- increased row spacing to reduce tractor movements and reduce soil compaction;
- reduced tillage intensity and number of machinery operations, also to reduce soil compaction;
- introduction of GPS guidance on tractors and harvesters, to facilitate the above controlled traffic measures, but also to enable precision application of fertilisers and pesticides;
- changes to machinery and implements to enable the above;
- reduced N application rates to address a past tendency for over application of N ;
- introduction of a legume break crop, which is turned-in as green manure to supply N (both microbiologically fixed and in the residues), to reduce reliance on synthetic urea-N, but also to reduced weed pressure and herbicide use;
- use of knockdown rather than residual herbicides, with reduced toxicity, and reduced application rates through more precise application methods (banded or variable rate application). There were some changes in fungicides and insecticide use, but herbicides have been an emphasis of the practice changes.

The data required for the CaneLCA analyses were collected by agricultural extension officers during a single consultation session with each farmer, with some follow-up clarification by phone and email. The time taken for data collection was between 6.75 and 13 hours for both the before and after cases for each farm. The collected data was then entered into CaneLCA, which took between 3.75 and 6 hours for both cases at each farm.

The analyses of the six case study farms were used to construct a representative case for cane growing practices in the Wet Tropics region before and after the practice changes. This was required to avoid presenting results of the individual farms for data confidentiality reasons. The representative case was developed by defining from the sample average practices and calculating farming inputs and yields based on production-weighted averages. The derived data was entered into CaneLCA to generate results for the representative case. The resulting inventory of inputs and outputs for the representative case are summarised in Table 3.

Cane yields are 5-yr averages up to the completion of the changes, and are net yields after a portion of the harvested ratoon cane has been diverted for planting. For the representative case, yields were assumed to remain the same after practice change, because for most of the individual farms it was difficult to discern yield changes due to the practice change within the significant seasonal yield fluctuations.

Insert Table 3

2.6 Criteria for evaluating effectiveness

The effectiveness of practice parameterisation in CaneLCA for evaluating alternative practices was evaluated in terms of i) whether the scope of alternative practices represented in the case study sample can be adequately assessed by the tool, ii) whether the environmental impact implications of the alternative practices are adequately captured by the tool, and iii) the uncertainty of the results.

3. Results of the case study analysis

The results generated by CaneLCA for the representative case before and after practice changes are reported in this section. They demonstrate how practice parameterisation in the tool enabled the quantification and interpretation of the environmental implications of alternative cane growing practices. Our observations about the effectiveness of the practice parameterisation are described in the Discussion section.

Table 4 shows the absolute values of the life cycle impact assessment (LCIA) results generated by CaneLCA, for the representative case and also the ranges for the sample of case study farms. Fig. 4 shows the contributions analysis of sources of impacts and percentage changes in the LCIA results for the representative case. The sources of impacts in the contributional analysis are colour coded according to the practice categories to which they relate, to see the influence of the practice changes.

Insert Table 4

Insert Fig. 4

Best practice implementation was estimated to reduce NRE by 11% for the representative case (range is 10% to 34%). More than half of this reduction is due to less fertiliser produced at the factory and transported to the farm, and occurs off-farm. Avoided urea-N production, due to reduced N application rates and alternative N sources, is the biggest energy-saver because urea production is energy-intensive, but there are also savings from reducing other fertiliser inputs (DAP, KCl, Gran-am). The remaining savings are due to on-farm reductions in fuel use for tractor and harvester operations as a result of wider row spacing and reduced tillage. The introduction of a legume break crop to displace some urea does add additional machinery operations but the energy cost of this is not significant.

GHG emissions were estimated to reduce by 10% for the representative case (range is 7% and 32%). Most of the reduction is due to less on-farm emissions of nitrous oxide (a strong GHG) due to reduced N application rates, and the use of legume crops to supply N which was assumed to have a lower rate of denitrification than N from synthetic fertilisers. The rest is due to the previously-mentioned reductions in energy use for producing and supplying fertilisers (mostly urea), and reduced tractor and harvester movements.

EUT potential was estimated to reduce by 13% for the representative sample. The range is between 3% and 41%, depending on the extent to which N application rates are reduced. This is mostly due to a reduced potential for N loss to surface water runoff and groundwater infiltration, because less N has been applied.

ETOX potential was estimated to reduce by 19% (range is 17% to 41%). A focus of the best practice program has been to reduce the aquatic toxicity impacts associated with pesticide use, and this can be seen to have occurred to various extents. However there have also been toxicity reductions due to reduced fertilizer production and fossil fuel use.

The most significant environmental improvements were due to the changed nitrogen application practices (reduced N application rates and alternative sources of N), changed pesticide application practices, and reduced tractor and harvester operations due to greater row spacing were less significant.

The LCIA results generated by CaneLCA were found to be consistent with those generated previously using LCA software (Renouf et al. 2010) (see Table 4). The aspect with the greatest uncertainty in the CaneLCA method are cane yields and the assumed emission factors for nitrogen species, phosphorus and pesticide. Fukushima and Chen (2009) had previously found that when comparing alternative cane growing practices and systems, estimates of GHG emissions are most sensitive to cane yields and the assumed N_2O emission factor. We infer that the EUT and ETOX impacts would similarly be sensitive to yields and emission factors for nitrogen species, phosphorus and pesticide. This uncertainty is due to fact that the method currently can't predict the influence of practice parameters on cane yields or on emissions. Furthermore, the methods cannot take into account site- or region-specific condition (soil type, climate, slope etc.), which are known to strongly influence emission factors (Schmidt Rivera et al. 2017). Hence some important implications may be hidden.

4. Discussion of the effectiveness of practice parameterisation

4.1 Scope of practice alternatives that can be assessed

The parameterization of practice variables allowed for all the practice changes represented in the Wet Troipcs case studies to be assessed. It is recognized that other alternative practices exist in other Australian cane-growing regions and also in other regions of the world, which were not represented in the assessed sample. These include different types of pesticide spraying equipment that reduces overspray losses of pesticides (shielded sprayers etc.), different irrigation systems, the use of biodiesel in farm machinery, pre-harvest burning of cane, and manual rather than mechanical harvesting, The parameterization in CaneLCA allows for these alternatives to be evaluated, but they were not tested as they were not represented in the assessed sample.

The tool currently would not enable very innovative practices to be assessed, such as new fertiliser formulations (such as those with nitrification inhibitors or slow release coatings), or the use of soil additives to manage the micro-organism environments of soils, as examples. Therefore the tool is effective for evaluating known practice alternatives, such as the ‘best practices’ assessed here, but may be less effective for evaluating very innovative alternatives. This is because alternative inputs and processes that have not been foreseen cannot be evaluated by the tool without modifying the underlying algorithms and factors within the tool. Therefore the scope of practice alternatives that can be assessed by customised tools such as CaneLCA is limited by the in-built analysis algorithms and factors.

The examples of actual practice changes evaluated in this work made it possible to account for the full implications of the practice alternatives. For example, the changed pest management practices influenced the type and amount of pesticide products applied, but also machinery operations. Changed row spacing to reduce machinery movements necessitated capital goods changes to tractors and harvesters. Ceasing the burning of harvest residues introduced additional machinery operations for management of the retained harvest residues and changed fertilizer application rates. Introduction of a legume break crop changes the nitrogen applied to the follow-on cane crop also influenced weed management practices. These are examples of the inter-relationships between individual practices that make up a farming system. The tool provided a whole-of-farming system assessment framework to enable the full implications of practice change to be accounted for. However, it needed the knowledge of the farmer to define what the full implications would be. This is an important consideration for assessing eco-efficiency in agriculture.

4.2 Scope of environmental implications considered

The tool was able to account for most of the implications associated with the practice changes, for the impact categories assessed. Those that could not be assessed were the effects of changed tractor movement, tillage intensity, retention of harvest residues, and use of organic soil ameliorants on soil quality (compaction, erosion, soil organic carbon). These are known to influence nitrous oxide emissions, water use, soil carbon exchanges and even pesticide emissions (Bessou et al. 2010; Luis Antille et al. 2015; Masters et al. 2013; Page et al. 2013), but easily quantifiable relationships have not yet been established. This means that assessment of some GHG and EUT implications were omitted, and the significance of this is not known. It is recommended that once methods for predicting soil quality effects are developed within emerging frameworks for land-use related impact assessment (Garrigues et al. 2012; Koellner et al. 2013), these aspects be accounted for in future iterations of the method. For example, the soil compaction model proposed by Garrigues and colleagues (2013) is a good candidate.

Given the previously mentioned uncertainty in relation to emissions estimates, it is recommended that in future iterations of the tool consideration be given to integrating simple dynamic models that can better estimate emissions based on site- or region-specific conditions, instead of default emission factors. Examples of where this has been attempted are the FarmLife (Herndl et al. 2015) and CropLCA (Goglio et al. in press) tools, which integrate the SALCA emission models for N emissions (Nemecek and Schnetzer 2011). Other models which may be considered are PestLCI for pesticide emissions (Dijkman et al. 2012) and RUSLE for phosphorus emissions via soil erosion (Ouyang and Bartholic 2001).

For cane yields, it is not feasible to replicate in CaneLCA the agronomic modelling needed to simulate yields under varying practice parameters, as in models such as APSIM (Keating et al. 2003). We therefore recommend that sensitivity analyses of the results to potential yield variances be conducted when comparing alternatives.

4. Conclusions

We developed a customised LCA method and tool for cane growing (CaneLCA) by focusing on the ‘cradle to farm gate’ system and relevant impact categories. The novelty of the tool is the parameterisation of practice variables in order evaluate the environmental implications of agricultural practice alternatives in more detail than is generally possible with LCA software. The tool is suited for use by agricultural extension advisors and the farmers they support, but also agricultural researchers and natural resource managers.

The effectiveness of the tool’s parameterization for evaluating practice alternatives was tested by assessing six case studies of actual practice changes at cane farms in the Wet Tropics regions of Australia. The parameterization of practice variables allowed for all of the practice changes represented in the sample to be evaluated. However we noted that the scope of assessable practice alternatives is limited by the inbuilt analysis algorithms and factors, and so is more suited to evaluating known practice alternatives, and less so for evaluating very innovative alternatives. Many of the environmental implications to be accounted for, except for those that effect soil quality (compaction, soil organic carbon, erosion) and the consequent implications for nitrous oxide emissions, nitrate leaching and soil carbon exchanges. This will be an important area for future tool development to fully understand the implications of agricultural practice change. The aspects of greatest uncertainty were found to be potential yield changes from changed practices, and the use of generic emission factors for estimating nutrient and pesticide losses. As yield simulations are too complex to be accommodated in a customised tool, sensitivity of the results to potential yield variances is necessary. Simple dynamic models that better estimate emissions based on site- or region-specific conditions is also warranted for future iterations of the tool.

The tool is a step forward in the development of customised tools that make the LCA of alternative agricultural practices easier, thereby speeding up progress towards more sustainable agriculture. It provides a template that could be adapted to regions other than Australia, because practices are not too dissimilar across the world. This would require modifications of the impact categories assessed, underlying emission factors, embodied impact factors and impact characterisation factors to suit the regional context. This approach could also be adapted to other perennial crops.

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Table 1 Practice variables and parameters for generating the inventory of inputs and outputs in CaneLCA

Category	**Practice variables**	**Practice parameters**	**Environmental aspects influenced**
System definition	Composition and yields of crops in the cane system	crop classes included in the cane system - cane crop classes (type /areas / yields) - other crops (type /areas / yields) - non-productive fallows (type /areas) - non-productive headland areas (area) - seed cane requirements	Crop production influences all impacts The higher the crop production, the lower the impacts per unit of product, and vice versa
		for break crops included in the cane system - type of N-fixing crop - fate of N-fixing crops (harvested, turned in)	Production and supply of synthetic N fertilisers Emissions of N
Machinery	Machinery and implements in service	- number of pieces of machinery and implements - power rating of machinery, size of implements - life span	Production of machinery (steel, aluminium, rubber, plastics pipe, concrete, etc)
	Tractor / truck operations for calculating fuel use	- machinery and implement selection - power rating - operating factors (row width, load factor, field efficiency and speed) - type of fuel / energy used - number of machinery operations for cultivation, nutrient application, pesticide application and other farm operations	Production of fuel Emissions of fuel combustion gases to air
Nutrient application	Type and amount of nutrient products	- form of fertiliser products (synthetic, organic) - nutrient content of products (NPKS) - application rates - N provided by legume fixing and in residues	Production and supply of synthetic fertilisers and ameliorants Emissions of nitrous oxide (N_2O) to air from denitrification of applied N Emissions of N and P to water Emissions of ammonia (NH_3) to air from volatilisation of NH_4-N
	Type and amount of soil ameliorant products	- type of ameliorant (lime, dolomite, gypsum) products - application rates	
	Application methods	- type of application (to soil surface, sub-surface or foliar)	
Pest application	Type and amount of pest products	- active ingredients (herbicide, insecticide, fungicide) - application rate	Production and supply of pesticides Emissions of pesticide to water
	Application methods	- type of spray system	
Harvesting (including residue management)	Pre- or post-harvest burning and trash retention	- harvesting practice (green, burnt, whole) - proportion of residues that are retained in the field	Trash retention influences N cycling and hence the demand for synthetic N fertilisers Emissions of combustion gases to air from cane burning
	Harvesting / haulout operations for calculating fuel use	- operating factors (row width, speed) - type of fuel / energy used	Production of fuel Emissions of fuel combustion gases to air
	Harvesting efficiency with respect to product loss	- type of fan on the harvester - fan speed	Emissions of sugar to water from harvesting
Water management	Irrigation infrastructure	- type and area of irrigation infrastructure - life span	Production of infrastructure components (steel, aluminium, rubber, plastics pipe, concrete, etc)
	Water use for irrigation	-volume of water applied -source of water	Extraction of water from managed sources
	Energy use for pumping water	- head pressure - energy efficiency of pumps - source of energy used (fuel, electricity)	Production of energy Emissions of fuel combustion gases to air
Transport effort	Transport effort to supply inputs to farm	- delivery distances from manufacturer and retailer for fertilisers, soil ameliorants, pesticides, fuels	Impacts associated with transportation

Table 2 Environmental impact categories and performance indicators reported by CaneLCA(1.03)

Environmental impact category	**Environmental performance indicators in CaneLCA** (% of estimated industry maximum)	**Impact assessment methods**	**Industry maximum LCIA value used a for generating relative environmental performance indicator** (derived from Renouf et al. (2010))
Non-renewable energy use (NRE) (MJ/t cane)	Fossil fuel use	Abiotic depletion (of fossil fuels) (Guinee et al. 2002), as used in the CML collective set of methods (Guinee et al. 2002). It is the aggregation of the lower (net) calorific values of fossil fuels consumed over the product life cycle.	900
Greenhouse gas emissions (GHG) (kg $CO_{2\text{-eq}}$/t cane)	Carbon footprint	Global Warming Potentials (GWP) for a 100 year time horizon from the IPCC Fifth Assessment Report (Myhre et al. 2013), as used in most method sets.	100
Water scarcity (WS) (m3 $H_2O_{\text{-eq}}$//t cane)	Water use	Method of Ridoutt and Pfister (2010) with water stress indices of Pfister et al. (Pfister et al. 2009)	185
Eutrophication potential (EUT) (kg $PO_{4\text{-eq}}$/t cane)	Water quality risk (from nutrients)	Aquatic eutrophication potentials based on Heijungs et al. (1992), as used in the CML collective set of methods (Guinee et al. 2002). It assumes both N- and P-species contribute to eutrophication	0.75
Eco-toxicity potential (ETOX) (freshwater) (CTUe/t cane)	Water quality risk (from toxic substances)	USEtox Version2.01 (March 2016) (Rosenbaum et al. 2008), factors for Australia (Kounina et al. 2014).	5,000

Notes:
Abbreviations: MJ = megajoules (net calorific value); $H_2O_{\text{-eq}}$ = water use equivalent; $CO_{2\text{-eq}}$ = carbon dioxide equivalent; $PO_{4\text{-eq}}$ = phosphate equivalent; CTUe = comparative toxicity unit for ecosystems

Table 3: Representative cane growing practice parameters before and after implementation of alternative practices in the Wet Tropics region

Parameters		Before	After
System definition			
Crop cycle [1]		P,4R,F	P,4R,B
Total farm area (ha)		298	298
Area of cane (ha)		238	238
Area of fallow (ha)		37	0
Area of break crop (ha)		0	37
Headlands (ha)		23	23
Production (kt/yr) [2]		19.9	19.9
Average yield (t/ha) [3]		84	84
Seed cane input (t/ha)		8	8
Machinery			
No. of tractors		6	6
No. of implements		14	13
Row spacing (m)		1.5	1.8
GPS guidance		No	GPS
No. of operations		24	19
Fuel use-tractor (L/t cane)		0.69	0.51
Nutrient application (kg/t cane)			
N , from fertiliser (urea)		1.8	1.5
N, from legume		0.0	0.28
N, from crop residues		0.5	0.5
N - total		2.3	2.3
P total		0.3	0.3
K total		1.2	1.1
S total		0.2	0.2
Pesticide application			
AI applied (g/t cane) / *Toxicity* [4]			
2,4-D	954	7.5	5.6
Atrazine	100,835	2.1	1.0
Diuron	66,445	15.2	3.2
Fluroxypyr	3,360	1.1	1.9
Glyphosate	337	13.1	9.3
Haloxyfop	183,606	-	0.1
Hexazinone	130,854	2.6	1.6
Imazapic	5,779	0.01	0.2
Isoxaflutole	57,448	-	0.7
MCPA	989	-	1.4
Metolachlor	77,327	0.1	2.4
Metribuzin	10,495	-	2.5
MSMA	154	-	0.04
Paraquat	128,913	6.3	4.8
Pendamethalin	521,149	2.1	0.3
Picloram	6,681	0.2	0.3
Mercury	21,813	-	0.01
Biphenthrin	7,106,910	0.1	0.1
Chlorpyrifos	7,534,934	0.1	0.1
Imidichlorprid	3,688	1.7	0.6
Propiconazole	25,423	0.01	0.04
AI – total		52.2	36.1
Harvesting			
Type of harvesting		GCH	GCH
Fuel use–harvester (L/t cane)		2.3	2.0

Notes:

[1] Crop classes: P=plant cane; R=ratoon cane; F=fallow; B=break crop

[2] Cane production is based on recorded amount of harvested cane received at the sugar mill, and does not include cane harvested for seed.

[3] Cane yields are 5-yr average for the 5 years leading up to the completion of the changes The average cane yields were derived from the annual net production and the total area under cane.

[4] Toxicity unit is CTUe= Comparative toxicity unit for ecosystems (Rosenbaum et al. 2008)

Table 4: LCIA results generated by CaneLCA(1.03) and LCA software

Impact category	**CaneLCA** (this study)				**LCA software** (Renouf et al. 2010))
	BEFORE		AFTER		
	Range for the sample	Representative case	Range for the sample	Representative case	
NRE (MJ /t cane)	272 – 426	317	219 – 352	282	416
GHG (kg $CO_{2\text{-eq}}$/t cane)	41 – 65	44	36 – 49	39	54
WS (m3 $H_2O_{\text{-eq}}$/t cane)	0.04 – 1.45	0.14	0.02 – 1.11	0.13	<1
EUT (kg $PO_{4\text{-eq}}$/t cane)	0.27 – 0.43	0.30	0.22 - 0.29	0.26	0.35
ETOX (CTUe/t cane)	1,420 – 3,909	2,014	938 – 2,827	1,640	-

Appendix A: Algorithms and factors used in CaneLCA

Table A1: Algorithms for calculating inputs and outputs

	Algorithm – for emissions factors (EF) see Table A2	Equation number
Machinery and farm infrastructure in service	Machinery mass (kg) = 40.77 x Power (HP) + 189.87	1
	Machinery input (kg/ t cane) = (Machinery mass (kg) x allocation of machinery to the farm (%)) ÷ (cane production (t/yr) x years in service (yr))	2
Machinery operations	Work rate for an operation (ha/hr) = row width (m) x speed (m/hr) x field efficiency factor ÷ 10,000	3
	Fuel use per ha of operation (L/ha) = specific fuel use (L/hr) x load factor ÷ operating rate (ha/hr)	4
	Specific fuel use (L/hr) = power (HP) x 0.75 (kW/HP) ÷ 4	5
	Total fuel use for an operation (L/operation) = fuel use per ha (L/ha) x area treated (ha) x number of passes	6
	Fuel use by combine harvester (L/ t crop harvested) = (6 L/ha + 0.5 L/t crop) ÷ crop production	7
Nutrient products applied	Fertiliser product used (kg, L, m^3) = application rate (kg, L, m^3/ha) x number of applications x area treated (ha)	8
	N,P,K,S used (kg) = amount of fertiliser product applied (kg, L, m^3) x N,P,K,S content of fertiliser product (%)	9
	Urea used (kg) = [total N applied – (N from DAP + N from Granam)] (kg) ÷ N content in urea (46%)	10
	DAP used (kg) = P used (kg) ÷ P content in DAP (20%)	11
	KCl used (kg) = K used (kg) ÷ K content in KCl (50%)	12
	Gramam used (kg) = S used ÷ S content in Granam (24%)	13
	Ameliorant product used (t) = application rate (t/ha) x number of applications x area treated (ha)	14
	N from cane or legume residues (t) = crop production (t) x residue to crop ratio x dry matter content of crop residue x mass fraction of C in crop residue x N:C ratio in crop residue x fraction of crop retained (%)	15
	N fixed by legume crop (kg) = area of legume crop production (ha) x N fixation factor (kg:ha)	16
Pesticide products applied	Pesticide product used (kg, L) = application rate (kg/ha, L/ha) x number of applications x area treated (ha)	17
	AI used (kg) = amount of pesticide product applied (kg, L) x AI content of pesticide product (%)	18
Water management	Water used (ML) = area irrigated (ha) x application rate (ML/ha), OR	21
	Water used (ML) = pumping rate (ML/hr) x pumping duration (hrs/application x no. of applications)	22
	Electricity use for pumping (kWh) = gravity acceleration constant (9.81) ÷3.6 x volume of water pumped (ML) x head pressure (m) ÷ pump efficiency (%)	23
	Fuel used for pumping (L) = gravity acceleration constant (9.81) x volume of water pumped (ML) x head pressure (m) ÷ (pump efficiency (%) x 38 kWh/L)	24
Transport effort	Transport effort for fertiliser products per mode (t.km) = total Urea / DAP / KCl / Granam used (t) x transport distance per mode (km)	25
	Transport effort for pesticide products per mode (t.km) = total pesticide product used (t) x transport distance per mode (km)	26
Emissions	Ammonia emissions via urea volatilisaton (kg NH_3) = total N applied (kgN) x fraction that is surface applied (%) x NH_3 EF x 1.21 kg NH_3 /kgN	27
	Direct nitrous oxide emissions via denitrification (kg N_2O) = N applied from fertiliser, mill by-products and residues (kgN) x N_2O EF-d	28
	Nitrate emissions via groundwater leaching and surface runoff (kg NO_3) = (total N applied (kgN) – NH_3-N lost via volatiliation – N2O-N lost via denitrification) x fraction of remaining N available for loss (Nav) x NO_3 EF x 4.43 kg NO_3 /kgN	29
	Indirect nitrous oxide emissions (kg N_2O) = (Ammonia emissions from urea volatilisaton (kg NH_3-N) x N_2O EF-i + NO_3 emissions to leaching and runoff (kgNO_3-N) x N_2O EF-i) x 1.57 kg N_2O/kgN	30
	Phosphorus loss through runoff (kg P) = total P applied (kgP) x P EF	31
	Pesticide AI emissions through runoff (kg AI) = total AI applied (kgAI) x AI EF	32
	Rate of sugar extrusion (kg sugar / t cane) = $e^{0.0058 \text{ x harvester speed}}$ x 0.0054	33
	Sugar losses in the field (kg sugar) = rate of sugar extrusion (kg sugar / t cane) x harvest yield (t/ha) x area harvested (ha)	34
	Sugar emissions off-farm (kg sugar) = sugar losses in the field (kg sugar) x fraction of harvest days that are wet x Sugar EF	35
	COD emissions via runoff (kg COD) = sugar emissions off-farm (kg sugar) x 1.12 kg COD/kg sucrose	36
	Dry matter burnt (t) = crop yield (t/ha) x area harvested (ha) x residue to crop ratio (0.25) x dry matter content (0.2) x burning efficiency (0.96) (28)	37
	Carbon mass in crop residue (t) = dry matter burnt (t) x carbon mass fraction (0.4)	38
	Nitrogen mass in crop residue (t) = carbon mass in crop residue (t) x N:C ratio (0.025)	39
	CO_2, CH_4, NMVOC emissions (kg) = carbon mass in crop residue (t) x EF for each species x 1000	40
	N2O, NOx emissions (kg) = nitrogen mass in crop residue (t) x EF for each species x 1000	41
	Carbon dioxide emissions from carbonation (kg CO_2) = total lime / dolomite applied (t) x CO_2 EF (kg	42

CO_2/kg)

Table A2: Emission factors

	Value	Unit	Source
Ammonia (NH_3) to air from volatilisation of (NH_3 EF):			
- fertiliser-N surface-applied to bare soil	0.1313	kg N/kg N surface-applied	(Chapman et al. 1995)
- fertiliser-N surface-applied to trash blanketed soil	0.2313	kg N/kg N surface-applied	(Chapman et al. 1995)
-byproduct-N surface-applied to bare soil	0.0875	kg N/kg N surface-applied	(Chapman et al. 1995)
-byproduct-N surface-applied to trash blanketed soil	0.1625	kg N/kg N surface-applied	(Chapman et al. 1995)
Nitrous oxide (N_2O) to air from **direct** denitrification (N_2O EF-d)			
- synthetic fertilisers and mill by-products applied to sugarcane	0.0199	kg N_2O-N/kg N applied	(DEE 2016, S 5.6.2)
-cane harvest residue and legume residues	0.01	kg N_2O-N/kg N applied	(DEE 2016, S 5.6.6) and (IPCC 2006)
-biologically fixed N from legumes	0.00	kg N_2O-N/kg N applied	(IPCC 2006)
Nitrous oxide (N_2O) to air from **indirect** denitrification (N_2O EF-i)			
- for gaseous N redeposited on soil (NH_3 and NOx)	0.0199	kg N2O-N/kg N redeposited	(DEE 2016, S 5.6.9)
- for soluble N species in leaching and runoff	0.0075	kg N2O-N/kg N leached/ runoff	(DEE 2016, S.5.6.10) and (IPCC 2006)
Nitrate (NO3) to water via runoff and leaching:			
-fraction of applied nitrogen available for runoff/ leaching (Nav)	0.656	kg N available /kg N applied	(DEE 2016, S 5.6.10)
-fraction of available N emitted via runoff and leaching (NO_3 EF)	0.300	kg N emitted/kg N available	(DEE 2016, S.5.6.10)
Phosphorus emissions to water: -fraction of phosphorus lost via runoff (P EF)	0.128	kg P/kg P applied	(Bloesch et al. 1997)
Pesticide (active ingredients) emissions to water: - fraction of pesticide active ingredients lost to freshwater (AI EF)	0.100	kg AI/kg AI applied	Estimate
Sugar emissions to water: - fraction of in-field sugar loss that is emitted in runoff in post-harvest rainfall events (Sugar EF)	0.500	kg sucrose /kg in-field sugar loss	Estimate
Carbon dioxide (CO_2) to air from carbonation (CO_2 EF):			
-limestone ($CaCO_3$)	0.3960	kg CO2/kg limestone applied	(DEE 2016, S 4.3.4)
-dolomite ($CaMg(CO_3)_2$)	0.4530	kg CO2 /kg dolomite applied	(DEE 2016, S 4.3.4)
Cane burning emissions to air			
- methane (CH_4)	0.0035	kg CH_4-C/kg C burnt	(DEE 2016, S 5.8.1)
- carbon monoxide (CO)	0.0780	kg CO-C/kg C burnt	(DEE 2016, S 5.8.1)
- non-methanic volatile organic compounds (VOC)	0.0091	kg NMVOC-C/kg C burnt	(DEE 2016, S 5.8.1)
- nitrous oxide (N_2O)	0.0076	kg N_2O-N/kg N burnt	(DEE 2016, S 5.8.1)
- nitrogen oxide (NOx)	0.2100	kg NOx-N/kg N burnt	(DEE 2016, S 5.8.1)

Fig. 1 Components of CaneLCA Version 1.03 workbook

Fig. 2 Components of study method

Fig. 3 Scope of the cane growing system assessed in CaneLCA

Fig. 4 Life cycle environmental impact assessment (LCIA) results before and after best practice implementation.

Note: The x-axis is the eco-efficiency performance relative to sector performance (% of the highest sector value. The length of the bar is the relative eco-efficiency performance (%), the percentage values above the bars are the change in the absolute impacts, the colour-coded contributional breakdown shows the activities contributing to impacts.

Figure 1

Methods used in the CaneLCA tool

- 2.1 Goal and scope definition
  - 2.2.1 Goal
  - 2.2.2 System definition
  - 2.2.3 System boundary and functional unit
  - 2.2.4 Spatial scale of evaluation
- 2.2 Inventory of inputs
  - 2.2.1 Machinery and implements in service
  - 2.2.2 Fuel use for tractor / truck operations
  - 2.2.3 Fuel use for harvester operation and haul out
  - 2.2.4 Irrigation infrastructure
  - 2.2.5 Nutrient inputs
  - 2.2.6 Pesticide inputs
  - 2.2.7 Water input
  - 2.2.8 Eneregy inputs for pumping water
  - 2.2.9 Transport effort for the supply of inputs
- 2.3 Inventory of emissions
  - 2.3.1 Nitrogen emissions
  - 2.3.2 Phosphorus emissions
  - 2.3.2 Pesticide emissions
  - 2.3.4 Sugar emissions
  - 2.3.5 Combustion emissions from cane burning
  - 2.3.6 Carbon fluxes
- 2.4 Impact assessment and performance indicators

Testing effectiveness of CaneLCA for evaluating practice alternatives

- 2.5 Case study evaluations of practice change
- 2.6 Criteria for evaluating effectiveness

Figure 2

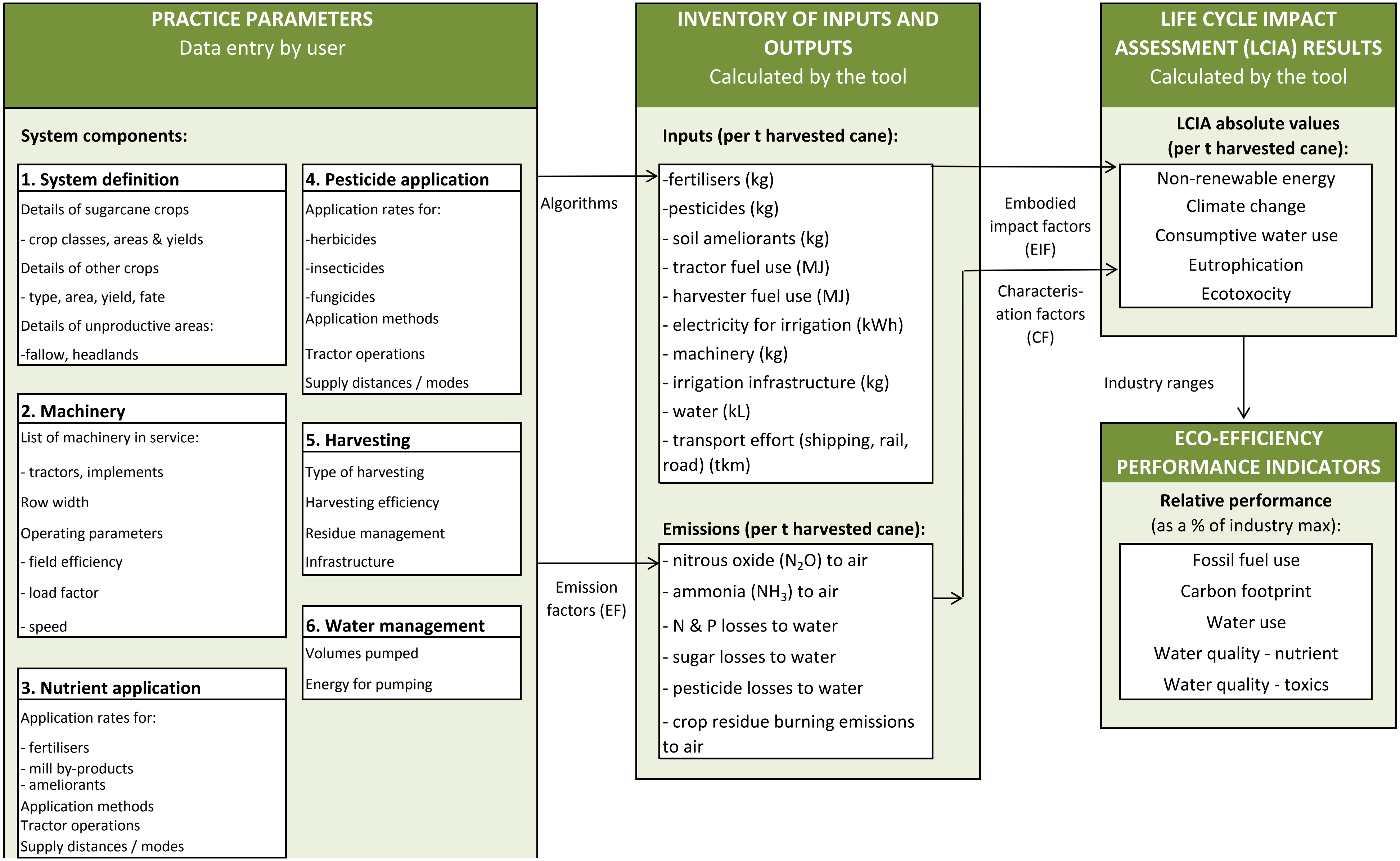

PRACTICE PARAMETERS
Data entry by user
System components:
1. System definition
Details of sugarcane crops
- crop classes, areas & yields
Details of other crops
- type, area, yield, fate
Details of unproductive areas:
-fallow, headlands
2. Machinery
List of machinery in service:
- tractors, implements
Row width
Operating parameters
- field efficiency
- load factor
- speed
3. Nutrient application
Application rates for:
- fertilisers
- mill by-products
- ameliorants
Application methods
Tractor operations
Supply distances / modes
4. Pesticide application
Application rates for:
-herbicides
-insecticides
-fungicides
Application methods
Tractor operations
Supply distances / modes
5. Harvesting
Type of harvesting
Harvesting efficiency
Residue management
Infrastructure
6. Water management
Volumes pumped
Energy for pumping
Algorithms
Emission factors (EF)
INVENTORY OF INPUTS AND OUTPUTS
Calculated by the tool
Inputs (per t harvested cane):
-fertilisers (kg)
-pesticides (kg)
- soil ameliorants (kg)
- tractor fuel use (MJ)
- harvester fuel use (MJ)
- electricity for irrigation (kWh)
- machinery (kg)
- irrigation infrastructure (kg)
- water (kL)
- transport effort (shipping, rail, road) (tkm)
Emissions (per t harvested cane):
- nitrous oxide (N_2O) to air
- ammonia (NH_3) to air
- N & P losses to water
- sugar losses to water
- pesticide losses to water
- crop residue burning emissions to air
Embodied impact factors (EIF)
Characteris-ation factors (CF)
LIFE CYCLE IMPACT ASSESSMENT (LCIA) RESULTS
Calculated by the tool
LCIA absolute values (per t harvested cane):
Non-renewable energy
Climate change
Consumptive water use
Eutrophication
Ecotoxocity
Industry ranges
ECO-EFFICIENCY PERFORMANCE INDICATORS
Relative performance (as a % of industry max):
Fossil fuel use
Carbon footprint
Water use
Water quality - nutrient
Water quality - toxics

Figure 3

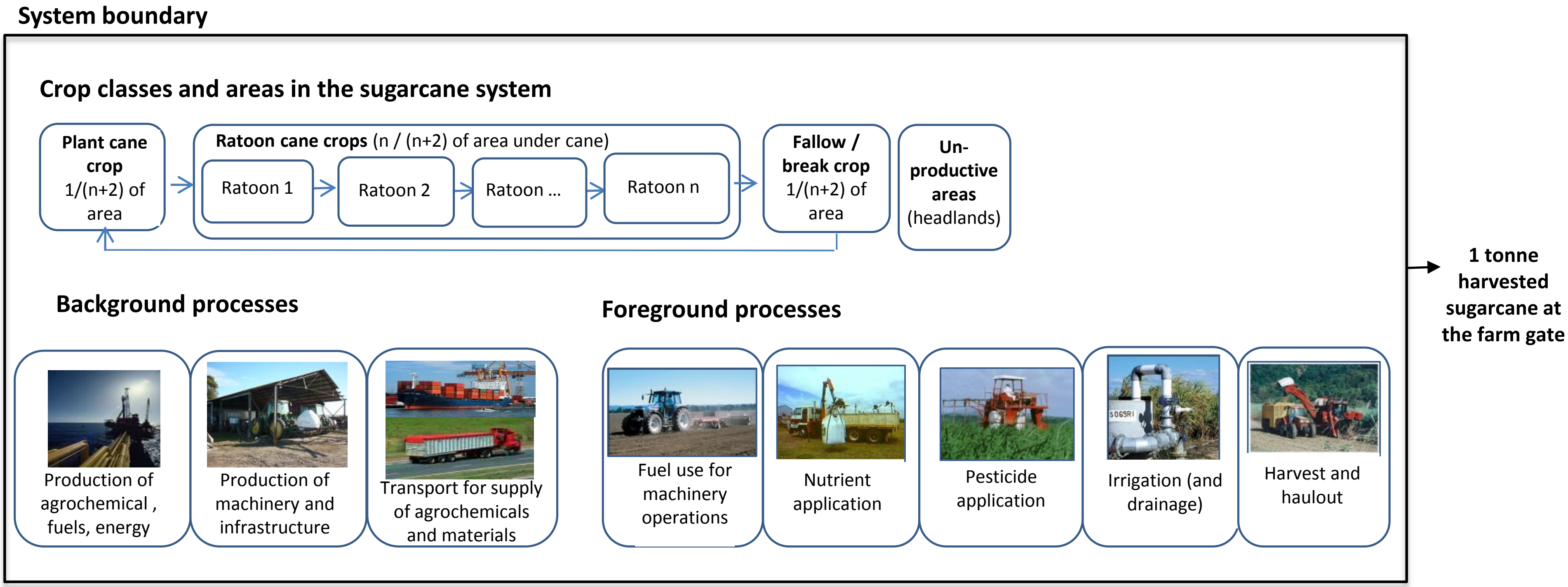
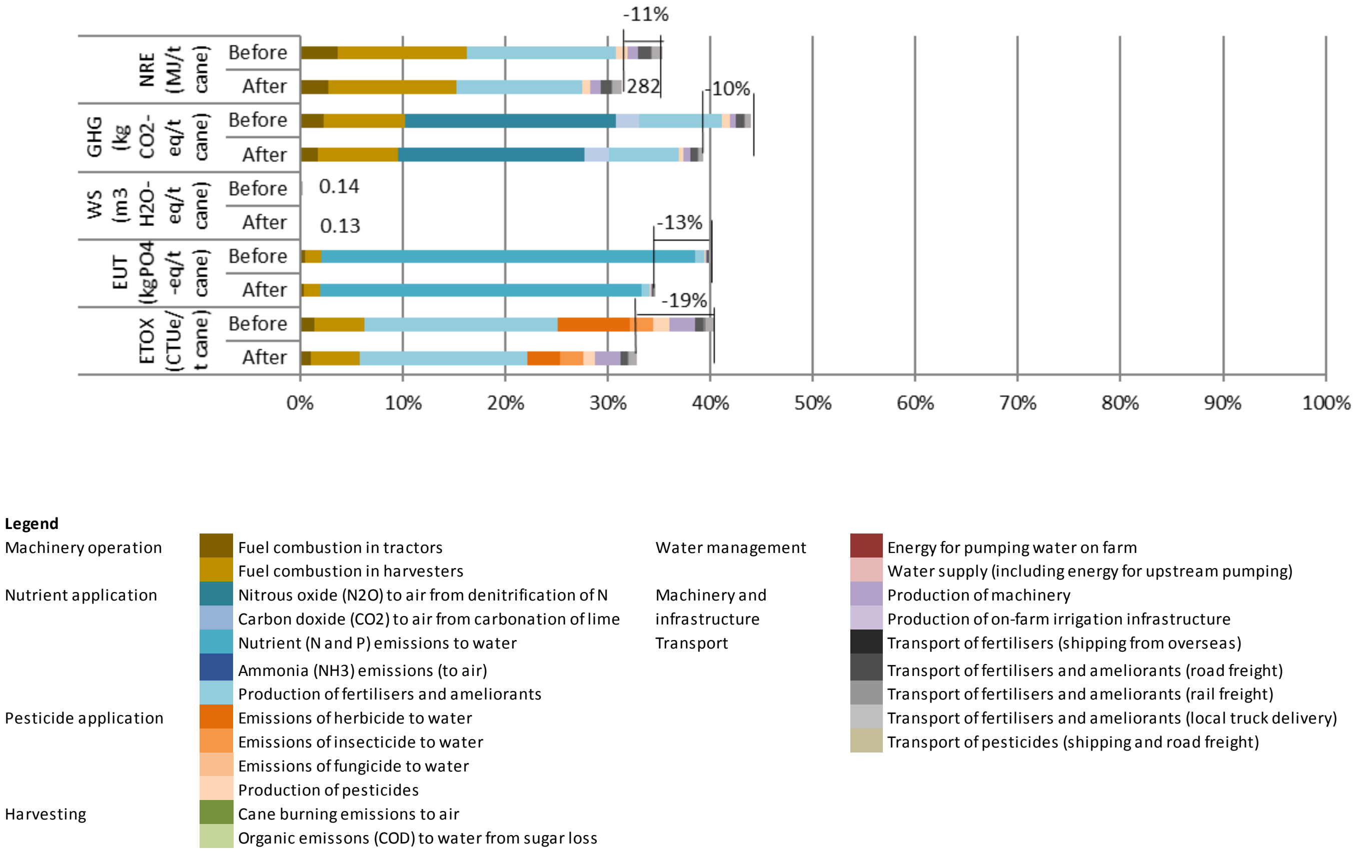

System boundary
Crop classes and areas in the sugarcane system
Plant cane crop 1/(n+2) of area
Ratoon cane crops (n / (n+2) of area under cane)
Ratoon 1
Ratoon 2
Ratoon ...
Ratoon n
Fallow / break crop 1/(n+2) of area
Un-productive areas (headlands)
Background processes
Production of agrochemical , fuels, energy
Production of machinery and infrastructure
Transport for supply of agrochemicals and materials
Foreground processes
Fuel use for machinery operations
Nutrient application
Pesticide application
Irrigation (and drainage)
Harvest and haulout
1 tonne harvested sugarcane at the farm gate

Figure 4


-11%
282
-10%
-13%
-19%
NRE (MJ/t cane)
GHG (kg CO2-eq/t cane)
WS (m3 H2O-eq/t cane)
EUT (kgPO4-eq/t cane)
ETOX (CTUe/t cane)
Before
After
0.14
0.13
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Legend
Machinery operation
Fuel combustion in tractors
Fuel combustion in harvesters
Nutrient application
Nitrous oxide (N2O) to air from denitrification of N
Carbon doxide (CO2) to air from carbonation of lime
Nutrient (N and P) emissions to water
Ammonia (NH3) emissions (to air)
Production of fertilisers and ameliorants
Pesticide application
Emissions of herbicide to water
Emissions of insecticide to water
Emissions of fungicide to water
Production of pesticides
Harvesting
Cane burning emissions to air
Organic emissons (COD) to water from sugar loss
Water management
Energy for pumping water on farm
Water supply (including energy for upstream pumping)
Machinery and infrastructure
Production of machinery
Production of on-farm irrigation infrastructure
Transport
Transport of fertilisers (shipping from overseas)
Transport of fertilisers and ameliorants (road freight)
Transport of fertilisers and ameliorants (rail freight)
Transport of fertilisers and ameliorants (local truck delivery)
Transport of pesticides (shipping and road freight)