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Evaluation of the environmental impacts of ethanol production from sweet sorghum

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ABSTRACT

Ethanol from biomass feedstocks has the potential to reduce greenhouse gas emissions for fuel production. This work calculates the potential environmental impact from the production of ethanol from sweet sorghum using several processing options. The following three processing options were evaluated: 1) a farm scale decentralized option where all steps except the dehydration are performed on the farm, 2) a semi-centralized process where distillation and dehydration are performed at a biofuel refinery, and 3) a centralized process where sorghum stem is transported to a facility where all processing is performed. Results show that a centralized process where sweet sorghum stem is transported to a processing facility to produce ethanol has significant negative environmental impacts when compared to corn ethanol and other processing options. The centralized option resulted in a 62% increase in GHG emissions and a 50% increase in non-renewable energy use compared to corn ethanol. When the decentralized and semi-centralized options were compared to corn ethanol production, GHG emissions were reduced by 39% and 25% respectively. Non-renewable energy use reductions were 27% in the decentralized process and a 15% reduction in the semi-centralized process.

Introduction

Surging energy demand, fossil fuel depletion, increased climate awareness, and energy security concerns have resulted in research on alternative sources of energy with biomass being one of those sources. Biomass feedstocks have the potential to replace conventional fuels and reduce greenhouse gas (GHG) emissions. Common biomass feedstocks include corn, wheat, sugarcane, sugar beets, and sweet sorghum (Bai et al., 2010). Increased crop yields, improved fertilizer efficiency and innovation in biomass conversion processes are leading to improved profitability of ethanol biofuel production (Cassman and Liska, 2007).

Annual ethanol production in the United States in 2012 was 12.7 billion gallons (U.S. Ethanol Production and the Renewable Fuel Standard RIN Bank), most of which was produced from corn. Because corn is the most dominant biomass feedstock in the United States, there have been numerous life cycle assessments (LCAs) performed on corn ethanol production (Kim et al., 2009; Liska et al., 2009; Wang et al., 2007; Spatari et al., 2005; Adler et al., 2007). These studies have focused primarily on GHG emissions and fossil fuel use and have not focused on land usage, respiratory effects, and land and water pollution. Sweet sorghum is a high energy, drought resistant crop that can thrive in a variety of climates and soil conditions. When compared to corn, sweet sorghum could be a potentially more attractive biomass feedstock because of its low nutrient and water requirements. There are studies on the production of biofuels from sweet sorghum. Cai et al. (2013) investigated the life-cycle energy use and GHG emissions from the production of ethanol from grain sorghum, forage sorghum and sweet sorghum, the results are summarized in Table 1. Köppen et al. (2009) performed a screening assessment that analyzed the GHG emissions and energy use along the entire life cycle of the sweet sorghum ethanol process for different production and use scenarios. There has been a major research effort at Oklahoma State University to investigate feasible approaches for ethanol production from sweet sorghum, and this study is an addition to the research effort. Agricultural production of biomass can be an environmentally intensive process; therefore, the environmental sustainability of biofuel production processes must be assessed. Land use can be intensive, there are emissions to air, water, and soil from the use of fertilizers and plant protection, and harvesting and processing can be energy intensive (von Blottnitz and Curran, 2007).

Process description

Three processing options are evaluated in this work: 1) a farm scale decentralized process where all steps except the dehydration are performed on the farm, 2) a semi-centralized process where the distillation and dehydration are performed at a biofuel refinery, and 3) a centralized process where the sorghum stem is transported to a

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Table 1
GHG emissions and energy use for different sorghum feedstocks, per MJ of ethanol produced.

Feedstock	GHG emissions (kg CO_2/MJ)	Fossil energy use (MJ/MJ)
Grain sorghum	0.04–0.06	0.2–0.5
Sweet sorghum	0.03	0.2–0.3
Forage sorghum	0.05	0.4

facility where the juice extraction, fermentation, distillation and dehydration are performed.

Cultivation and harvesting

In this analysis, sweet sorghum is grown without the use pesticides, insecticides, and irrigation. The process for producing ethanol from sweet sorghum includes a modified forage chopper that harvests and cuts the sweet sorghum stalk down to six to eight inch billets. In the centralized processing option, billets are transported to a processing facility where the remaining steps are performed.

Juice extraction and fermentation

The billets are sent to a screw press that extracts the juice. Bagasse is a by-product of this process, in the decentralized and semi-centralized options; bagasse is dried and fed to cattle. In the centralized process, the bagasse is burned to produce steam for the distillation column and electricity for the process. The juice is fermented using *Saccharomyces cerevisiae* in polyethylene tetraphthalate vessels where ethanol is produced (Kundiyana et al., 2010). In the semi-centralized process, the ethanol produced after fermentation is transported to a processing facility where the distillation and dehydration are performed.

Distillation and molecular sieve

A distillation column is used to produce 95 wt.% ethanol, the decentralized and semi-centralized processes use natural gas to provide steam for the distillation column while the centralized process uses bagasse. The 95 wt.% ethanol produced in the decentralized process is transported to a facility where ethanol dehydration occurs. A molecular sieve is used to dehydrate the ethanol produce 99.7 wt.% anhydrous ethanol.

Materials and methods

Life cycle assessment

Life cycle assessment (LCA) is a methodology for evaluating the potential environmental associated to product systems. The framework also leads to technological innovation by focusing research efforts on the parts of the process that are energy and environmentally intensive. This technique identifies areas of environmental impact, and it provides quantitative data that facilitates compliance with environmental regulations. It can also assist in informing decision and policy makers in areas of environmental protection (ISO, E., 14040: 2006, 2006). An LCA investigation requires a goal and scope definition, inventory analysis, impact assessment, and an interpretation of the results, as outlined by ISO 14040:2006 (2006) and ISO 14044:2006 (2006).

Software used

This work utilizes the IMPACT 2002 + and BEES + impact assessment methods in SimaPro 7.3.3 to aid in the development of the LCAs.

Goal and scope

The goal of the LCA is to evaluate the environmental impact of the production of ethanol from sweet sorghum. The following three processing options were considered: 1) decentralized, 2) semi-centralized, and 3) centralized processing. The production of ethanol from sweet sorghum was also compared to the production of ethanol from corn. The functional unit that served as the basis of comparison was 1 MJ of anhydrous ethanol produced. The impact categories include: respiratory inorganics, terrestrial ecotoxicity, land occupation, GHG emissions, non-renewable energy use, and water intake. The impact categories were chosen with the aid of SimaPro's normalization tool, and the impact categories with larger significant impacts were chosen for this LCA. A summary of the chosen impact categories and a description are available in Table 2. This analysis only seeks to quantify the environmental impacts of the processes; it is not focused on the economics or the logistics.

System boundary

The Relative Mass Energy Economic (RMEE) is a system boundary selection method that uses mass, energy, and economic value to define the system boundary for LCAs. Defining rigorous system boundaries reduces subjectivity, increases repeatability, and minimizes unreliable results (Raynolds et al., 2000a). Because the selection of the system boundary affects the completeness of the LCA, the goal is to have a system boundary that includes all major environmental impacts. The general rule for excluding steps from an LCA study is that a step may be excluded only if doing so does not change the conclusions of the study (ISO, E., 14044: 2006, 2006; Raynolds et al., 2000a). It is difficult to prove that the exclusion of a step from a LCA study would not change the conclusions of a study. However, by using the RMEE methodology, a system boundary can be selected that excludes unit processes from the study without having to examine the entire system (Raynolds et al., 2000a) and in this comparative LCA, provides equivalent system boundaries.

The selection of the cut-off criteria (Z_{RMEE}), the ratio (mass, energy, economic value) of inputs to the final product, is crucial. Inputs that do not meet the cut-off are excluded from the system boundary and this contributes to uncertainty in the LCA results. For an input to be excluded, the mass, energy and economic ratio must be less than Z_{RMEE}. Statistical tests showed that as Z_{RMEE} increases, the 95% confidence interval also increases, therefore it is not recommended to use a Z_{RMEE} greater than 0.25 (ISO, E., 14040: 2006, 2006). The tests also show that Z_{RMEE} values from 0.05 to 0.25 have more than 90% of total environmental impacts likely to be inside the system boundary

Table 2
Impact category definitions and reference units.

Impact category	Description	Reference unit
Respiratory inorganics	Respiratory effect from the emission to air of inorganic particulate matter	kg of particulate matter
Land occupation	Occupied organic arable land	m^2 of arable land
Terrestrial ecotoxicity	Emissions to air, water, and soil that affect the ecotoxicity of soil	kg of triethylene glycol
GHG emissions	Emissions to air of greenhouse gases (ex. CO_2, CH_4, N_2O, CO)	kg of CO_2 eq.
Non-renewable energy use	Total primary energy use (Higher heating value)	MJ
Water intake	Water used during production	liters

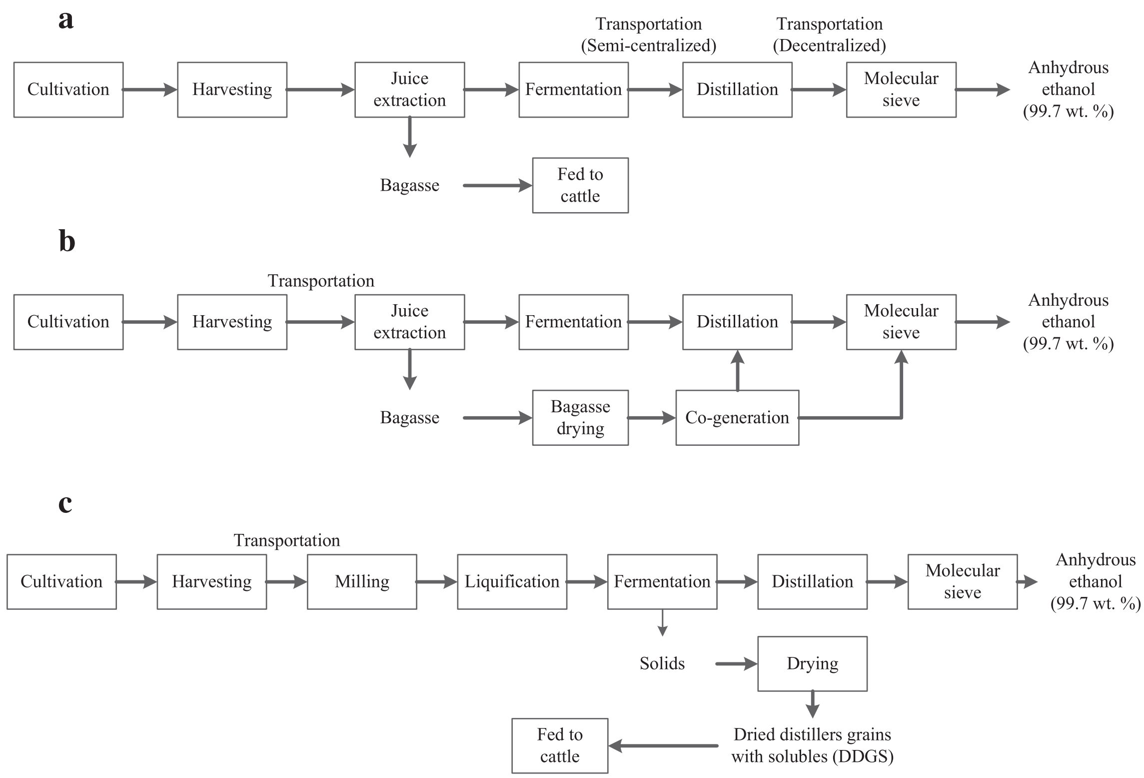

Fig. 1. a. Process diagrams for a) decentralized and semi-centralized processing options, b) centralized processing option, and c) corn ethanol process.

(Raynolds et al., 2000b). A Z_{RMEE} value of 0.05 was chosen for this assessment to provide for a more detailed analysis. Z_{RMEE} is not a calculated value, a lower Z_{RMEE} results in more of the process being included in the analysis. The process schematic for the three processing options and corn ethanol process is available in Fig. 1.

Co-products

The sweet sorghum and corn ethanol production processes produce co-products, bagasse from sweet sorghum and dried distillers grains with solubles (DDGS) from corn. According to ISO 14040 and 14044, when considering the environmental impacts of co-products, three options are available: avoid allocation, expand the system boundary to include the use of co-products, or use allocation (ISO, E., 14040: 2006, 2006; ISO, E., 14044: 2006, 2006). System boundary expansion that is used in this LCA is used to deal with the environmental impact from the co-products. The analysis was expanded to include the use of DDGS as cattle feed and so account for the use of sweet sorghum bagasse as fuel only for the centralized processing option. In the decentralized and semi-centralized options, the bagasse will be fed to cattle since juice extraction step, occurs on the farm for both of those processes. The LCA will reflect an environmental credit for the cattle feed that is displaced by the DDGS and bagasse and also an environmental credit for extra electricity that is produced by burning of sweet sorghum bagasse. Table 3 provides a summary of sorghum and corn ethanol production practices.

Data collection

The data for sweet sorghum crop yields were gathered from a farming facility located on the campus of Oklahoma State University. These data include fertilizer usage and cultivation practices (Fryer, 2008). Data for the decentralized distillation was taken from the process simulation of a pilot plant. The pilot plant was scaled up to provide information for the semi-centralized and centralized distillation facilities. Fertilizer application of 107.6, 44.8, and 44.8 kg per hectare of nitrogen, phosphorus, and potassium (Fryer, 2008) respectively was used for the analysis. Emissions from fertilizer use were collected from Nemecek et al. (2000). Transportation costs per loaded mile and equipment costs were collected from Fryer (2008) and fertilizer prices were collected from the USDA Economic Research Service, Fertilizer Use and Price. A National Renewable Energy Laboratory corn ethanol LCA (Hsu et al., 2010) was modified and used as the basis for the comparative assessment. Energy use in the corn ethanol process is from a projected energy use study conducted by the Energy Resources Center at the University of Illinois at Chicago (Mueller, 2007). The ratios of avoided products to co-products for the corn ethanol process were obtained from a study on distillers grains displacement ratios for corn

Table 3
Summary of sorghum and corn ethanol production practices and allocation.

	Decentralized	Semi-centralized	Centralized	Corn ethanol
Plant protection (pesticide & insecticide)	N	N	N	Y
Irrigation	N	N	N	Y
Fertilizer use	Y	Y	Y	Y
System boundary expansion	Y	Y	Y	Y
Co-products	Bagasse	Bagasse	Bagasse	DDGS
Product displaced	Animal feed	Animal feed	Electricity production	Animal feed

Table 4
Avoided products displacement ratios for sweet sorghum and corn ethanol, kg of avoided product per kg of co-product.

	Sweet sorghum ethanol	Corn ethanol
Corn	0.10	0.96
Soybean meal	0.03	0.29
Urea	2.5E−03	0.03

Table 5
Transportation distances for all process configurations.

Process configuration	Item transported	Distance (km)
Decentralized	95 wt.% ethanol	40
Semi-centralized	Fermented ethanol	125
Centralized	Sweet sorghum stalk	125
Corn ethanol	Corn grain	37 (Yu and Hart)

ethanol by the Argonne National Laboratory (Arora et al., 2008) (Table 4).

Assumptions

A biomass yield of 78.5 wet metric tons per hectare is used as the basis for sorghum cultivation for all processing options. A fermentation efficiency of 90% is used and a juice expression ratio equal to 0.55 was used. The juice expression ratio is defined as the ratio of the mass of the sorghum juice to the mass of the sorghum stem. Land use changes were not taken into account for this evaluation when calculating potential GHG emissions. The environmental impacts from the construction of the processing facility only considered impacts from the construction of the distillation columns and molecular sieve. Data from corn ethanol facility construction is used in place of sweet sorghum (Galitsky et al., 2003). Since the processing of sugarcane and sweet sorghum ethanol is similar, sweet sorghum bagasse was assumed to be similar to sugarcane bagasse (Houx et al., 2013). Crude protein for sweet sorghum bagasse ranges from 16 to 41 g kg^{-1}, while sugarcane crude protein ranges from 11 to 31 g kg^{-1} (Houx et al., 2013). The avoided products for the corn ethanol process include corn grain, soybean meal and urea. An estimate of transportation distances from the farm to the processing facility is made using average transportation distance from farms in Iowa to corn ethanol processing plants (Yu and Hart). A summary of transportation distances and items transported is available in Table 5.

The United States electricity grid mix in the ecoinvent database in SimaPro is used to account for environmental impacts of electricity use for both the sweet sorghum processes and corn ethanol process. Natural gas is the primary fuel for the decentralized, semi-centralized and corn ethanol processes. Trucks, tractors, and harvesters are all powered by diesel fuel.

Results

In this process, six impact categories are evaluated: respiratory inorganics, terrestrial ecotoxicity, land occupation, GHG emissions, non-renewable energy, and water intake. The IMPACT 2002+ impact

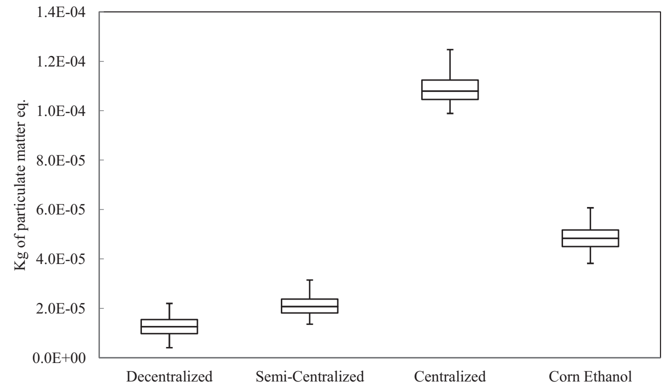

Fig. 2. Impact assessment results for respiratory inorganics, per MJ of anhydrous ethanol produced. The top of the box is the 75th percentile, the middle is the mean, and the bottom of the box is the 25th percentile. The top whisker is 97.5th percentile and the bottom whisker is 2.5th percentile.

assessment method does not include water use as an impact category. To remedy this, another impact assessment method, BEES+, developed by the National Institute of Standards and Technology (NIST) (BEES), is used and only its water intake results are recorded. The results for each impact category for all evaluated processes are available in Table 6.

Respiratory inorganics

Fig. 2 shows a comparison between the three processing options and corn ethanol production for five impact categories. The impact category that falls under human health is respiratory inorganics and the reference substance is kg of particulate matter less than 2.5 μm. The centralized processing option stands out in this impact category. Fig. 2 shows a 123% increase in particulate matter released when compared to corn ethanol while the decentralized and semi-centralized options show a 74% and 57% reduction when compared to corn ethanol. The difference in this impact category is due to transportation. The centralized option transports sweet sorghum stalks to a processing facility while the decentralized option transports distilled ethanol to a molecular sieve site. The mass required to fill a truck transporting ethanol versus sweet sorghum stalk is different, this difference increases the impacts from transportation for the centralized processing option. When the decentralized and centralized options are compared, 58% of respiratory inorganics impacts for the centralized option are from the transportation of sweet sorghum stalk while the transportation of ethanol accounts for less than 1% of the impacts for the decentralized option. Process contributions for all configurations are available in Fig. 3, for all three processing options, a majority of respiratory inorganics impacts are from sorghum cultivation and transportation.

Terrestrial ecotoxicity

Terrestrial ecotoxicity results in Fig. 4 show a comparison between the terrestrial ecotoxicity for the sweet sorghum processing options and corn ethanol. A negative number denotes a positive impact on

Table 6
Impact assessment results for the evaluated processes, per MJ of ethanol produced.

Impact category	Decentralized	Semi-centralized	Centralized	Corn ethanol	Unit
Respiratory inorganics	1.3×10^{-5}	2.1×10^{-5}	1.1×10^{-4}	4.9×10^{-5}	kg particulate matter eq.
Terrestrial ecotoxicity	−15.1	−15.1	−19.7	0.6	kg triethylene glycol
Land occupation	2.9×10^{-2}	2.9×10^{-2}	1.2×10^{-1}	2.9×10^{-2}	m^2 arable
GHG emissions	3.7×10^{-2}	4.6×10^{-2}	9.7×10^{-2}	6.0×10^{-2}	kg CO_2 eq.
Non-renewable energy	0.7	0.8	1.3	0.9	MJ
Water intake	8.2	8.2	14.9	94.4	liters

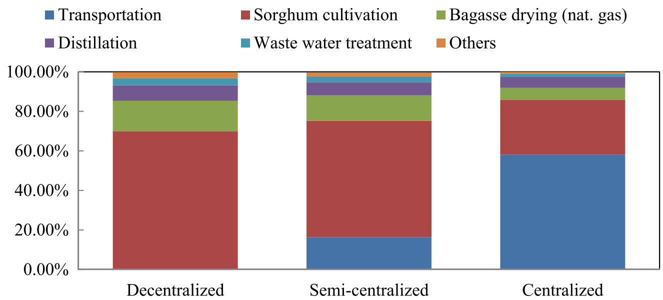

Fig. 3. Process contributions, respiratory inorganics. Sorghum cultivation includes impacts from: fertilizer use & production, tillage, and harvesting.

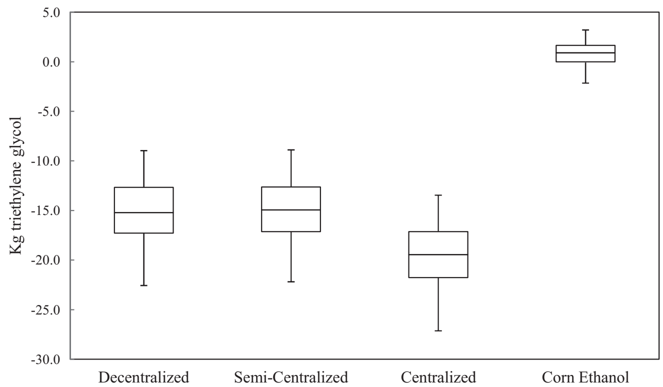

Fig. 4. Impact assessment result for terrestrial ecotoxicity, per MJ of anhydrous ethanol produced. The top of the box is the 75th percentile, the middle is the mean, and the bottom of the box is the 25th percentile. The top whisker is 97.5th percentile and the bottom whisker is 2.5th percentile.

terrestrial ecotoxicity. All the sweet sorghum processes result in positive environmental impacts and these are from the cultivation of sweet sorghum. There is a net sequestration of emissions to air, water, and soil that affect soil ecotoxicity by the sweet sorghum crop.

Land occupation

The land occupation impacts include the area required to grow the crop and land required to build facilities and factories, although the latter only accounts for approximately 0.1% of the land occupation impacts for all processes that are being evaluated. In Fig. 5, though the three sweet sorghum processing options utilize the same biomass yield, the centralized option results in higher land occupation. This is

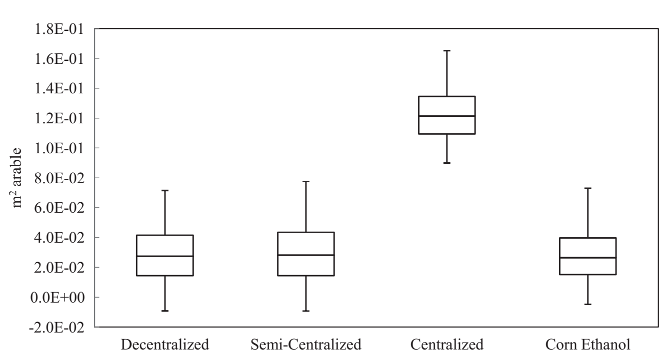

Fig. 5. Impact assessment results for land occupation, per MJ of anhydrous ethanol produced. The top of the box is the 75th percentile, the middle is the mean, and the bottom of the box is the 25th percentile. The top whisker is 97.5th percentile and the bottom whisker is 2.5th percentile.

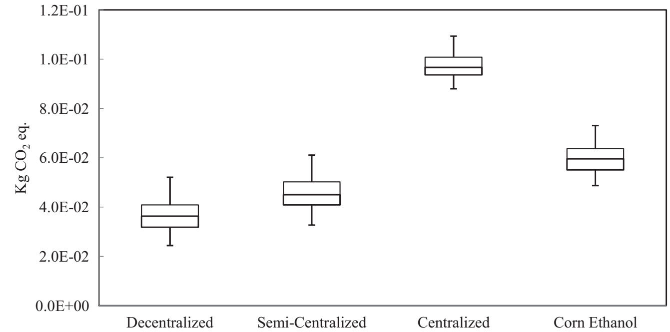

Fig. 6. Impact assessment results for GHG emissions, per MJ of anhydrous ethanol produced. The top of the box is the 75th percentile, the middle is the mean, and the bottom of the box is the 25th percentile. The top whisker is 97.5th percentile and the bottom whisker is 2.5th percentile.

a result of avoided products, in the centralized process; bagasse displaces natural gas production while the bagasse in the decentralized and semi-centralized option displaces animal feed. When all options are compared, the centralized processing option results in a 358% increase in land occupation while the decentralized and semi-centralized options are similar to corn ethanol.

GHG emissions

GHG emissions is an important metric that is a major focus of most life cycle assessments, the reference unit is kg of equivalent carbon dioxide (CO_2) released to the atmosphere. In this process, the major

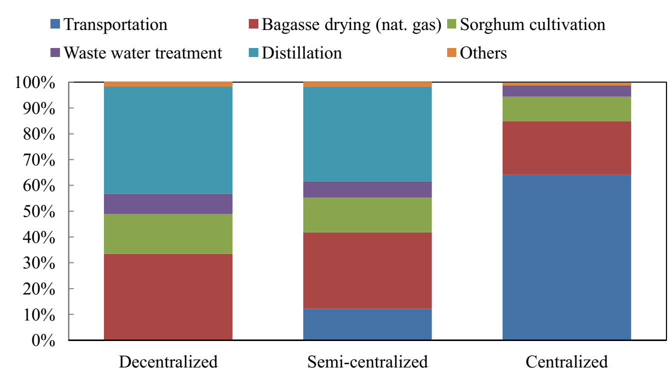

Fig. 7. Process contributions, GHG emissions. Sorghum cultivation includes impacts from: fertilizer use & production, tillage, and harvesting.

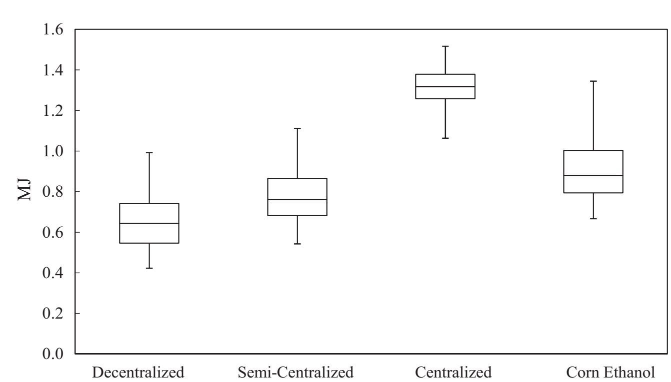

Fig. 8. Impact assessment results for non-renewable energy, per MJ of anhydrous ethanol produced. The top of the box is the 75th percentile, the middle is the mean, and the bottom of the box is the 25th percentile. The top whisker is 97.5th percentile and the bottom whisker is 2.5th percentile.

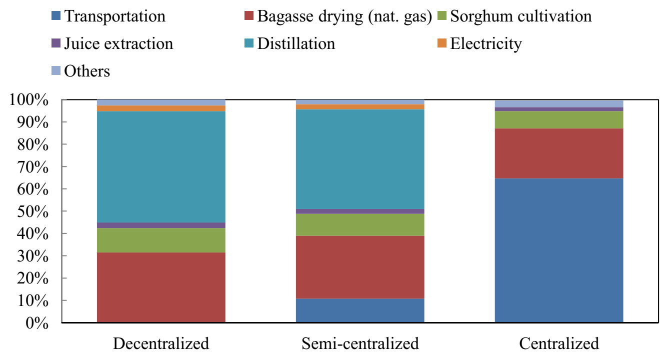

Fig. 9. Process contributions, non-renewable energy use. Sorghum cultivation includes impacts from: fertilizer use & production, tillage, and harvesting.

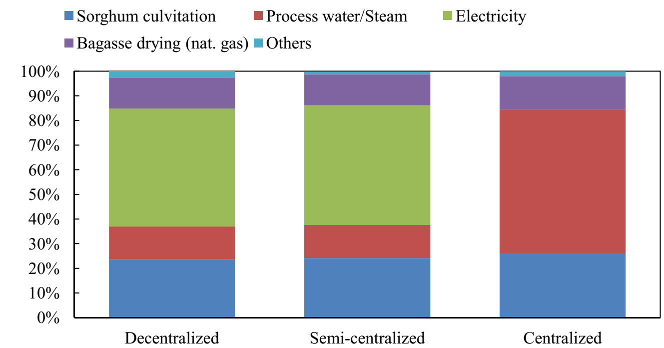

Fig. 11. Process contributions, water intake. Sorghum cultivation includes impacts from: fertilizer use & production, tillage, and harvesting.

greenhouse gases that are released are CO_2, methane (CH_4), and nitrous oxide (N_2O). Fig. 6 shows the amount of equivalent CO_2 released to the air for every MJ of ethanol produced. The centralized option GHG emissions are significantly higher than the other processing options. When compared to corn ethanol there is a 62% increase in equivalent CO_2 released to the air for every MJ of ethanol produced in the centralized option, while for the decentralized and semi-centralized options there is an 39% and 25% decrease, respectively, when compared to corn ethanol. The difference is again due to the transportation; for the centralized option the transportation of sweet sorghum stem accounts for 64% of GHG emissions while distillation and reducing bagasse water content accounts for 21%. For the decentralized option, less than 1% of GHG emissions come from transporting ethanol while 76% come from distillation and reducing the bagasse water content. Fig. 7 shows the contribution of other parts of the process.

Non-renewable energy use

The resources damage category quantifies the amount of raw material required to produce the functional unit, and in this case non-renewable energy usage is the focus. This category would include any use of crude oil, natural gas, coal or uranium. Fig. 8 shows a comparison between the evaluated processes for every MJ of ethanol produced. Like in the GHG emissions impact category, the centralized option has a larger non-renewable energy use than the other processing options. When compared to corn ethanol, there is a 50% increase in non-renewable energy required to produce 1 MJ of ethanol for the centralized option; it requires 1.3 MJ of non-renewable energy to produce 1 MJ of ethanol. The decentralized and semi-centralized options result in a 27% and 15% reduction, respectively, when compared to corn ethanol. The difference is again due to the transportation of the sweet sorghum stalks. Process contribution results in Fig. 9 show that 65% of the impacts are from transportation of sweet sorghum stem while 23% come from distillation and bagasse water removal steps. When the decentralized option is evaluated, less than 1% of the non-renewable energy use comes from transportation of ethanol while 82% comes from the distillation and bagasse water removal steps.

Water intake

Water usage is an important metric to be considered when evaluated biofuel production processes. This includes water used for irrigation and during fuel processing. The corn ethanol and sweet sorghum ethanol processes have some differences. Since sweet sorghum is a hardy and drought resistant crop, this LCA does not include irrigation for the sweet sorghum crop but it is included for corn cultivation. In Fig. 10, all three sweet sorghum processing options have a lower water use compared to corn ethanol. The decentralized and semi-centralized processing options result in a 91% reduction while the centralized processing options only results in an 84% reduction in water use during its entire life cycle when compared to corn ethanol. In Fig. 11, process contributions for the decentralized and semi-centralized processes are similar. The largest contributions are from electricity production, sorghum cultivation and process water. The impact of transportation distances on selected impact factors is shown in (Figs. 12–14).

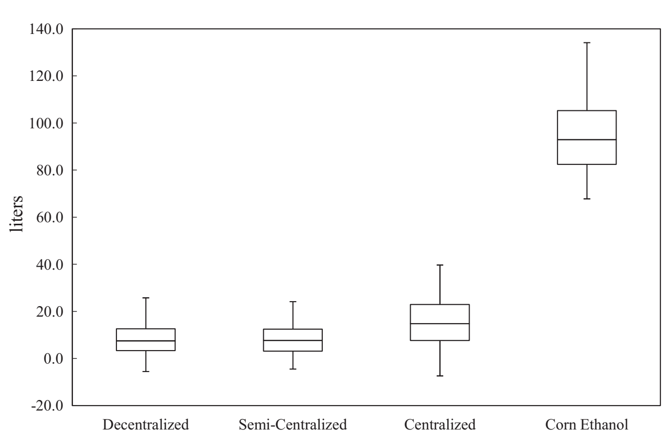

Fig. 10. Impact assessment results for water intake, per MJ of anhydrous ethanol produced. The top of the box is the 75th percentile, the middle is the mean, and the bottom of the box is the 25th percentile. The top whisker is 97.5th percentile and the bottom whisker is 2.5th percentile.

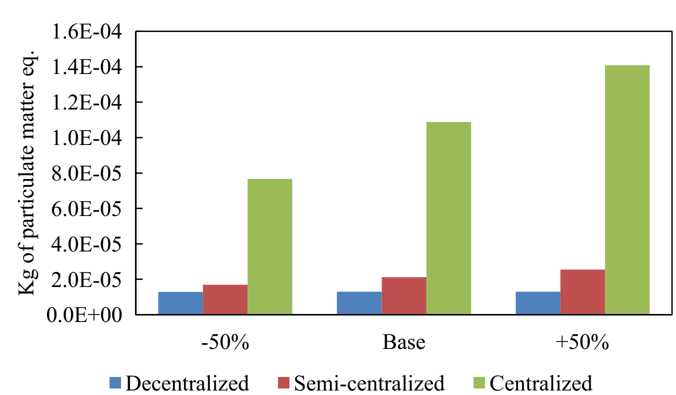

Fig. 12. Transportation distance sensitivity analysis for respiratory inorganics, per MJ of anhydrous ethanol produced.

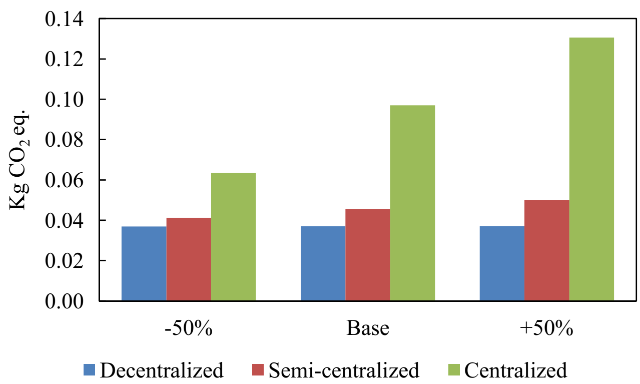

Fig. 13. Transportation distance sensitivity analysis for GHG emissions, per MJ of anhydrous ethanol produced.

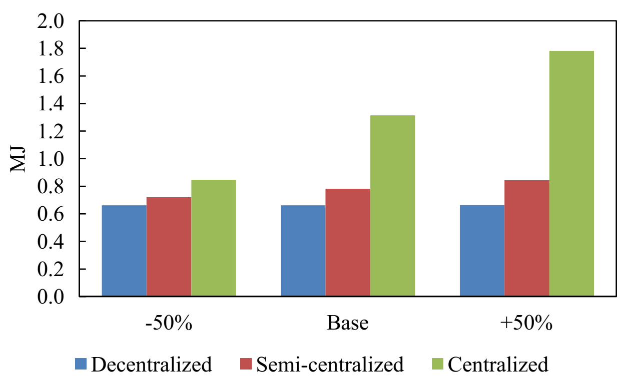

Fig. 14. Transportation distance sensitivity analysis for non-renewable energy use, per MJ of anhydrous ethanol produced.

Uncertainty analysis

An uncertainty analysis was carried out in SimaPro 7.3.3 to test the uncertainty in the LCA impact category results for all processes. The uncertainty for each input is calculated using a pedigree matrix. The pedigree matrix has 6 factors: Reliability (U_1), Completeness (U_2), Temporal correlation (U_3), Geographical correlation (U_4), Further technological correlation (U_5), and Sample size (U_6) (Frischknecht et al., 2004). These factors have a score and value associated with them and the user assigns the score and value according to which category the life cycle inventory data source is used. A basic uncertainty factor (U_b) is also added (Frischknecht et al., 2004), which is based on expert judgment associated with certain inputs, outputs and emissions. These six factors from the pedigree matrix and the basic uncertainty factor are used to calculate an overall uncertainty factor that can be entered for each input, output, and emission. Since this LCA uses the ecoinvent database extensively, there are inputs to the process in SimaPro that are from different geographic regions, this uncertainty analysis helps account for differences due to geographic location.

Table 8
Transportation distance sensitivity analysis. −/+ 50% change in transportation distance from base case.

	Respiratory inorganics	GHG emissions	Non-renewable energy use
Decentralized	−/+1%	−/+0%	−/+0%
Semi-centralized	−/+20%	−/+10%	−/+8%
Centralized	−/+30%	−/+35%	−/+36%

Sensitivity analysis

A sensitivity analysis was performed on biomass yield for the decentralized option. Biomass yields of 56, 78.5, and 101 metric tons per hectare were used. The sensitivity analysis on biomass yield in Table 7 shows an improvement in all impact categories as biomass yield increases. When compared to the base case, the 56 and 101 metric tons per hectare biomass yields result in a 10% increase and 5% reduction respectively in equivalent CO_2 released. A similar trend occurs for non-renewable energy use, 56 and 101 metric tons per hectare yields result in an 8% increase and 3% reduction respectively in non-renewable energy use. As biomass yields increase, environmental impacts for all categories decrease.

A sensitivity analysis is also performed on transportation distances for all three sweet sorghum processing options. Environmental impacts from a 50% decrease and a 50% increase in transportation distances for all configurations are evaluated and the results are available in Figures 12–14. Table 8 shows that changes in transportation distance have less of an effect on environmental impacts for the decentralized option compared to the centralized option. For GHG emissions and non-renewable energy use, there is no difference in impacts with a 50% decrease or increase in transportation distances for the decentralized option. In the centralized option, the same change results in a 35% and 36% change in GHG emissions and non-renewable energy use, respectively.

Conclusion

For the production of ethanol from sweet sorghum, the choice of processing options has a significant impact on the environmental outlook of the process. The decentralized and semi-centralized options are the most attractive from an environmental impact standpoint. Both processing options yield similar or lower environmental impacts in all impact categories when compared to corn ethanol production. The density of material being transported has an impact on the environmental impacts.

When the sweet sorghum options are compared to GHG emissions and non-renewable energy use for gasoline production (Elsayed et al., 2003), the decentralized and semi-centralized options result in a 54% and 43% reduction in GHG emission respectively while the centralized option results in a 21% increase. When compared to gasoline production, the decentralized and semi-centralized non-renewable energy use is 42% and 33% lower, respectively, while the centralized process results in an 8% increase.

Table 7
Sensitivity analysis on biomass yield for the decentralized processing option, per MJ of anhydrous ethanol produced.

Impact category	56 metric tons/ha	78.5 metric tons/ha	101 metric tons/ha	Unit
Respiratory inorganics	1.9×10^{-5}	1.3×10^{-5}	9.5×10^{-6}	kg particulate matter eq.
Terrestrial ecotoxicity	−14.9	−15.1	−15.2	kg triethylene glycol
Land occupation	7.7×10^{-2}	2.9×10^{-2}	1.7×10^{-3}	m^2 arable
GHG emissions	4.1×10^{-2}	3.7×10^{-2}	3.5×10^{-2}	kg CO_2 eq.
Non-renewable energy	7.1×10^{-1}	6.6×10^{-1}	6.4×10^{-1}	MJ
Water intake	12.9	8.2	5.5	liters

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