Impact of Agricultural Practices on Energy Use and Greenhouse Gas Emissions for South African Sugarcane Production

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Abstract

The environmental footprint of agricultural production can vary significantly both between countries and within a country based on regional conditions and agricultural practices. A life cycle assessment approach was used to model fossil fuel energy inputs and greenhouse gas emissions associated with the production of sugarcane in South Africa. Results were calculated for sugarcane produced in two distinct regions, the irrigated North and the non-irrigated North Coast. Regional differences also include terrain, soil, and use of mechanization. Models were adapted to estimate the impacts of burning prior to harvest, leaving a biomass mulch blanket with green cane harvesting, and increasing the level of mechanization for harvest and other field operations. Irrigation contributes to a higher energy input in the irrigated North but differences are mitigated by the lower fertilizer, agro-chemical, and diesel use per ton of sugarcane produced there. Despite higher energy inputs in the irrigated North, greenhouse gas emissions are similar for sugarcane produced in each region. Green cane harvesting reduces energy inputs and greenhouse gas emissions by 4% and 16%, respectively, in both regions. Impacts of mechanization on soil compaction and stool damage result in lower yields and proportionally higher energy inputs and greenhouse gas emissions. Results demonstrate the potential for variability in LCA results based on regional differences in production practices within a country.

Keywords

Life Cycle Assessment (LCA), Agriculture, Irrigation, Mechanization, Sugarcane, Variability

1. Introduction

Documenting the life cycle impacts of agricultural production provides insights for improving system efficiencies and decreasing associated environmental burdens. Such analyses have been especially important when evaluating bioenergy impacts, but may also become increasingly important for production of food and feed. Agricultural diversity at the global, regional, and national scales dictates that life cycle assessment (LCA) results be critically analyzed for applicability based on local geography and production practices.

Sugarcane is an important crop for the production of sweeteners, beverage alcohol, biofuels, and other biobased chemicals. Although Brazil and India produce more than 55% of the world's sugarcane, the crop is grown commercially in over 50 countries on 5 continents. Several LCA studies have been conducted on sugarcane products, but most focus specifically on biofuel production (Chauhan et al., 2011; von Blottnitz and Curran, 2007). Therefore, agricultural production, transport and post-harvest processing inputs are combined and results are presented on the basis of fuel production. Furthermore, these studies typically use data from the largest global producers which may not be indicative of growing conditions elsewhere (Kadam, 2002; Seabra et al., 2011; Tsiropoulos et al., 2014). Renouf et al. (2010) conducted an LCA on sugarcane production in Australia and highlighted considerable variability in results based on factors including nitrogen fertilizer efficiency, harvest yield, irrigation, and pre-harvest burning. Garcia et al. (2016) showed that agricultural production contributed more than 59% of greenhouse gas emissions from sugar production in Mexico, and also identified fertilizer production and application as the largest contributors to emissions.

South Africa is the largest sugarcane producer of the 14 cane growing countries in Africa, and processes an average of 19 million tons of sugarcane per year from over 22,500 registered

growers (SASA, 2015). Sugarcane is grown in 14 different mill areas which are diverse in terms of soil, terrain, water availability, temperature, and prevalence of pests. Although less than 35% of South African sugarcane is grown in irrigated areas (SASA, 2015), there is concern over the use of irrigation given the water scarcity in the country. For example, the Department of Water and Sanitation and the Department of Energy have expressed concerns over the use of irrigated crops for biofuel production (SA Department of Energy, 2014; Zhuwakinyu, 2014). However, biofuel production from irrigated cane co-products or byproducts, such molasses and bagasse, has not been addressed. Irrigation impacts not only water use, but also energy use, associated emissions, and crop yield (Cardozo et al., 2016). The specific impacts of irrigation on total input energy and greenhouse gas emissions for South African sugarcane production have not been identified for cane produced either for biofuels or other products.

Although sugarcane fields have traditionally been burned prior to harvest to get rid of excess biomass and to ease harvesting, this practice is on the decline globally (Leal et al., 2013). It is currently estimated that over 90% of South African sugarcane is burned prior to harvest, but this practice may shift to more green cane harvesting take advantage of agronomic benefits and processing opportunities, and to reduce environmental pressures and concerns about air quality related to burning (Appleton, 2013). Green cane harvesting has the potential to increase cane yields because leaving tops and green leaves as a residue blanket covering the soil can reduce soil moisture evaporation (Olivier and Singels, 2012). Green harvesting also increases the available cellulosic biomass and improves the quality of the cane (Solomon, 2000).

Increased farm mechanization is another trend in global sugarcane production (Leal et al., 2013). Despite this, sugarcane in South African is typically harvested manually because of steep terrain, availability of inexpensive labor, and the high cost of agricultural machinery (Smithers, 2014).

Mechanization can speed up harvesting and improve cane quality and transportation logistics, but requires more energy, and can increase soil compaction and cause stool damage if not managed properly (van Antwerpen et al., 2000). It is also associated with increased social and environmental impacts (Prasara-A and Gheewala, 2015). It is therefore important to take note of how global trends such as mechanization could impact cane production in South Africa and elsewhere.

Mashoko et al. (2010) conducted an LCA of the South African sugar industry but focused on the combined cane production and processing systems without separating agricultural production in the results. Agricultural input data was taken from country-wide averages and did not consider differences by sub-region. Van der Laan et al. (2015) also used an LCA approach to look at the effects of improved management of cane production in an irrigated area of South Africa. They identified the potential for emissions reductions with more efficient management of irrigation and fertilization based on model data for cane growing in the irrigated Pongola area of South Africa. They also considered the effects on other environmental indicators including water consumption and eutrophication. Boote et al. (2014) found that irrigation accounted for as much as 50% of on-farm energy use and 80% of greenhouse gas emissions from irrigated cane production in South Africa, but calculations did not include agro-chemical production, soil emissions from fertilizer application, or pre-harvest burning.

A regional analysis of sugarcane production in South Africa is valuable not only because such studies have not been done, but because it provides perspective on the diversity of production around the world. The aim of this study was to analyze primary fossil energy inputs and greenhouse gas emissions for South African sugarcane production in order to 1) identify variation based on irrigation, green cane harvesting, and mechanization, 2) illustrate how

regional conditions and growing practices can impact LCA results within a country, and 3) identify potential areas to reduce the environmental footprint for sugarcane cultivation. Data and model estimations were compiled and analyzed using an LCA approach.

2. Materials and Methods

An LCA approach, as outlined in the current ISO standards, was used to assess the impact of regional production differences on fossil energy input and greenhouse gas emissions for South African sugarcane production (ISO, 2006a, b). Stages included goal and scope definition, inventory analysis, impact assessment, and interpretation of results. Inventory data were compiled from industry experts, relevant literature, and GREET databases. Results were compiled using Microsoft Excel 9redmond, WA0.

2.1 Goal, system boundaries, and functional unit

The goal of this study was to estimate the variation in primary fossil energy inputs and greenhouse gas emissions associated with production of sugarcane in South Africa. For this assessment, two growing regions were chosen based on differences in irrigation prevalence, and regional soil and terrain differences. Models for the baseline system in each region were adjusted to determine the influence of green cane harvesting and increased farm mechanization on model results. The scope of the analysis included agricultural production and delivery of harvested cane to a sugar mill or biorefinery. Capital equipment such as farm machinery and transportation vehicles were assumed to have a minor contribution over the equipment life and were not included in the system boundaries.

Impact categories included in the study were fossil energy and greenhouse gas emissions. Impacts were assessed for fuel and electricity production, as well as the production, transportation, and application of agricultural chemical inputs. Agricultural inputs were

estimated on an area basis and adjusted based on cane yield under each production scenario. Resultant values were adjusted again based on the estimated cane sucrose content, determined from a five-year (2010-2014) average of industry-reported values for each mill (Smith et al., 2010, 2011; Smith et al., 2012, 2013, 2014). Fossil energy use and emissions were calculated based on a functional unit of 1 metric ton of extractable sucrose delivered at the mill gate in the form of sugarcane stems or billets.

2.2 Production areas

There are 14 commercial sugar mills in South Africa and only 4 receive cane from land that is primarily irrigated. In the non-irrigated area, sugarcane mills are located in the North and South Coasts regions and the Midlands (high altitude). Two mills (Pongola and Malalane) from the irrigated North, and two mills (Maidstone and Amatikulu) from the non-irrigated North Coast were selected to collect input data for this LCA study (Figure 1).

2.3 Life Cycle Inventory (LCI)

Table 1 contains a summary of the inputs and yields used to model the baseline scenario.

Agricultural inputs, energy use, and emissions from the two milling areas in each region (irrigated North and North Coast) were combined as weighted averages based on average mill throughput resulting in a single composite profile for each region (Smith et al., 2010, 2011; Smith et al., 2012, 2013, 2014).

Estimates of fertilizer, herbicide, and pesticide use were based on personal communications with extension specialists working with cane growers in each mill area, as well as researchers based at the South African Sugar Research Institute (SASRI). Pesticide application estimates were based on reported percentage of growers using the most common pesticides for *Eldana Saccharina* (eldana) and nematode control, and associated application rates and timings were estimated

based on an Insect Resistance Action Committee (IRAC) compliant spray program provided by SASRI. Reported herbicide and pesticide application rates in Table 1 were derived from the fraction of growers using a given product in conjunction with manufacturer-recommended application rates. For example, application rates given in Table 1 may be one-third of the recommended rates if only one-third of growers in an area use the product.

Calculations for diesel fuel use for cane harvesting and transport were based on modeled total biomass (cane stem plus brown leaves) removal rates, description of collection and transportation systems from local extension specialists, and SASRI estimates for machinery capacity, speed, and fuel use (SASRI, 2015a). Collection and delivery options included stacking with intermediate loading, windrow with intermediate loading, direct haul to the mill, and use of a chopper harvester with direct haul. A 60-kW tractor was modeled for stack and windrow systems and a 70-kW tractor was used for in-field collection with a chopper harvester.

Transloaders were used for loading and unloading in the stacking system. Windrow systems were assumed to be split between use of three wheeler-type cane loaders for collection and loading, and a three wheeler-type loader in the field and crane-type transloader at the field edge prior to transport. All road transport was modeled using trucks with a 30-ton capacity and an average roundtrip distance of 50-km to transport sugarcane and residue from the field edge to the mill. Diesel fuel use (l/ha) for field operations tends to be higher in the irrigated North due to a lower percentage of growers using manual labor for agrochemical application and ratoon management. Diesel fuel use was higher on the North Coast for in-field collection while the irrigated North had significantly higher transportation diesel use. This was due to the high percentage (75%) of growers using a direct haul system in the irrigated North and more intermediate stacking or windrowing (95% of growers) on the North Coast.

2.4 Production scenarios and changes to baseline LCI

A summary of the modeled production scenarios is shown in Table 2. The baseline system was based on best estimates of current production practices in each region. All cane production was assumed to have a ratoon cycle of 10 crops. For the baseline scenario, all cane is burned prior to harvest, and only burned cane is collected and delivered to the mill or biorefinery. The fraction of land in each area that used mechanization for planting and for herbicide, pesticide, and fertilizer application was estimated by extension specialists. Diesel requirements for each of these mechanized operations were taken from SASRI guidelines and adjusted according to mechanization prevalence in the area (SASRI, 2015b). Irrigation was assumed to be used on 100% of land in the irrigated North and 1% of the predominantly non-irrigated North Coast. Estimates for irrigation demand in the irrigated North were extracted from Jones et al. (2013). Water demand for the irrigated areas of the North Coast was based on the crop water requirement for Pongola, and adjusted to account for the differences in annual average rainfall between the North Coast and Pongola (Jones et al., 2013).

A second scenario was modelled to show the effect of green cane harvesting in each region. In these scenarios, all cane was assumed to be harvested manually without burning (Table 2). Tops and green leaves were left in the field as a residue blanket and brown leaves were harvested and loaded for transport with the cane. Cutting and collection was all done manually, and in-field loading was done with the same systems modeled in the baseline scenario. Diesel use for manual harvest of green cane was adjusted proportionally based on the increase in harvested biomass. Potential residue (dry weight) was estimated as 16.3% of cane yield, although cane variety has a much stronger influence on residue weight than does cane yield (Romero et al., 2009). Tops and green leaves were assumed to be 46% of potential residue dry weight and left in the field as a

mulch blanket; the balance are brown leaves which were collected and transported to the mill or biorefinery (Franco et al., 2013). Harvest yields after green cane harvesting were assumed to increase by 20% (9.2-9.4 t/ha) on non-irrigated areas due to increased water availability from reduced evaporation. On irrigated land, yield did not change but irrigation requirements were assumed to drop by 100-mm per year with green cane harvesting (Olivier and Singels, 2012). Fertilizer (inorganic N, P, and K) inputs were changed proportionally with yield differences from the baseline scenario. Herbicide use for ratoon years was reduced due to the presence of mulch blanket mass. Reductions in the active herbicide ingredient ranged from 50% for a residue blanket of 3 dry t/ha to 90% for a blanket of more than 7.5 dry t/ha, based on work by Manechini et al. (2005).

A third scenario for each region assumed that in addition to green cane harvesting, all field operations were mechanized where technically feasible (Table 2). Estimates of mechanical harvesting feasibility were made by local extension specialists based on knowledge of field slopes and sizes in the general area. Production yields were assumed to decrease by 15% on fields with increased mechanization as a result of soil compaction and stool damage. Reports of mechanization impacts on cane yields vary tremendously based on factors such as traffic patterns and soil conditions. Mean yield decreases from the literature range from 5% losses for inter-row traffic to 24% losses for row-traffic, with considerable variation around those means (Tweddle, 2013). An additional 10% mechanical harvest loss was assumed due to biomass loss at harvesting, sucrose loss in juice, or inclusion of extraneous material (Larrahondo et al., 2009; Ma et al., 2014; Meyer, 2001). Collection losses were assumed to contribute to the trash blanket and subsequent reduction in the need for herbicides. Adjustments to irrigation levels, yields,

herbicides, and fertilization for the mechanical harvest scenario were handled as described for green cane with manual harvesting.

2.5 Primary fossil energy estimates

Primary fossil energy inputs for the production of diesel, electricity, and all agricultural inputs are listed in Table 3. Irrigation electricity requirements were based on work from van der Laan et al. (2015) and adjusted for the depth of irrigation water applied in each scenario. Primary fossil energy inputs for all energy and chemical inputs are listed in Table 3. Fossil energy inputs for electricity production were determined for South Africa based on a local utility report showing 0.55 kg of coal used per kWh delivered and negligible use of other fossil fuels (Eskom, 2015). Coal is used to generate 90% of South Africa's electricity with much of the remainder coming from nuclear power. Fossil energy (coal, oil and natural gas) requirements for diesel, fertilizers, herbicides, and pesticides were taken from the GREET database (GREET, 2015). Phosphorus fertilizer was modeled as triple super phosphate and potassium was modeled as potash (KCl). The herbicides acetochlor, atrazine, cyanazine, and metachlor were identified in the GREET database for use with sugarcane production. The mean values for fossil energy inputs of those four were used for all other herbicides. Coefficients of variation between the different herbicides for inputs of each fossil fuel was approximately 20%. All insecticides and nematicides were modeled with a common fossil fuel input based on mass of active ingredient for insecticides (GREET, 2015).

2.6 Emissions estimates

Pre-harvest burning of cane fields results in net greenhouse gas emissions because the uncontrolled conditions lead to incomplete combustion and production of N_2O and CH_4 .

Emissions from cane field burning were estimated at 2.1 and 6.2 kg CO₂-e per dry ton of potential residue for N₂O and CH₄, respectively (Macedo et al., 2008).

Greenhouse gas emissions associated with production of diesel, electricity, and all agricultural inputs are also listed in Table 3. Emissions factors for N, P, and K production were taken from Skowronska et al. (2014). Soil N₂O emissions were assumed to be 3.87% of N applied, based on a review of sugarcane production literature by Lisboa et al. (2011). Although soil emissions are expected to vary based on the nitrogen source (Brentrup and Pallière, 2008), this variation was not accounted for since it was not included in the source model. Organic nitrogen application in the form of filter cake (2% N) or condensed molasses solubles (0.28% N) was assumed to be volatilized to N₂O-N at a rate of 1% of the applied nitrogen load (Lisboa et al., 2011). Remaining field residue was modeled with a N-volatilization factor of 1% to estimate N conversion to N₂O (IPCC National Greenhouse Gas Inventories Programme, 2006). Emissions related to production of specific herbicides and pesticides were based on the mass of active ingredient applied (Lal, 2004). Mean herbicide or pesticide emissions values were used whenever specific product values were not identified.

South Africa derives a significant fraction of its transportation fuel from Fischer-Tropsch synthesis coal-to-liquids (CTL) production, and all diesel fuel was modeled as a mix of 70% petroleum diesel and 30% CTL fuels (World Coal Institute, 2006). Conventional diesel is assumed to produce 4.58 kg CO₂-e L⁻¹ during combustion and CTL emissions are assumed to be 214% of conventional diesel due to high coal use during production (Kalnes et al., 2009; Macedo et al., 2008).

3. Results (Impact assessment)

The primary fossil energy inputs and associated greenhouse gas emissions associated with cane production in each production scenario is presented in the following sections.

3.1 Primary Fossil Energy Use

Figure 2 shows the compiled primary fossil energy inputs for production of South African sugar cane for the modeled scenarios. The irrigation energy requirements in the irrigated North lead to a 20% higher total primary energy input than the non-irrigated North Coast for both manual harvest scenarios. That difference increases to more than 40% with mechanical harvest but the primary difference in that scenario is the fact that 80% of the irrigated North is suitable for increased mechanization, while it is limited to just 20% of the North Coast. This result highlights the higher energy requirements with increased mechanization more than any other differences between the regions.

The model results show a modest (4%) decrease in primary energy requirements when switching from cane burning to green cane harvest in each region. The main reasons for this decrease are the projected yield increase on the North Coast and the decrease in irrigation requirements in the irrigated North due to the retention of cane residue as a surface mulch layer. Although fertilizer and most diesel inputs increase proportionally with yields under the green cane harvesting scenarios, other inputs remain static or even decline. Herbicide use declines since a residue blanket suppresses weeds, and pesticide use remains the same. Approximately 10% of diesel inputs are for field operations, as opposed to cane collection and transportation, and those inputs do not change with higher or lower yields. With increasing yields and some inputs remaining constant or declining, resultant energy input per ton decreases. Lower energy inputs in the irrigated North are attributed to decreased irrigation energy and, to a lesser extent, lower herbicide use.

Increased mechanization (with green cane harvesting) resulted in an 18% higher fossil energy requirements for the irrigated North compared to the manual harvest scenario. In the North Coast, little difference was seen between these scenarios because only a small portion of land is suitable to increased mechanization. Diesel, electricity, and pesticide use all increased by 25-28% with increased mechanization while there was negligible change for fertilizers or herbicides. The primary driver of increased energy inputs was the projected decrease in yield as a consequence of soil compaction and stool damage, with little change in most inputs on an area basis. Fertilizer inputs (area basis) decreased proportionally with yield projections and therefore did not change when adjusted for yield. Herbicide use declined due to the increased residue blanket left with manual harvest, but that decline was balanced by the yield decrease associated with mechanical harvest.

As shown in Figure 2, green cane harvesting leads to small decreases in energy requirements per ton of delivered sucrose. Energy data was expressed on a sucrose mass basis and all energy used in cane production was allocated to the sucrose in this analysis. This is reasonable for the chemical inputs since sucrose is the primary product and those inputs are needed with or without green cane harvesting. However for green cane harvesting scenarios, 9% of the extracted biomass was field residue which would be used as a feedstock for energy or chemical production. Diesel accounted for 40% and 25% of the total energy input for the North Coast and irrigated North, respectively, under green cane scenarios, and that energy could reasonably be allocated between the cane and biomass according to harvest mass. Such an allocation would reduce the overall energy requirements for green cane harvesting by 3-4%. However, manual harvest of green cane harvesting leads to reductions in energy use per unit of sucrose due to

higher yields and decreased irrigation and herbicide use. Those energy reductions could similarly be allocated to the non-cane biomass fraction if it were used for energy or chemical production.

The results in Figure 3 highlight the difference in contributions to energy inputs in the two regions, especially the large contribution of irrigation (45%) to the total energy demand in the irrigated North. Despite the magnitude of the irrigation energy requirements there, the difference in total energy input between the regions is not as great because of the higher inputs (per ton of sugarcane) for fertilizer, diesel, and, to a lesser extent, herbicides and pesticides for the non-irrigated North Coast. Energy inputs for fertilizer use on the North Coast are more than 40% higher than in the irrigated North. The effect of the higher fertilizer application rates (kg fertilizer/ton cane) on the North Coast is exacerbated by the lower sucrose content of cane grown there. The irrigated North also uses more ammonium sulfate which has an 18% lower energy production requirement than urea (GREET, 2015).

Energy inputs from herbicide use is almost four-fold higher on the North Coast but the net impact is relatively small. Herbicide use per unit area is higher on the North Coast but that effect is multiplied by the two-fold differences in yield between the areas. That yield difference, however, declines with green cane harvesting and declines further with mechanical harvest. Pesticide use is also much more prevalent on the in the warmer, sandier North Coast due to prevalence of eldana and nematodes. Pesticide use still has a relatively minor impact and accounts for less than 4% of the North Coast energy input.

Figure 2 also highlights that the difference between the irrigated and non-irrigated areas was not only the amount of energy input for each scenario, but the distribution of fossil fuels used for each area. For the baseline scenario on the North Coast, natural gas was the greatest fossil fuel input (46%) while coal was the lowest (23%). However 59% of the energy input for cane

production in the irrigated North was from coal. Oil and natural gas use in the irrigated North were lower in magnitude and as a percentage of total energy input. South Africa has abundant coal reserves so, without considering water use, it could be argued that cane irrigation in South Africa makes better use of local energy sources. However, overall environmental impacts would likely be much higher when considering coal mining and increased carbon and other emissions from coal combustion.

Figure 4 shows the contribution of different agricultural input categories to each of the fossil fuel types from Figure 2. Natural gas was the largest energy input on the North Coast and Figure 4 shows that gas use comes mostly from fertilizer production. Fertilizer production is also the greatest contributor to gas use in the irrigated North, but fertilizer use efficiency (ton cane/kg-N) is 22% lower on the North Coast (Table 1). Diesel fuel is the other major contributor to energy inputs on the North Coast and contributes significantly to both coal and oil inputs due to the use of CTL technology in the country. The irrigated North has much greater use of coal than the North Coast and this is due mostly (78%) to irrigation energy requirements. Diesel fuel and fertilizer production are the primary factors contributing to oil and gas use, respectively.

3.2 Greenhouse Gas Emissions

Figure 5 shows the contribution of different agricultural inputs to total greenhouse gas emissions for each production scenario. Total emissions from the irrigated North are very similar to the North Coast for each production scenario, despite the higher energy inputs from irrigation. Emissions were slightly higher (4%) on the North Coast than the irrigated North for both manual harvest scenarios, but 6% lower with increased mechanization. Figure 5 also shows that pre-harvest cane burning is responsible for approximately 15% of net emissions in each region.

Higher North Coast emissions (per ton of sucrose) for fertilizers production and use outweighed the increased emissions associated with irrigation in the irrigated North, despite the fact that irrigation accounted 23% of total emissions in that region and was a negligible factor on the North Coast. Soil emissions and fertilizer production accounted for 66% of the total baseline emissions in the North Coast and were 38% higher than in the irrigated North, but soil emissions accounted for nearly all of that difference.

Increased mechanization on the irrigated North increased net emissions there by 12%. Total emissions for that scenario were greater there than on the North Coast but emissions were still lower than the baseline scenario for either region. This change is due to the varying potential of mechanization in each area. If mechanization could be implemented on a wider scale on the North Coast, the regional differences would remain and the irrigated North would have comparable or lower net emissions.

4. Discussion

4.1 Comparison with other studies

Few other studies are available documenting the total fossil energy input or greenhouse gas emissions associated strictly with sugarcane production. Renouf et al. (2010) calculated a fossil energy input for cane production in different regions of Australia and found inputs between 400 MJ/t cane and 600 MJ/t with a mean of approximately 550 MJ/t. Our results, when expressed on a cane basis (rather than sucrose), are 367 MJ/t and 470 MJ/t for cane grown on the North Coast and irrigated North, respectively. Mechanical harvest of green cane in the irrigated North had the highest inputs at 485 MJ/t. The analysis by Renouf et al. (2010) included capital equipment (5-10% contribution) and did not distinguish between different categories of agro-chemical inputs. Other notable differences in the studies are that Australia burns just 39% of its cane

(compared to 100% for the South African baseline scenario), is fully mechanized for harvesting and other field operations, and transports most of its cane by rail rather than truck.

Van der Laan et al. (2015) reported fossil energy inputs for cane production in an irrigated area of South Africa (Pongola). Although fossil energy input was reported as only 1685 MJ/t sucrose, compared to 3359 MJ/t sucrose in this study (for the irrigated North), the life cycle inventories had some significant differences. The biggest difference was in irrigation energy requirements of 421 and 1567 MJ/t sucrose in the earlier study and here, respectively. However, our analysis accounted for the fossil energy used to produce the electricity while the previous study did not appear to account for this factor. Both studies show irrigation and fertilizer production as the two largest contributors to energy input, but we show a 50% greater impact from irrigation. In both studies, diesel fuel was noted as the third greatest energy contributor but the earlier study reported 30% lower diesel use, contributing to the lower overall energy input (van der Laan et al., 2015).

Renouf et al. (2010) reported GHG emissions of sugarcane production in Australia to be between 50 and 100 kg CO₂-e/t cane for several growing regions. When recalculated our data on a cane basis, our results were much less variable, between 86 and 89 kg CO₂-e/t cane in the baseline scenarios, but trends were similar between the studies. Soil emissions were the dominant emissions factor for cane production in both studies, accounting for approximately 50% of average emissions. Combined production of all agro-chemical inputs accounted for 10-15% of emissions in each study. Van der Laan et al. (2015) calculated a global warming potential of 468 kg CO₂-e/t sucrose compared to 636 kg CO₂-e/t here. The primary differences noted between the studies were the quantification of coal input for both electricity and diesel production in this study and differences in soil emissions factors and emissions from fertilizer

production. Lisboa et al. (2011) reported on a literature survey which indicated that 3.87% of applied N may be volatilized as N₂O while the IPCC factor is only 1% (IPCC National Greenhouse Gas Inventories Programme, 2006).

4.2 Life Cycle Interpretation

These results demonstrate that although irrigation represents a significant fraction of energy inputs and associated emissions for sugarcane production, irrigated sugarcane production may still have equivalent carbon emissions to some non-irrigated production in South Africa.

Powering irrigation equipment with renewable electricity (such as solar, wind, or biopower produced from excess bagasse and field residues) could further reduce the carbon footprint for irrigated sugarcane production and bring energy inputs to below those of some non-irrigated areas.

A shift to green cane harvesting will have a minor decrease in fossil energy use associated with harvest and transport of harvested field residues but will lead to an approximately 10% reduction in overall emissions. The choice of soil emissions factor for N application has a sizable impact on the emissions profile. The higher estimate taken from Lisboa et al. (2011) seems more appropriate because it is based on field data specifically for sugarcane. Emissions may even be higher with increased mulch blanket due to more water logging and anaerobic activity in soils (Lisboa et al., 2011). Nevertheless, use of the more conservative IPCC value for soil emissions would lower the overall emissions estimate and therefore increase the relative impact of cane burning (16% of total emissions). Use of a lower soil emissions factor decreases the magnitude of total emissions but has a small effect on the trends between production scenarios.

The largest factor that could be changed to lower the energy input and carbon footprint of sugarcane production on the North Coast would be fertilizer use efficiency. Reported nitrogen

use on the mainly non-irrigated North Coast was 28% higher per ton of cane than in the irrigated North. Average fertilizer application rates will vary widely from farmer to farmer, and from field to field depending on soil conditions and other factors, but it seems likely that growers with lower yields may try to extend them by adding fertilizer when precipitation could be the more limiting production factor. In addition, the use of limestone ammonium nitrate accounts for only 10% of the nitrogen applied on the North Coast but the associated emissions from its production are four times that of urea (Skowrońska and Filipek, 2014).

5. Conclusions

This study shows that the high energy requirements for sugar cane irrigation can be partially offset based on lower yields in the non-irrigated areas. In South Africa, the higher fertilizer, agro-chemical, and diesel inputs per ton of sugar on the non-irrigated North Coast, reduced the difference in energy inputs with the irrigated North. Distribution of fossil fuel inputs can also vary significantly with irrigation and other regional agricultural differences. Irrigated cane production required a much higher percentage of coal for primary energy while the non-irrigated North Coast consumed more natural gas and oil. Fertilizer and diesel fuel production were the largest contributors to energy use for North Coast cane production while irrigation electricity was the largest contributor for irrigated lands. Despite higher energy inputs associated with irrigation, life cycle greenhouse gas emissions are comparable for cane production across the two regions except when mechanization is increased in the irrigated North. Differences in feasibility of increasing mechanization in the irrigated and non-irrigated areas of South Africa was the primary cause of regional energy and emissions differences for the mechanized harvest scenario. Results suggest that opportunities to reduce energy input and greenhouse gas emissions from sugarcane production vary based on local agricultural conditions and practices. Feasibility of

integrating renewable electricity use could be a focus of further work in the irrigated North. Improved fertilizer efficiency and use of alternate nitrogen sources could be explored on the North Coast. Shifting to green cane harvesting could reduce net GHG emissions by 15% across both regions, but that difference drops to 5% with increased mechanization in the irrigated North. Increased mechanization has a negative impact on both energy consumption and carbon emissions but those effects could be mitigated through controlled traffic to reduce impacts on soil tilth and cane yields.

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Table 1. Life Cycle Inventory inputs for base case scenario of manual harvest of burned cane in each region. Input data based on personal communication with local extension specialists. Cane and sucrose yields were based on industry averages and diesel fuel use is calculated based on SASRI guidelines (SASRI, 2015a, b; Smith et al., 2010, 2011; Smith et al., 2012, 2013, 2014).

Factor	North Coast	Irrigated North
Cane yield (t/ha)	46.5	90.4
Irrigation (mm/ha/yr)	4	850
Cane sucrose content	13.1%	13.9%
Fuel Use (L/ha/yr)		
- Planting preparation	5.4	6.0
- Planting	1.9	3.1
- Ratoon management	4.9	5.4
- Fertilizer application	0.3	1.9
- Herbicide application	0.3	1.7
- Collection	50	45
- Transport	55	110
- TOTAL	117	173
Fertilizer		
- Filtercake (t/ha/yr)	2.8	2.6
- flyash (t/ha/yr)	28.9	0.0
- Condensed molasses solubles (t/ha/yr)	1.0	0.1
- Urea (kg/ha/yr)	91	29
- Ammonium sulfate (kg/ha/yr)	0	125
- Limestone ammonium nitrate (kg/ha/yr)	10.1	0.0
- P [as triple super phosphate] (kg/ha/yr)	15	34
- K [as KCl] (kg/ha/yr)	111	168
- Lime (t/ha/yr)	0.4	0.1
Herbicide (g/ha/yr)		
- Hexazinone	600	129
- DCMU	900	466
- Isoxaflutole	2.6	0.0
- Triazine	555	260
- MCPA	80	61
- Metribuzen	150	150
- Glyphosate	240	240
- Acetochlor	2,025	1,148
- Pendimethalin	0	750
- Fluazifop-p-butyl [as ripener]	8.4	14.4
- Ethephon [as ripener]	118	144
Pesticide [active ingredient] (g/ha/yr)		
- Imidacloprid	30	2
- Alpha-cypermethrin	17	0
- lambda-cyhalothrin	7	0
- Chlorantraniliprole	36	0
- Indoxacarb	70	0
- Acetamiprid	0	0.01
- Oxamyl [nematicide]	1,950	150

Table 2. Modeled production scenarios for LCA for sugarcane production in South Africa.

Production Area	Harvest Condition	Harvest Method
North Coast (Non-irrigated)	Burned	Manual
North Coast (Non-irrigated)	Green cane	Manual
North Coast (Non-irrigated)	Green cane	Mechanized (where possible)
Irrigated North	Burned	Manual
Irrigated North	Green cane	Manual
Irrigated North	Green cane	Mechanized (where possible)

Table 3. Emissions factor and fossil energy input for agricultural inputs used in the life cycle inventory. All values are listed per unit of input noted for each factor.

Factor (Base Unit)	Emissions (kg CO ₂ -e)	Coal (MJ)	Oil (MJ)	Gas (MJ)	References
Diesel fuel [30% coal-to-liquids (L)]	4.58	23.1	27.1	3.3	(GREET, 2015; Höök and Aleklett, 2010; Kalnes et al., 2009; Macedo et al., 2008)
Electricity (kWh)	1.03	10.88	-	-	(Eskom, 2015)
Fertilizer					
- Urea (kg-N)	1.59	2.1	3.9	60.9	(GREET, 2015; Skowrońska and Filipek, 2014)
- Ammonium sulfate (kg-N)	3.0	1.2	5.7	50	(GREET, 2015; Skowrońska and Filipek, 2014)
- Limestone ammonium nitrate (kg-N)	6.3	1.8	6.1	54	(GREET, 2015; Skowrońska and Filipek, 2014)
- P [as triple super phosphate] (kg-P)	1.66	8.3	14.1	18.4	(GREET, 2015; Skowrońska and Filipek, 2014)
- K [as KCl] (kg-K)	0.60	4.4	4.2	5.2	(GREET, 2015; Skowrońska and Filipek, 2014)
- Lime (t)	0.15	4.2	0.54	0.48	(GREET, 2015; Skowrońska and Filipek, 2014)
Herbicide (g)					
- Hexazinone	0.023	0.043	0.13	0.085	(GREET, 2015; Lal, 2004)
- DCMU	0.020	0.043	0.13	0.085	(GREET, 2015; Lal, 2004)
- Isoxaflutole	0.023	0.043	0.13	0.085	(GREET, 2015; Lal, 2004)
- Triazine	0.023	0.043	0.13	0.085	(GREET, 2015; Lal, 2004)
- MCPA	0.0095	0.043	0.13	0.085	(GREET, 2015; Lal, 2004)
- Metribuzen	0.023	0.043	0.13	0.085	(GREET, 2015; Lal, 2004)
- Glyphosate	0.033	0.043	0.13	0.085	(GREET, 2015; Lal, 2004)
- Acetochlor	0.023	0.050	0.15	0.10	(GREET, 2015; Lal, 2004)
- Pendimethalin	0.023	0.043	0.13	0.085	(GREET, 2015; Lal, 2004)
- Fluazifop-p-butyl [as ripener]	0.039	0.043	0.13	0.085	(GREET, 2015; Lal, 2004)
- Ethephon [as ripener]	0.023	0.043	0.13	0.085	(GREET, 2015; Lal, 2004)
Pesticide [active ingredient] (g)					
- Imidacloprid	0.019	0.053	0.15	0.10	(GREET, 2015; Lal, 2004)
- Alpha-cypermethrin	0.043	0.053	0.15	0.10	(GREET, 2015; Lal, 2004)
- lambda-cyhalothrin	0.043	0.053	0.15	0.10	(GREET, 2015; Lal, 2004)
- Chlorantraniliprole	0.019	0.053	0.15	0.10	(GREET, 2015; Lal, 2004)
- Indoxacarb	0.019	0.053	0.15	0.10	(GREET, 2015; Lal, 2004)
- Acetamiprid	0.019	0.053	0.15	0.10	(GREET, 2015; Lal, 2004)
- Oxamyl [nematicide]	0.019	0.053	0.15	0.10	(GREET, 2015; Lal, 2004)

Figure 1. Map showing the sugarcane growing areas in the provinces of KwaZulu Natal and Mpumalanga in the eastern part of South Africa. Specific mill areas identified are Malalane and Pongola which represent the irrigated North, and Amatikulu and Maidstone which represent the North Coast.

Figure 2. Fossil energy inputs for South African sugarcane production on the North Coast and in the irrigated North under different production scenarios.

Figure 3. Contributions of input categories towards total fossil energy inputs for South African sugarcane production on the North Coast and in the irrigated North under the baseline scenario of burned cane with manual harvest.

Figure 4. Relative contributions of input categories towards coal, oil, and natural gas energy inputs for South African sugarcane production on the North Coast and in the irrigated North under the baseline scenario of burned cane with manual harvest.

Figure 5. Contributions of input categories towards net greenhouse gas emissions for South African sugarcane production on the North Coast and in the irrigated North under different production scenarios.

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Figure1

Figure2

Figure3

Figure4

Figure5