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LIFE CYCLE ASSESSMENT: A TOOL FOR INNOVATION IN LATIN AMERICA

A comparative life cycle assessment of the sugarcane value chain in the province of Tucumán (Argentina) considering different technology levels

Andrea Lorena Nishihara Hun[1] · **Fernando Daniel Mele**[1] · **Gonzalo Antonio Pérez**[2]

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Abstract

Purpose The purpose of this work is to quantify the environmental impact of the sugarcane industry in Tucumán (Argentina) through the life cycle analysis (LCA). The distinctive feature is the consideration of different technology levels (TLs) in the agricultural stage: high (HTL), medium (MTL), and low (LTL).

Methods The scope of the study covers the agricultural and industrial stages through a "from cradle to gate" approach (from sugarcane cultivation until production of finished products: sugar and alcohol). The system is divided into *Agriculture*, *Sugar Factory*, and *Distillery*. Data used for the inventory are mainly provided by local experts, sugarcane growers, and processing companies. The characteristics of each TL are taken from a regional classification. For the impact assessment, the CML 2001 model (nine impact categories) is used.

Results and discussion Regardless of the TL, in most of the impact categories, an important contribution attributable to the use of synthetic agrochemicals is evident. As for the comparison among TLs, the ethanol produced with HTL has less impact values than the ones produced with MTL and LTL in seven categories. These results can be mainly explained by the better cultural yields obtained with HTL, and to the fact that sugarcane is not burnt before harvesting in HTL as it is in MTL and LTL.

Conclusions This study explores the implications of using different TLs for the agricultural tasks on the sugarcane supply chain in Tucumán, which is characterized by a vertically non-integrated productive scheme. If practices associated to HTL are implemented, a reduction of the environmental impact is observed in most categories. It is necessary to compare these results with economic and social implications to ensure sustainability of the sugarcane value chain.

Keywords Bioethanol · Biofuels · Biorefinery · Environmental profile · Sugar · Sustainability

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✉ Fernando Daniel Mele
fmele@herrera.unt.edu.ar

[1] Departamento de Ingeniería de Procesos y Gestión Industrial, Universidad Nacional de Tucumán, Av. Independencia 1800, T4002BLR San Miguel de Tucumán, Argentina

[2] EEA Famaillá, Instituto Nacional de Tecnología Agropecuaria (INTA), RP 301 km 32, Famaillá 4132, Argentina

1 Introduction

Sugar industry is an important activity at global level. The sugar world production during campaign 2014/2015 reached 174 million tons (USDA 2015). Most sugar is derived from sugarcane (*Saccharum officinarum*) and the remainder from sugar beet (*Beta vulgaris*). In contrast to sugar beet production, which has declined in recent decades, sugarcane cultivation has undergone strong growth, leading to world production values of about 1.7 billion tons in the last years (FAO 2013). Sugarcane production is concentrated in tropical regions, particularly in developing countries in America, Asia, and Africa. Nowadays, 80 % of the global production of sugar and a big portion of the fuel ethanol come from sugarcane cultivation. Brazil and India rank first as world sugar producers; Argentina occupies position number 14, with a production rate very similar to Indonesia, Ukraine, Colombia, and South Africa. Regarding sugarcane-based ethanol, Brazil leads the worldwide production (Cremonez et al. 2015). The

Latin American countries have abundant natural resources and a big deal of agricultural potential, which challenges them to become global suppliers of bio-based products, among them those derived from sugarcane. It is a species with outstanding features such as resistance, rapid growth, and uptake capacity for atmospheric carbon. The ethanol production from sugarcane can help to mitigate global warming. Nevertheless, there are some drawbacks associated with sugarcane intensification, such as land use change, competition with food, the environmental impact associated with the transport sector, and the generation of large amounts of wastewater. In addition to this, the rapid expansion of one of the products production can affect the international market of the others. Such a complex context poses significant challenges for practitioners, researchers, and the government.

The Argentine sugar industry is based exclusively on sugarcane, and its primary focus is the domestic market. Sugarcane production concentrates in two zones: the Northwest (Tucumán, Salta and Jujuy) and the Northeast. The sugarcane industry features 23 sugar mills, 16 ethanol distilleries, and 9 plants for ethanol dehydration. This industry is one of the cornerstones of the economy of the province of Tucumán (15 sugar mills) (Argentine Sugar Centre 2015), with a plantation area for sugarcane covering about 250,000 ha and a sugar production, during campaign 2014, of 65.1 % of the national production (EEAOC 2015). There prevails a productive system formed by more than 5000 independent growers, with different technology levels (TLs) and different degree of access to the productive factors, which sell their production to the sugar mills through different commercial schemes (INDEC 2002). This exchange structure between growers and sugar mills—a nonvertically integrated supply chain—is different from the main sugarcane areas of the world where sugarcane production and mills are vertically integrated (Acreche and Valeiro 2013). From an environmental point of view, a worse behavior of nonintegrated systems would be expected since there is no central management between stakeholders; this is specifically seen in the following aspects:

1. There are no long-lasting contracts to collect crop trash to be used as boiler fuel in sugar mills. This would allow to avoid fossil fuel usage as well as to sell electricity surplus to the electric grid. Furthermore, it would avoid open-air trash burning and decomposition in the fields.
2. Usually, cane growers do not permit fertigation with filter cake and vinasses coming from the industrial stages. If they did, this practice would decrease the synthetic fertilizer requirements.
3. A better logistic management between crop fields and factories could result in lower transport needs, decreasing the emission releases.

It is worth noting that sugarcane stands out by its socioeconomic relevance. In the sugarcane crop areas, a higher degree of industrialization can be observed as well as an expansion of the productive infrastructure. This generates an increase of employment, especially during harvesting (*zafra*). Furthermore, the sugar sector acts as a promoter of a variety of other activities which develops around the agroindustry, such as trading and supply systems.

Sugarcane industry also generates a big portion of the Argentine ethanol as a sugar co-product. Argentina published Law 26,093, which brings the framework for biofuel investment, production, and commercialization. With this, sugarcane industry was given a boost, as this law, implemented in 2010, establishes a minimum content of bioethanol to be blended with gasoline at 5 %. The main objective of this measure is to reduce the emissions of carbon dioxide and other greenhouse gases (GHGs), to diversify energy supply and to promote the development of rural zones, especially beneficiating the small- and medium-sized sugarcane growers.

In this work, we propose to assess the environmental impacts of the sugarcane activity in Tucumán by using the life cycle assessment (LCA). The novelty of our approach is that we explicitly take into account the three different TLs currently applied in the agriculture stage.

The LCA studies conducted on the Argentine sugarcane value chain are just emerging. Some relevant contributions on this last issue, of recent appearance in the literature, correspond to the joint efforts of two research groups belonging to the Universidad Nacional de Tucumán and the Universitat Rovira i Virgili (Mele et al. 2011; Amores et al. 2013; Nishihara Hun 2014). Precisely, the motivation for the proposed work comes from a conclusion drawn in the aforementioned studies: agriculture tasks have been identified as the main source of impacts in sugar and ethanol production. It is important to mention that there has been many important contributions related to sugarcane industry in other countries in the last years, e.g., Australia (Renouf et al. 2011), Brazil (Macedo et al. 2008; Ometto et al. 2009; Seabra et al. 2011; Cavalett et al. 2012; Galdos et al. 2013), Mexico (García et al. 2011), and Thailand (Nguyen and Gheewala 2008; Jenjariyakosoln et al. 2014), among others. None of these studies are comparable enough to the case of Argentina as they analyze specific geographic situations and practices. To the best of our knowledge, there is no environmental study discriminating different agricultural practices (technology) in sugarcane agricultural management, in which sugarcane production and mills are not integrated.

Through this work, it is expected to shed light on the decisions to make so as to increase the sustainability of the Argentine sugarcane activity, which will consequently lead to the sustainability of its main products: sugar and bioethanol.

2 Methods

The methodological structure used in this study follows the guidelines of the International Standardization Organization (ISO) 14040 and 14044 standards on LCA (ISO 14040 2006a, b). The main goal is to outline the environmental profile of the sugarcane value chain in Tucumán, taken into account three TLs for the agricultural labors: high (HTL), medium (MTL), and low (LTL), as defined by local researchers (Giancola et al. 2012). Currently, the approximate distribution of these TLs in the cultivated area is 40, 50, and 10 %, respectively. The main features of each TL are shown in Table 1. While working on the same basis, the LCA is a very suitable tool to carry out this comparison. The approach is "from cradle to gate," which covers the activities from raw material extraction (agricultural stage) to products at the "exit gate" of the manufacturing plants (sugar factories and distilleries). The system description and inventory data were to a large extent the existing ones for this industry in Argentina in 2013 (country-specific approach). System boundaries are expanded to include the impact associated with the production of all inputs (e.g., agrochemicals and fuel). Neither storage nor transport tasks after production have been considered as they lie outside the system boundaries. The functional unit (FU) is referred to 1 kg of bulk anhydrous ethanol.

To build the inventory (life cycle inventory (LCI)), agricultural and industrial data are, as much as possible, specific to the Argentine conditions. However, it is worth noting that since sugarcane industry in Argentina is a secondary activity, data are not fully available nor gathered into a unified database. Therefore, some data are based on average values. Information related to agricultural tasks has been taken from local producers, the Argentine National Institute of Agricultural Technology (INTA), and other governmental institutions. For the industrial stage, standard mass and energy balance coefficients provided by experts from sugar mills and distilleries as well as from the National University of Tucumán has been considered. Data gaps have been filled using specialized literature, handbooks, and databases (e.g., Ecoinvent v3.1). These data, in part, have already been used in other works by the authors (Mele et al. 2011; Kostin et al. 2011a, b; Amores et al. 2013; Nishihara Hun 2014). Although the ISO standards recommend subdividing the system or performing system expansion so as to avoid allocation, as described in the next section, some allocation criteria has been necessary to apply.

For life cycle impact assessment (LCIA), nine impact categories corresponding to the CML 2001 Baseline model (Guinée et al. 2002), one of the most widely applied midpoint LCIA method, are assessed: abiotic resource depletion (AD), acidification (AC), eutrophication (EU), global warming (GW), stratospheric ozone depletion (OD), human toxicity (HT), freshwater aquatic ecotoxicity (FE), terrestrial ecotoxicity (TE), and photochemical oxidants formation (PO). Calculations are performed with the support of Simapro® 8.0.3 (PRé Consultants. SimaPro® 8.0.3 2014).

3 Case study

The system under study is the sugarcane industry of Tucumán (Argentina), which has been split into three subsystems: *Agriculture*, *Sugar Factory*, and *Distillery*, as represented in Fig. 1.

3.1 Agriculture

The subsystem *Agriculture* includes all the activities involved in sugarcane production such as planting, cultivation, and harvesting. Sugarcane (ready-to-transport sugarcane stalks leaving the crop fields) is regarded as the main product of this subsystem. As said before, in the province of Tucumán, production of this crop is developed following practices that have been classified into three TLs: HTL, MTL, and LTL, characterized by a system of hand plantation with low use of agrochemicals. Artificial irrigation is not significant (Romero et al. 2009). As a usual practice, sugarcane is allowed to grow with the same stalk several times after harvesting. The annual renewal percentage depends on the TL. The portion of the plantation formed by new plants will be henceforth referred as "cane plant," whereas the rest of the plantation, of two or more years old, will be called "cane ratoon." The subsystem *Agriculture* is thought as a unit process, in which all contributing processes are accounted. This unit process and their contributors (cane plant, cane ratoon, and harvesting) are illustrated in Fig. 2.

Figure 3 describes the unit process corresponding to cane plant. This process has as inputs and output several streams related to the net CO_2 uptake (photosynthesis-respiration balance), water use (machinery washing, agrochemicals dilution), cultivation, and pulverization. The CO_2 uptake has been

Table 1 Main features of the three technology levels (TLs) considered for the agricultural labors

Main differential aspects	High (HTL)	Medium (MTL)	Low (LTL)
Crop yield (t/ha)	75	62	55
Harvest system	Mechanized	Semi-mechanized	Semi-mechanized + manual
Trash burning	Scarce	Total	Total
Agrochemicals use	Intensive	Moderate	Scarce

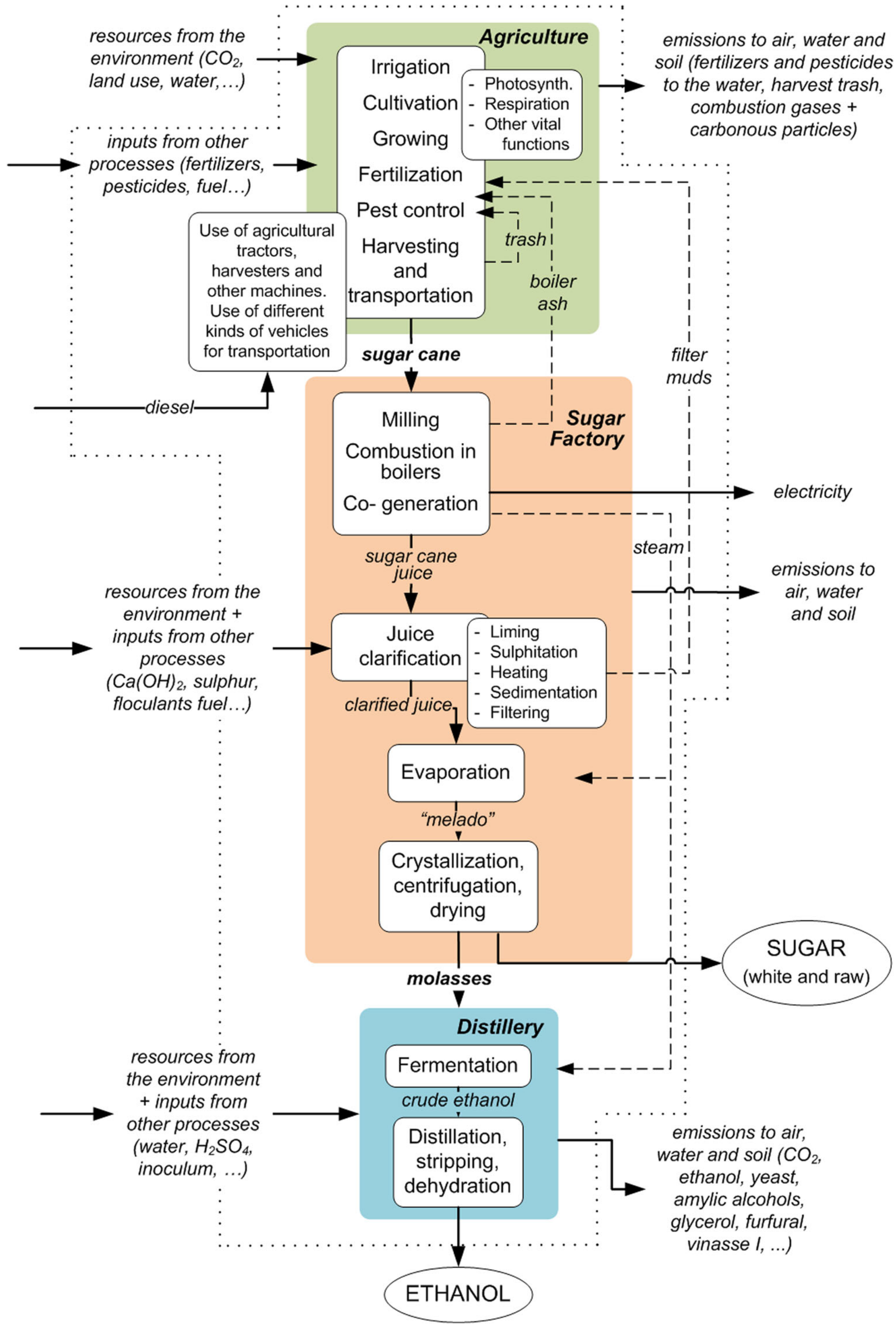

Fig. 1 Schematic of the overall system under study with three subsystems: *Agriculture*, *Sugar Factory*, and *Distillery*

taken from the carbon balance proposed by Beeharry (2001), and its value per hectare varies according to the TL. Those tasks associated to sugarcane seed have not been considered as they are negligible if compared to the remaining agricultural labors. Cultivation includes infrastructure plus fuel used for the tasks of ploughing, chiseling, furrowing, among others, corresponding to soil preparation. The infrastructure accounts for the manufacturing of tractors, nonmoving machinery, and sheds. The pulverization tasks for cane plant consider the infrastructure and fuel used for agrochemicals application. In general, N fertilizer is supplied as urea and P fertilizer as triple super phosphate. No K fertilizer is applied in sugarcane production in Tucumán. Other agrochemicals used are ametryn, atrazine, and 2,4-D. The type and dose of each agrochemical strongly depend on the TL (see Table 2).

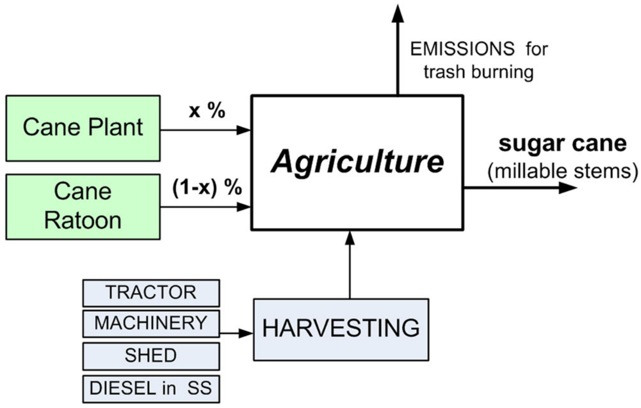

Fig. 2 Subsystem *Agriculture*. Detail of the processes that bring environmental burdens to the subsystem *Agriculture*. The main subsystem output is harvested sugarcane

Along the whole study, the production and distribution processes for diesel and electricity is adapted as much as possible to the Argentine context by taken as starting point data belonging to Ecoinvent v3.1 database (PRé Consultants. SimaPro® 8.0.3 2014). The following energy matrix for Argentina is considered: coal (1.8 %), diesel (2.9 %), oil (9.4 %), natural gas (44.5 %), hydro (35.5 %), and nuclear (5.9 %) (Secretaría de Energía 2009).

Due to space limitations, not all the processes are thoroughly described; however, data are available upon request from the authors. Therefore, in the same way as for cane plant, the analysis has included the process cane ratoon, which is not reported in the article.

The process harvesting gathers information related to infrastructure and fuel used during harvesting, taking into account that the harvesting method varies with the TL: mechanized (green harvest), semi-mechanized, or manual. In the first case, a harvester machine harvests, chops, cleans, and handles the cane in the form of billets, which are then loaded into a lorry. No preharvest burning is necessary. In the second method, sugarcane leaves and tops are burnt before harvesting to facilitate the operation, then cane stalks are cut and a loader machine put the stalks into a lorry. The third method consists of manual felling, topping, de-trashing, bundling, and loading the stalks into the transportation vehicles. Usually, part of the remaining trash is burnt on the field (post-harvest burning).

Intrinsic emissions for the unit process *Agriculture* come mainly from the open-air burning of crop trash. Although it is currently penalized by law, burning before or after harvesting to facilitate cane cutting and diminish the amount of crop residues are carefully considered according to the TL. The GHG emissions have been estimated on the basis of the trash chemical composition, using the emission factors proposed by IPCC (2006) for this kind of material: 2.7 kg CH_4 and 0.07 kg N_2O per ton of dry matter burnt. It is considered that crop trash is 18 % sugarcane (Beeharry 2001). Burning percentage is 50, 70, and 90 % of the cultivated area for HTL, MTL, and LTL, respectively.

Other group of emissions has its origin in the agrochemical transformation after being applied onto the crop: denitrification, volatilization, leaching, and runoff (Nemecek et al. 2007;

Fig. 3 Unit process cane plant. Detail of those processes that bring environmental burdens to cane plant. The main unit process output is raw sugarcane before harvesting

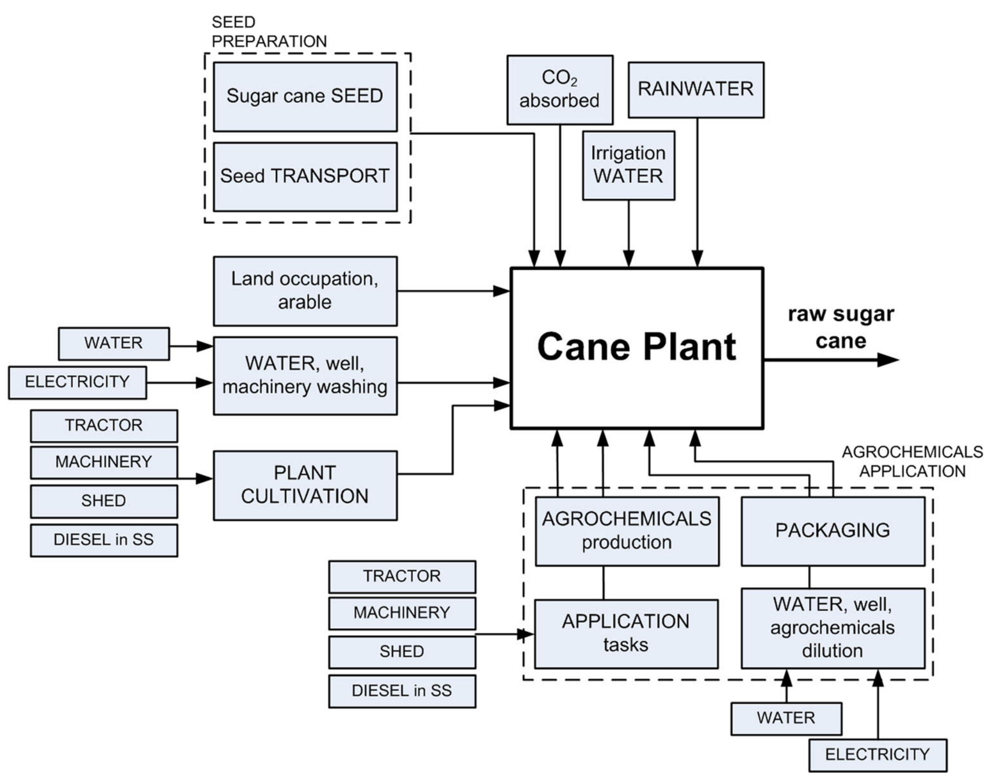

Table 2 Summary of the agrochemicals used in the unit process cane plant

	Commercial form[a]	Formulation (%)	Dose			Active principle (kg/ha)			Packaging (kg/ha)		
			HTL	MTL	LTL	HTL	MTL	LTL	HTL	MTL	LTL
Urea	50 kg (polypropylene bag)	46	120 kg/ha	120 kg/ha	–	55.20	55.20	–	1.200	1.200	–
Triple phosphate	50 kg (polypropylene bag)	45	20 kg/ha	20 kg/ha	–	10.00	10.00	–	0.200	0.200	–
Atrazine	20 L (HDPE bottle)	50	4 L/ha	4 L/ha	–	2.46	2.46	–	0.240	0.240	–
Ametryn	20 L (HDPE bottle)	50	1 kg/ha	–	–	0.50	–	–	0.051	–	–
Acetochlor	20 L (HDPE bottle)	80	2 L/ha	2 L/ha	–	1.79	1.79	–	0.120	0.120	–

[a] Taken from Portocarrero et al. (2011)

Renouf et al. 2008). Nitrous oxide emissions stand out for their contribution to GW, a fact that has been noted in several studies along with the uncertainty of their assessment (Smeets et al. 2009; Cardoso Lisboa et al. 2011; Acreche and Valeiro 2013, etc.). In this study, the emission factor used, 4.26 kg N_2O-N/100 kg N-applied, has been taken from Renouf et al. (2008), which lies within the range of the average value reported by Cardoso Lisboa et al. (2011) in their review work (3.87 ± 1.16 kg N_2O-N/100 kg N-applied). Note that this N_2O emission rate is considerably higher than the generic 1.00–1.25 % (IPCC 2006) for arable cropping. Our assumption is based on the fact that sugarcane in Tucumán is cultivated under conditions of high N availability and organic matter content (some application of filtercake from the sugar mill), factors which favor denitrification (Cardoso Lisboa et al. 2011). In addition, we use also the emission factors reported by Renouf et al. (2008) to account for NH_3 volatilization and NO_3^- leaching: 14.9 kg NH_3/100 kg N and 6.5 kg NO_3^-/100 kg N, respectively.

No emissions from land use change have been considered as the sugarcane area in Tucumán has remained stable for decades. Table 3 shows the main features of subsystem *Agriculture*, according to the TL. The entries for this table are referred to 1 ha of harvested sugarcane. Table 4 shows a summary of the final inventory for this subsystem, reporting the more significant inputs and output. These include entries from the nature (water, fossil fuels, minerals) as well as total emissions to the three compartments (gasses, ions, agrochemicals releases, etc.). Detailed inventory data regarding processes cane plant and cane ratoon for each TL are not included but are available to the interested reader.

3.2 Sugar factory

Harvested sugarcane is transported by lorry to the process through an average distance of 50 km. The productive process starts with sugarcane milling to originate two product streams: bagasse—the lignocellulosic part of the sugarcane—and sugarcane juice (Fig. 1).

Bagasse is burnt in boilers to generate steam and electricity in cogeneration plants to cover both power (mills, pumps, and boiler fans) and heating needs (e.g., evaporation, crystallization) of the sugar plants and distilleries. As for sugarcane juice, it undergoes a physicochemical treatment to remove substances that interfere with sucrose crystallization (sulphitation, liming, heating, and decantation). The filter muds (*cachaza*) generated are sent to the sugarcane fields. The clarified juice (12 wt% of dissolved solids) is concentrated by evaporation (65 wt% of solids), to be next sent to the crystallization section where sugar crystals and mother liquor (honeys) are produced. In Tucumán, crystallization is a three-staged process yielding white sugar, raw sugar and molasses (exhausted honey).

The inputs and output of the subsystem *Sugar Factory* are shown in Fig. 4. The output with economic value are white sugar, raw sugar, and molasses. Other output include ashes (2.4 % of the cane weight) and filter muds (4.05 % of the cane weight) which are not considered as net output because they are recycled to fields. Electricity generation to the external grid is considered negligible as only one of the 15 sugar mills currently exports electricity, in a discontinuous way. Regarding the bagasse usage, it is considered that it is thoroughly burnt in boilers for steam generation.

Being a multiproduct system, and following the criteria recommended by Amores et al. (2013), environmental burdens are allocated by the co-products mass. Therefore, the allocation factors for white sugar, raw sugar, and molasses are 60.6, 10.3, and 29.1 %, respectively, according to the production of each product (Argentine Sugar Centre. Available at: www.centroazucarero.com.ar. Accessed May 1 2015).

As additional inputs for this subsystem, apart from sugarcane coming from the subsystem *Agriculture*, we consider transport (infrastructure plus fuel), water, the energy not covered by bagasse (gas natural and external electricity), and other process supplies such as sulfur, lime, lubricants, and flocculants.

With respect to emissions from this subsystem, we assess those derived from combustion in boilers, from both natural

Table 3 Main features of subsystem *Agriculture* (reference: 1 ha harvested sugarcane)

		HTL	MTL	LTL
Harvested sugarcane (t)		63.75	52.7	46.75
Cane plant (t)		15	9.68	6.05
Cane ratoon (t)		60	53.32	48.95
Harvesting (ha)	Mechanized	0.8	0.6	0.2
	Semi-mechanized	0.2	0.4	0.6
	Manual	0	0	0.2
CO_2 fixation (t)		62.35	51.55	45.76
CO_2 due to burning (t)		4.94	4.41	4.49
Diesel, direct use (kg)		111.56	96.97	74.33
Agrochemicals consumption	Urea (46 % N) (kg)	216	188	178
	Triple phosphate (45 % P) (kg)	4.00	3.07	–
	Atrazine (50 %) (L)	3.20	0.61	–
	Ametryn (50 %) (kg)	1.00	1.27	–
	Acetochlor[a] (80 %) (L)	0.40	0.31	–
	2,4-D (50 %) (L)	0.96	1.69	1.78
	Monosodium methyl arsenate (MSMA) (69 %) (L)	0.80	1.02	–
	Metolachlor (90 %) (L)	0.80	–	–
	Paraquat (90 %) (L)	0.16	–	–

[a] Taken as similar to 2-chloro-*N*, *N*-diallylacetamide

gas and bagasse. Stoichiometric combustion is considered for natural gas, while a real analysis of the chimney gases is considered for bagasse (major energy source). The use of scrubbers (wet filters) for combustion gases is also taken into account. Table 5 shows the inventory values for this subsystem.

3.3 Distillery

Ethanol distilleries in Tucumán use molasses as raw material and operate associated to sugar factories; therefore, they share auxiliary services to a large extent (Fig. 1).

Molasses (total solids 85 wt%) are first diluted with water and enriched with N and P sources so that yeast (*Saccharomyces cerevisiae*) is able to convert fermentable sugars into ethanol and CO_2 (fermentation). This process is carried out in open-air discontinuous fermenters. After that, a complex solution (7–10 vol%) of ethanol is obtained, which is then centrifuged for yeast recovery and sent to the distillation sector.

A scheme of two to three distillation columns is typically used to separate water and impurities, producing azeotropic ethanol, i.e., ethanol with 96 vol% purity. Vinasses and phlegmasse are the residues of this stage. Vinasses is the most important liquid waste at distillery stage; while generated in a ratio about 12 L vinasses/L ethanol, it has a high content of salts and organic matter. Phlegmasse is practically pure water.

In order to obtain fuel grade anhydrous ethanol, higher alcohols which are formed in small amounts are not separated and the 96 vol% ethanol is dehydrated through azeotropic distillation. Cyclohexane is used as entrainer to produce ethanol at purity higher than 99.7 vol%.

Inputs and output of subsystem *Distillery* are depicted in Fig. 5, and the corresponding inventory values are shown in Table 6. The main product of this subsystem is anhydrous ethanol: 14.68 L/t cane (11.58 kg/t cane) for campaign 2013. Among the inputs of this system, molasses stands out, which bring the environmental burden inherited from subsystems *Sugar Factory* and *Agriculture*. Other inputs include water, yeast, urea (N source), antibiotics, sulfuric acid, and cyclohexane. The energy needs are mainly satisfied by bagasse combustion at the sugar factory plus a small amount of electricity from the grid.

With respect to the emissions to the air, two sources have been mainly considered: the CO_2 coming from fermentation (biogenic CO_2) and the ethanol lost by evaporation due to operation in open-air tanks. Vinasses can be treated in different ways; however, no treatment is generalized in Tucumán and the most common fate of vinasses is its disposal in the cultivation fields. As no information has been found regarding components mobility in soil, it is difficult to estimate the true environmental impact. However, transformation of vinasses carbon content into GHG (biogenic CO_2) has been accounted only at inventory level.

Table 4 Summary of the inventory data for the subsystem *Agriculture* (reference flow: 1 kg sugarcane)

	HTL	MTL	LTL	
Products				
Harvested sugarcane, from *Agriculture*	1	1	1	kg
Inputs				
Occupation, arable	0.1569	0.1897	0.2139	m^2a
Coal	0.7014×10^{-3}	0.7110×10^{-3}	1.1046×10^{-3}	kg
Gas, natural/m^3	2.1422×10^{-3}	2.1902×10^{-3}	2.3600×10^{-3}	m^3
Oil, crude	0.8179×10^{-3}	0.8602×10^{-3}	1.2022×10^{-3}	kg
Aluminum	5.5992×10^{-6}	6.7543×10^{-6}	1.5953×10^{-5}	kg
Copper, in crude ore	3.6130×10^{-6}	4.0444×10^{-6}	8.3308×10^{-6}	kg
Iron	1.1252×10^{-4}	1.4858×10^{-4}	4.7171×10^{-4}	kg
Zinc	1.9687×10^{-6}	2.4375×10^{-6}	6.2125×10^{-6}	kg
Water	0.0221	0.0224	0.0298	m^3
Emissions to air				
Carbon dioxide, fossil	7.6661×10^{-3}	8.1788×10^{-3}	1.0954×10^{-2}	kg
Ammonia	5.1381×10^{-4}	5.4326×10^{-4}	5.7744×10^{-4}	kg
Nitrogen oxides	1.1192×10^{-4}	1.2102×10^{-4}	1.3677×10^{-4}	kg
Dinitrogen monoxide	1.0848×10^{-4}	1.1601×10^{-4}	1.2453×10^{-4}	kg
Carbon monoxide, fossil	1.4054×10^{-5}	1.6127×10^{-5}	2.7941×10^{-5}	kg
Methane, fossil	1.9474×10^{-5}	1.8473×10^{-5}	2.0900×10^{-5}	kg
Sulfur dioxide	1.6950×10^{-5}	1.3889×10^{-5}	1.4781×10^{-5}	kg
NMVOC, unspecified origin	5.3160×10^{-6}	6.1626×10^{-6}	1.1034×10^{-5}	kg
Particulates, <10 μm	4.7476×10^{-6}	8.6498×10^{-9}	3.7041×10^{-9}	kg
Particulates, >10 μm	3.0200×10^{-6}	3.2802×10^{-6}	5.6220×10^{-6}	kg
Emissions to water				
Sulfate	1.7680×10^{-4}	1.7294×10^{-4}	1.8928×10^{-4}	kg
Chloride	1.3034×10^{-4}	9.8179×10^{-5}	6.3494×10^{-5}	kg
Nitrate	1.0290×10^{-4}	1.0858×10^{-4}	1.1550×10^{-4}	kg
Phosphate	5.8537×10^{-6}	5.7929×10^{-6}	7.3889×10^{-6}	kg
Ammonium, ion	1.0167×10^{-6}	9.9093×10^{-7}	6.6712×10^{-7}	kg
Biological oxygen demand (BOD_5)	1.3068×10^{-5}	1.2087×10^{-5}	1.5927×10^{-5}	kg
Oils, unspecified	2.5992×10^{-6}	2.7899×10^{-6}	3.7879×10^{-6}	kg
Suspended solids, unspecified	2.0497×10^{-6}	2.1277×10^{-6}	2.5893×10^{-6}	kg
Atrazine	7.4074×10^{-7}	9.8027×10^{-8}	–	kg
Ametryn	1.7412×10^{-7}	2.9374×10^{-7}	–	kg
Acetochlor[a]	8.4329×10^{-8}	7.1408×10^{-8}	–	kg
2,4-D	1.7732×10^{-7}	2.7171×10^{-7}	4.4738×10^{-7}	kg
Monosodium methyl arsenate (MSMA)	1.7405×10^{-7}	3.8349×10^{-7}	–	kg
Metolachlor	1.8974×10^{-7}	–	–	kg
Paraquat	5.0823×10^{-8}	–	–	kg
Emissions to soil				
Oils, unspecified	2.7058×10^{-6}	2.8919×10^{-6}	3.8592×10^{-6}	kg
Atrazine	2.6323×10^{-14}	2.6836×10^{-14}	–	kg
2,4-D	2.2169×10^{-12}	2.0281×10^{-12}	9.2113×10^{-13}	kg
Metolachlor	8.7237×10^{-11}	–	–	kg

Taken as similar to 2-chloro-*N*, *N*-diallylacetamide

4 Results and discussion

Figure 6 shows two graphs that represent the environmental profiles of subsystem *Agriculture* (Fig. 6a) and the process cane ratoon (Fig. 6b), considering HTL. The impact categories of the CML 2001 model are depicted along the abscissas, whereas the percentage with which each process contribute to the represented system are shown along the ordinates.

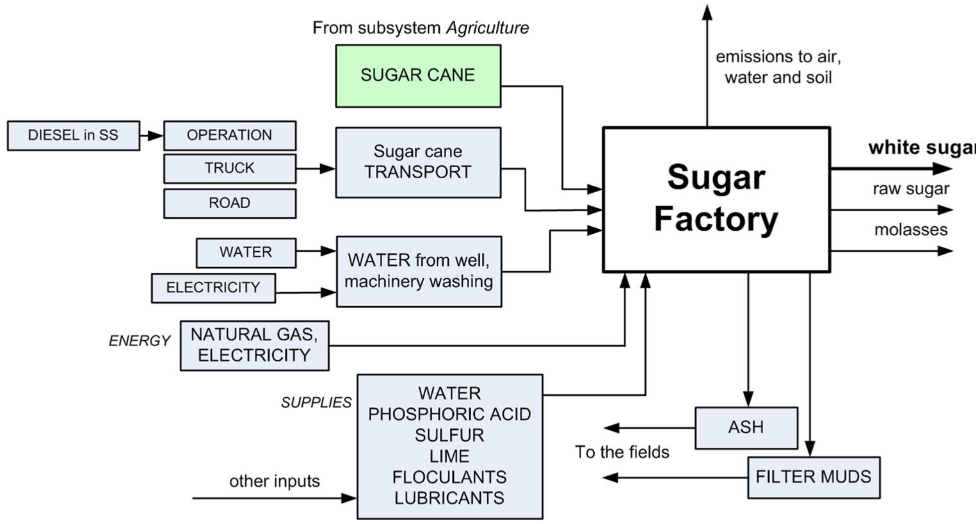

Fig. 4 Subsystem *Sugar Factory*. Detail of those processes that bring environmental burdens to *Sugar Factory*. The main subsystem output is white sugar. Raw sugar and molasses are co-products

Considering Fig. 6a, as expected for the bigger amount of ratoons compared with new plants in a sugarcane plantation, the contribution of the process cane ratoon is greater than that of the process cane plant in all categories evaluated over this subsystem. Intrinsic emissions of subsystem *Agriculture* (total cane in Fig. 6a), which come from trash burning, contribute appreciably only to two categories: N_2O emissions to GW and CH_4 to PO. For example, taking the case of total N_2O emissions of *Agriculture*, 85.7 % comes from cane ratoon, 10.7 % comes from cane plant, and 3.6 % comes from crop trash burning.

Figure 6b shows the contributions to the impact categories of cane ratoon production in HTL. The process cane ratoon has been selected to be shown because it is the most important process that acts as an input to the subsystem *Agriculture*. Having a look at categories AD, OD, HT, TE, and PO, it results evident the high degree of participation of the synthetic agrochemicals manufacturing process. Urea stands out in these five categories, atrazine in OD and PO, and monosodium methyl arsenate (MSMA) in OD. Processes including infrastructure such as cultivation and pulverization only produce a small contribution, some more notably in HT and PO. Direct impacts produced by the system cane ratoon itself—those which do not come from other systems associated to cane ratoon—significantly concern to categories AC, EU, GW, and FE. Figure 7 depicts four ring charts, each showing the main emissions contributing to these four impact categories. AC is mainly due to NH_3 (92 %), which comes from urea volatilization in the fields. EU is also determined by this NH_3 (87 %) emission. Nitrogen oxides from urea

Table 5 Summary of the inventory data for the subsystem *Sugar Factory* (reference flow: 1 kg white sugar)

Products			Emissions to air		
White sugar, from *Agriculture*	1	kg	Ammonia	2.12×10^{-5}	kg
Raw sugar, from *Agriculture*	0.1699	kg	Carbon dioxide, biogenic	3.0561	kg
Molasses, from *Agriculture*	0.4807	kg	Carbon dioxide, fossil	0.1587	kg
			Carbon monoxide	0.1664	kg
Inputs			Dinitrogen monoxide	2.8023×10^{-5}	kg
Harvested sugarcane	12.0163	kg	Hydrocarbons, aliphatic	3.3871×10^{-5}	kg
Sulfur, at refinery	2.21×10^{-3}	kg	Nitrogen oxides	2.2777×10^{-2}	kg
Phosphoric acid, industrial grade (85 %)	1.0022×10^{-3}	kg	Particulates, 2.5 to 10 µm	1.2016×10^{-3}	kg
Flocculants	9.457×10^{-4}	kg	Potassium	2.851×10^{-4}	kg
Lubricating oil	0.0303	kg	Sodium	1.5839×10^{-5}	kg
Limestone, milled, loose	0,0154	kg	Sulfur dioxide	4.0777×10^{-4}	kg
Electricity, medium voltage	0.1802	kWh			
Water (well)	0,1128	m^3			
Natural gas high pressure, at consumer	2.7736	MJ			
Transport, lorry 16–32 t	0.6008	tkm			

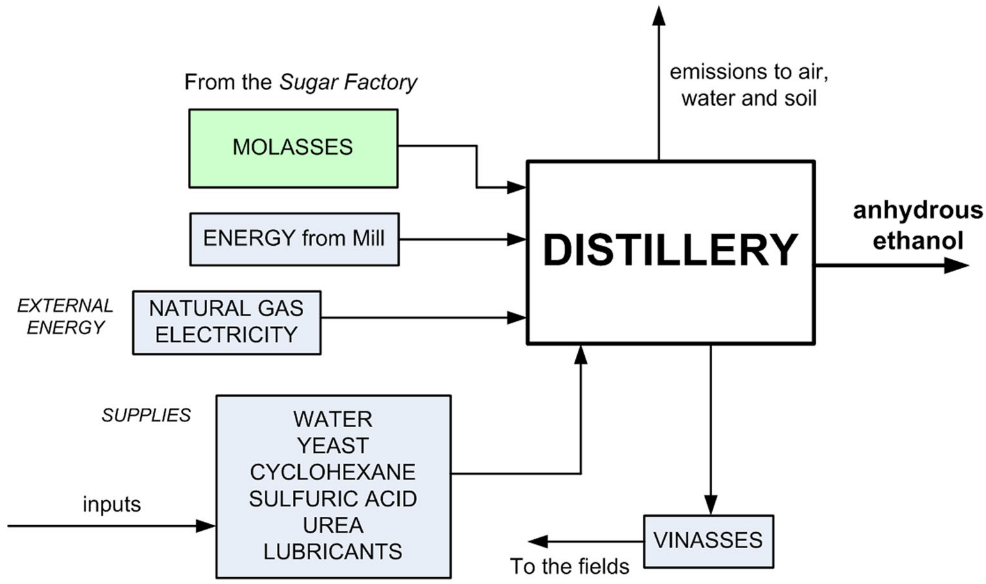

Fig. 5 Subsystem *Distillery*. Detail of the processes that contribute with environmental burdens to the subsystem *Distillery*. The main subsystem output is anhydrous ethanol

nitrification, and NO_3^- and PO_4^{3-} coming from fertilizers leaching contribute to EU in 6, 5, and 2 %, respectively. GW gases are dominated by N_2O formed by urea nitrification/denitrification (82 %). CO_2 and CH_4 represent 17 and 1 %, respectively. Regarding FE, it depends on organic synthetic agrochemicals, mainly metolachlor (63 %), followed by atrazine (27 %).

Figure 8 is a comparative graph, which shows the environmental profile of harvested sugarcane as it exits the fields, obtained by using the characterisation factors defined by the CML 2001 model. For each environmental impact category, there are three bars corresponding to the impact of each TL. To avoid any subjective weighting, the comparison is made on a percentage basis, corresponding 100 % to the TL with the highest impact. In seven impact categories, HTL has less impact values than MTL and LTL. These results can be explained to a large extent by the better cultural yields obtained with HTL. Because of this higher cultural yield, if we compare the three TLs, the larger diesel consumption per hectare associated to the higher degree of mechanization of HTL (Table 4) becomes lower than MTL when considering diesel consumption in terms of kilograms of diesel per ton of produced sugarcane. However, high yields are not enough to compensate the OD and FE impacts produced by HTL attributable to, in the first case, agrochemicals production (including packaging), and in the second case, agrochemicals leaching/runoff (atrazine, ametryn, MSMA, metolachlor, and paraquat). Furthermore, in HTL, sugarcane is mostly not burnt before harvesting as it is in MTL and LTL. Therefore, HTL has lower values for GW and PO due to lower emissions of N_2O and

Table 6 Summary of the inventory data for the subsystem *Distillery* (reference flow: 1 kg anhydrous ethanol)

Product			Emissions to air		
Ethanol, 99.7 % in H_2O	1	kg	Carbon dioxide, biogenic	3.0489	kg
			Ammonia	4.6297×10^{-5}	kg
Inputs			Dinitrogen monoxide	6.1197×10^{-5}	kg
Ammonium sulfate, as N	8.8123×10^{-3}	kg	Methane, biogenic	1.0356×10^{-5}	kg
Cyclohexane	7.6017×10^{-4}	kg	Nitrogen oxides	2.3414×10^{-3}	kg
Diammonium phosphate, as N	0.013218	kg	Nonmethane volatile organic compounds	1.4555×10^{-5}	kg
Lubricating oil	2.4424×10^{-4}	kg	Ethanol	0.006	kg
Molasses, from sugarcane, at sugar factory	3.4522	kg			
Other organic chemicals	1.0364×10^{-3}	kg			
Soda, powder	3.306×10^{-3}	kg			
Sulphuric acid, liquid	0.02914	kg			
Urea, as N	6.3347×10^{-4}	kg			
Water (well)	0.01123	L			

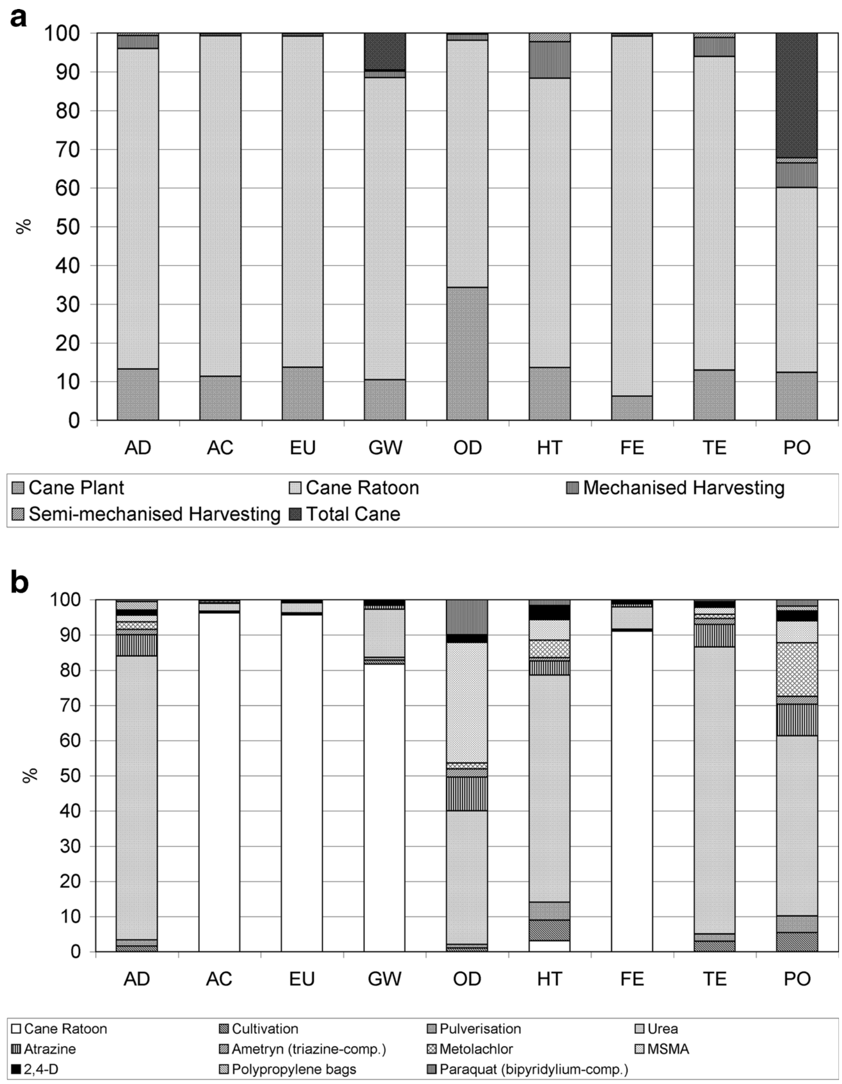

Fig. 6 **a** Environmental profile of the harvested sugarcane (reference flow: 1 kg harvested sugarcane) for HTL. **b** Environmental profile of cane ratoon production (reference flow: 1 kg sugarcane) for HTL. The acronyms in the abscissas stand for: abiotic resource depletion (AD), acidification (AC), eutrophication (EU), global warming (GW), stratospheric ozone depletion (OD), human toxicity (HT), freshwater aquatic ecotoxicity (FE), terrestrial ecotoxicity (TE), and photochemical oxidant formation (PO)

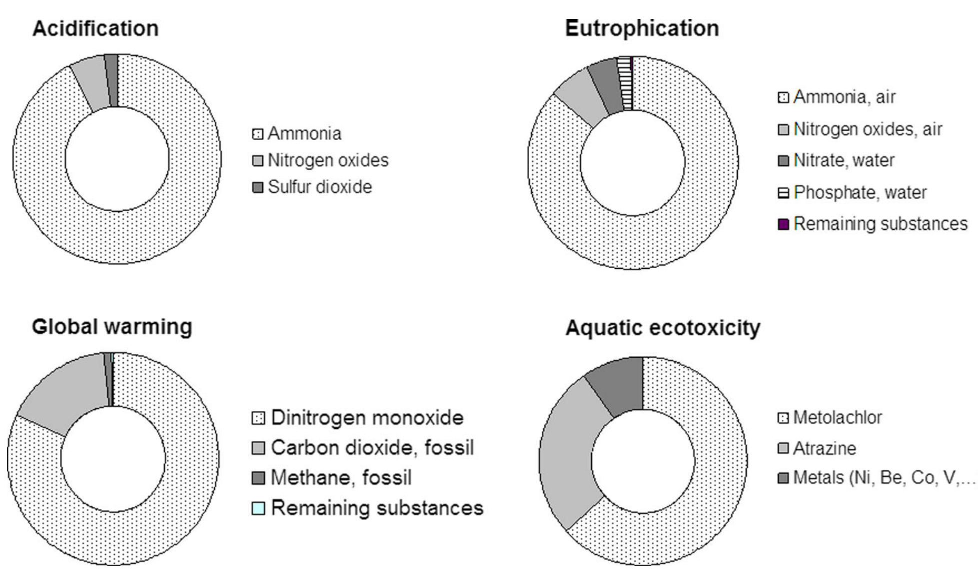

Fig. 7 Main emission contribution to acidification (AC), eutrophication (EU), global warming (GW), and freshwater aquatic ecotoxicity (FE) in cane ratoon production for HTL

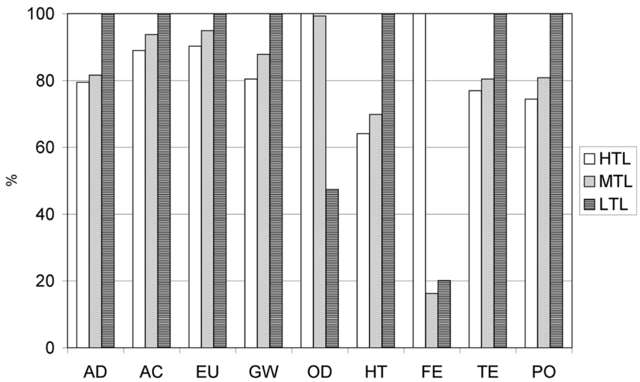

Fig. 8 Comparative environmental profile of harvested sugarcane for different technology levels: high (HTL), medium (MTL), and low (LTL) (reference flow: 1 kg harvested sugarcane). The acronyms in the abscissas stand for: abiotic resource depletion (AD), acidification (AC), eutrophication (EU), global warming (GW), stratospheric ozone depletion (OD), human toxicity (HT), freshwater aquatic ecotoxicity (FE), terrestrial ecotoxicity (TE), and photochemical oxidant formation (PO)

CH_4 from burning. Contribution to GW due to CO_2 emitted during sugarcane burning is not accounted in any case as it is biogenic CO_2 fixed by the crop during photosynthesis.

The calculated GHG emissions from the agricultural stage vary from 2760 to 2515 kg CO_2eq/ha for HTL and LTL, respectively (calculate from values in Table 4). When the analysis is performed considering the sugarcane yields, LTL shows higher GHG emissions than HTL (54 and 43 kg CO_2eq/t cane, respectively).

Figure 9 shows the profiles of the fuel grade ethanol at the distillery gate. In comparison with Fig. 8, it can be seen that Fig. 9 is qualitatively similar but the differences between TL appear smoothed. This is because, regardless of the TL of the agricultural practices, the manufacturing technology in sugar factories and distilleries is the same. Considering, for instance, the GHG emissions, absolute values for GW are 2.75, 2.85, and 3.01 kg CO_2 eq/kg ethanol for HTL, MTL, and LTL, respectively. More than 50 % of this impact is inherited from the agricultural stage. It has resulted difficult to contrast the ethanol profile values against those from other studies since many of them refer to cases with ostensibly different structures (e.g., autonomous distilleries) or conducted under different methodological criteria (e.g., allocation assumptions). As an example, Macedo et al. (2008) and Ometto et al. (2009) report very different values of GW for the industrial stage (0.055 and 0.369 kg CO_2eq/kg ethanol, respectively) that are much lower than those in our case (1.5 kg CO_2eq/kg ethanol) since they study less energy intensive processes: in the case of autonomous distilleries, it is not necessary to devote energy for sugar crystallization.

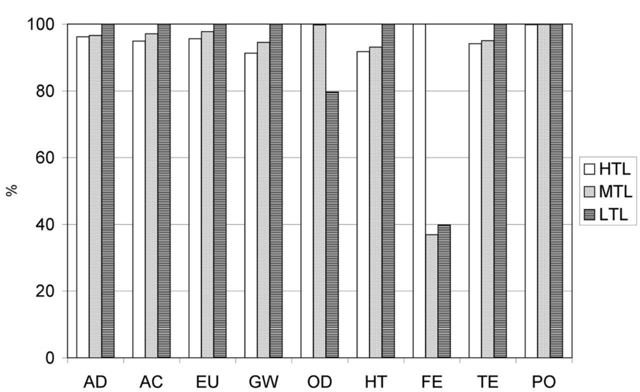

Fig. 9 Comparative environmental profile of anhydrous ethanol for different technology levels: high (HTL), medium (MTL), and low (LTL) (reference flow: 1 t anhydrous ethanol). The acronyms in the abscissas stand for: abiotic resource depletion (AD), acidification (AC), eutrophication (EU), global warming (GW), stratospheric ozone depletion (OD), human toxicity (HT), freshwater aquatic ecotoxicity (FE), terrestrial ecotoxicity (TE), and photochemical oxidant formation (PO)

Some studies conducted in Brazil (Macedo 1998; Días de Oliveira et al. 2005; Boddey et al. 2008; Luo et al. 2009) have been compared to this one of Tucumán in regard to the agricultural results. In these studies, N-fertilizers have a major influence in the environmental profile, except that by Luo et al. (2009). Regarding GHG emissions—the most studied impact category—reported emissions in the agricultural stage are close to the 2000–3000 kg CO_2eq/ha in Tucumán. However, these studies report a higher diesel oil consumption (600 L/ha in Días de Oliveira et al. 2005) in comparison with our average value of 113 L/ha, even when in Brazil, sugarcane harvest is 60 % manual (Cardoso Lisboa et al. 2011) whereas in Tucumán it is mainly mechanized.

As for Mexico, where a nonintegrated production scheme dominates, García et al. (2011) shows four time greater GHG emissions than those reported in our study.

At this point, it is important to mention some aspects that need to be further addressed. We use the IPCC (2006) factors to quantify N_2O and CH_4 emission due to sugarcane burning. If *green* mechanized harvest is applied, preharvest burning is avoided (mainly in HTL) and trash remains on the fields. Nitrogen in trash can be immobilized by soil microorganisms. However, the trash layer will also promote higher moisture and anaerobical conditions, potentially favoring N_2O release by denitrification (Cardoso Lisboa et al. 2011). Therefore, unburnt fields could generate higher N_2O emissions compared to burnt fields. On the other hand, avoiding preharvest burning increases organic matter inputs, thus increasing soil C stocks whereas tilling intensification do the opposite (Galdos et al. 2009a). Finally, a portion of the trash can be used for energy production in the sugar mills boilers. Unfortunately, the potential impact of all these aspects has not been assessed in Tucumán and should be accurately measured under local conditions to be able of reducing uncertainty in emissions estimation.

5 Conclusions

A contribution to the study of the environmental profile of the sugarcane industry in Tucumán, using an LCA-based approach, is presented. It is important to highlight the value of this article since research concerning the application of LCA in this area is rather limited in Argentina. Unlike large sugarcane areas of the world, which have received relatively more attention, Tucumán is an example of vertically nonintegrated system where many independent producers have to sell its product to different sugar mills. Specifically, this study explores from a systemic perspective the implications of using different TLs in agricultural tasks, which have been identified in previous studies (Amores et al. 2013) as the main source of impact related to the production of sugar and bioethanol. Unfortunately, the use of different assumptions on input data, functional units, allocation criteria, etc. complicates comparisons. Notwithstanding this drawback, we have tried to discuss our findings in the context of other similar studies.

As a conclusion, if practices associated to HTL are implemented, a reduction of the environmental impact is observed in most categories. This predominance relies on the assumption of a bigger production ratio associated to HTL, but if this is not the case, conclusions ought to be revised. A further study including sensitivity to sugarcane yields under each TL is envisaged to address this point.

Regardless of the TL considered, the study corroborates the use of fossil-based N fertilizers and fossil fuels for operating machinery as critical points. So, the improvements should go in line with the use of fertilizers with less impact (compost) and biofuels instead of fossil fuels. Other issues that require further attention are related to the use of crop trash for combustion in boilers instead of being burnt or decomposed to air and the development of different vinasses treatments.

Finally, it is important to mention that the sugarcane value chain in Latin America entails a complex system of interactions not only of material and energy flows. Latin America needs to expand its sugarcane industry to be regarded as a biorefining industry which produces not only sugar but a variety of products: sugar, biofuels, bioproducts, bioenergy, and so on. The sugarcane stakeholders will need to study the environmental performance of their products in order to comply with sustainability requirements. Within the latter, also economic and social assessment is waiting for a deeper study when adopting different TLs.

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