Life Cycle Analysis of Sugarcane Bagasse and Switchgrass under Dilute Phosphoric Acid Pretreatment and Simultaneous Saccharification and CoFermentation

Michael C. Fowler
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Abstract

Under provisions of the Energy Independence and Security Act and the Renewable Fuel Standard, production of cellulosic ethanol is mandated to increase. Corn dominates the first generation ethanol industry in the United States. Already a high-demand crop, when subject to agricultural intensification, the carbon-neutrality potential associated with biofuels, and other environmental implications, fall into question. Sugarcane bagasse, a lignocellulosic byproduct of sugarcane manufacturing with limited economic value, and switchgrass (*Panicum virgatum*), a native, perennial, high-yield crop, are alternative resources that might used to produce ethanol. Life cycle assessment of second generation feedstocks has focused exhaustively on global warming potential with minimal consideration to broader impact categories. In this study, traditional dry-milled corn ethanol is compared to sugarcane bagasse and switchgrass that is derived using dilute phosphoric steam acid pretreatment and simultaneous saccharification and cofermentation. Modeled over ten-year scales, using E85 and E15 fuel blends scenarios, switchgrass and sugarcane bagasse fuel blends had greater global warming potential (kg CO$_2$-eq) compared to corn at equal blend ratios. As the ethanol ratio increased, the hotspot would transition from fossil fuel production and emissions to fermentation driven by increases in enzymes, chemicals, and electricity. Water consumption, stratospheric ozone depletion, and marine eutrophication were reduced for switchgrass compared to corn due to lesser agricultural demands predominantly associated with upstream processes. Further research should include reduction of enzymes while maintaining ethanol yield and characterization of stillage.
Montclair State University

Life Cycle Analysis of Sugarcane Bagasse and Switchgrass under Dilute Phosphoric Acid Pretreatment and Simultaneous Saccharification and CoFermentation

by

Michael C. Fowler

A Master’s Thesis Submitted to the Faculty of
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In Partial Fulfillment of the Requirements
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College of Science and Mathematics
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LIFE CYCLE ANALYSIS OF SUGARCANE BAGASSE AND SWITCHGRASS UNDER DILUTE PHOSPHORIC ACID PRETREATMENT AND SIMULTANEOUS SACCHARIFICATION AND COFERMENTATION

A THESIS

Submitted in partial fulfillment of the requirements
For the degree of Master of Science

by
MICHAEL C. FOWLER
Montclair State University
Montclair, NJ
2018
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1. Introduction

a. Policy

Biomass derived ethanol is produced globally and, with traditional fossil fuels, serves as a blended gasoline transportation fuel. The transition to ethanol blended fuels is rooted in policy decisions that are driven by concerns regarding climate change projections, atmospheric carbon concentrations, economic uncertainty of fossil fuel, energy independence, and national security. Done with worthy intentions, the proliferation of first generation feedstock bioethanol has been problematic in minimizing environmental impacts in favor of economic gains or energy security. Ninety-seven percent of gasoline in the United States is an ethanol blend that is statutorily projected to climb (Alternative Fuels Data Center, 2016). Rapid, unplanned expansion of ethanol blends may be counterproductive to reducing environmental impacts that defined by renewable, sustainable fuels. A complete assessment of the life cycle of cellulosic ethanol must be taken into account for market expansion and competition beyond corn derived E15 gasoline blend in the United States. Environmental impact analysis of various potential cellulosic ethanol feedstocks will allow for reduction of high-emission methodologies without counterproductive trade-offs created by modifying individual processes. The development of system diagram, with product stages, and unit processes will inform commercial implementation strategies that fulfill policy demands of cellulosic technology. Various policies have driven the domestic development of ethanol and its’ infusion into the transportation fuel market.

The 2005 Energy Policy Act (EPAct 2005) covers a wide variety of energy production areas including fossil fuel, transportation, nuclear energy, and renewable fuel as well as climate change mitigation and adaptation strategies (Energy Policy Act of 2005). This includes, utilization of low or carbon-neutral energy, reduced intensity of economic development, improved infrastructure resilience, and decreased resource consumption. The policy intended to
improve energy efficiency, conservation, and modernization of infrastructure (Energy Policy Act of 2005; Hoekman, 2009). In name, it is largely branded as a policy to protect gasoline costs to citizens and national fuel supplies. It also sought to decrease greenhouse gas production (Bastianin et al., 2016; Farrell et al., 2006; Jensen et al., 2009; Solomon et al., 2007). Regarding biofuel production, the EPAct 2005 established the Renewable Fuel Standard (RFS) which required 4 billion gallons/year of ethanol be blended into gasoline by 2006, increasing to 7.5 billion gallons/year by 2012 (Bastianin et al., 2016; Energy Policy Act of 2005; Farrell et al., 2006; Jensen et al., 2009; Solomon et al., 2007). Stipulations for ethanol from biomass include identification of product stages, research and development of lignocellulosic ethanol production, public outreach, and stakeholder engagement (Hoekman, 2009; Jensen et al., 2009). The legislation provided approximately six billion dollars in annual subsidies to domestic producers from 2002-2011 and tariffs of fifty-four cents per gallon on imported ethanol (Babock, 2013; De Gorter, et al. 2008; Guzman, 2011; Skidmore, et al. 2013; Solomon, et al. 2007). EPAct 2005 was a successful policy driver, but it remained only the first significant incarnation of modern domestic bioethanol policies.

By 2007, EPAct 2005 RFS was amended in the Energy Independence and Security Act (EISA) to greatly expand on the 2012 goal. The 2007 RFS requires production of 9 billion gallons of renewable fuels in 2008, increasing to 15.2 billion gallons in 2012 and to 36 billion gallons in 2022 (State Energy Conservation Office, 2016). Recognizing some unintended consequences of the RFS under the EP Act 2005, now only 15 billion gallons/year is permitted to come from first generation feedstocks (Hsu, et al. 2010; Energy Security Act of 2007), thereby requiring significant innovation and technological deployment for 'advanced biofuels’. First generation feedstocks are crops whose primary purpose is food. Only non-edible plant material
that reduce greenhouse gas emissions by more than 50% of the fuels they replace are considered ‘advanced biofuels’ while cellulosic ethanol must be at least 60% (Chen & Önal, 2016; USEPA, 2016). When the EISA was passed, it was projected that the cellulosic ethanol sector would meet later mandates. However, cellulosic ethanol contribution to blended gasoline still remains a fledging technology at the commercial scale. By 2014, only three corn stover first generation feedstock ethanol facilities had been opened (USEPA, 2016). Numerous barriers hinder further commercialization. The lack of economic profitability, insufficient feedstock volumes, low willingness to adopt, technological innovation/efficiency, uncertain environmental impacts, and meeting life cycle carbon reduction requirements have all contributed to the lack of dissemination of cellulosic ethanol. Although there is legislative and research support for cellulosic ethanol, the United States market remains predominantly corn based and by 2013, 40% of domestic grown corn was allocated to ethanol production (Hoekman, 2009; Skidmore et al., 2013; USEIA, 2014; Wisner, 2013).

b. First Generation Feedstocks

The movement toward renewable fuels is framed in that the replacement will be sustainable, more efficient, or ‘greener’. Initial development of bioethanol policy did not protect corn demand for other sectors (livestock, food, exports), define classes of biofuels, or require greenhouse gas accounting requirement resulting in the amendment of the RFS (Bracmort, 2018). Although, this is not uncommon in other national ethanol policies, studies disagree about the carbon reduction potential of bioenergy (Searchinger et al., 2008; Tilman et al., 2006; Tillman et al., 2009; Yang and Peidong, 2011). Compared to gasoline production and use, greenhouse gas emissions are reduced on average by 40% with corn-based ethanol produced from dry mills and up to 108% if cellulosic feedstocks are used (Alternative Fuels Data Center,
However, the best reported results for bioethanol can produce 90% fewer lifecycle emissions than gasoline, but the worst cases can produce far more (IPCC, 2014; Tilman et al., 2009). The inconclusiveness regarding greenhouses gas emissions is significantly larger when assessing cellulosic technologies. Impacts are contingent on more than feedstock selection. Energy crops, inclusive of corn or switchgrass, require an agricultural product stage. The difference between the two being production intensity and corresponding inputs. This may be avoided when utilizing waste products such as corn stover or bagasse. Each feedstock will require, a potentially unique, biorefinery process. Feedstock selection, production choices, and assumptions regarding their lifecycles, if capable to reduced environmental impacts, will be the characteristics to be imposed in a real-world scenario for commercial expansion.

Corn, soybeans, wheat, rice, sorghum, oats, barely, potato, sugarbeets, sugarcane, rye, and alfalfa are all first generation feedstocks. Corn dominates the domestic market, but internationally, regionally specific first generation feedstocks might be highly efficient. Brazil’s use of sugarcane and bagasse is prominent and highly successful (Mingo, 2014). China’s policies required modification, similar to the United States, but opted to transition to less desirable first generation feedstocks like cassava and sorghum (Hongzhou, 2015; Qiu, et al., 2010). Initially, these crops are logical choices for ethanol conversion given their market prominence and high sugar or starch content. The modern process has become increasingly efficient to increase ethanol yields while limiting corn consumption. However, without major advancement in cellulosic ethanol, the 2022 goals remain out of reach (Chen & Önal, 2016; USEIA 2015). Regardless of production methodology or conversion efficiency, the preexisting environmental concerns associated with first generation corn ethanol persist.
Corn agriculture is highly resource consumptive and prior to the revision of the RFS, policy incentivized meeting of federal mandates with greater production intensity. Despite its conversion efficiency and dual-market capacity, in a life-cycle perspective corn is likely one of the poorest feedstocks for ethanol production (Bonin and Lal, 2012). Corn is an annual crop, sometimes grown continuously, requiring repetition of soil preparation, plantation, fertilization, chemical herbicides/pesticides, and harvesting. Corn energy cropping, the practice of harvesting solely to produce fuel, expands monoculture practices that increase synthetic fertilization and pesticide use (Larson, et al., 2010; USDA NRCS, 2007). To ensure survivability, atrazine and glyphosate are common, but some variety of one-hundred pesticides were reported in 97% of planted areas in 2015 (USDA NASS, 2016). Irrigation practices for corn pose severe water quality and quantity concerns (Schnoor, et al., 2008; Wu et al., 2009). Across expanding acreage, intensification of less fertile soil increases the demands of the domestic bioenergy production system (Larson, et al., 2010). The expansion of high-demand crops is contradictory to maintain economic profitability and mitigate environmental impacts.

Energy cropping with corn can be a major contributor to habitat destruction. Natural ecosystems, particularly grasslands, are ecologically diverse. Compared to conventional gasoline, corn energy-cropping is a potentially larger contributor to freshwater ecotoxity from pesticides and non-cancer human health impacts from heavy metals in fertilizers (Yang, 2013). Furthermore, indirect land use change can be one of the most unaccounted for environmental impacts that can negate sequestration capacity using energy crop carbon models (Menichetti and Otto, 2008; Morales et al., 2015; Plevin et al., 2010). The industrial agronomy corn monocultures, while easier for cultivation, have seasonal production gaps, tendency to be disease susceptible, and suffer from rapid distribution of pests, molds, and funguses that eventually
decrease potential ethanol yield (Fausti, 2015; Hartman et al., 2011; Price, 2008; Vyn, 2006). Life cycle analysis (LCA) acts as a decision making tool that, in the instance of biofuels, may require acknowledging a commercial structure be based on around environmental impact tradeoffs rather than a singular solution, or ‘perfect’ design.

c. Cellulosic (Second Generation) Feedstocks

Rather than relying on technological advancement to increase production yields and ethanol efficiency, cellulosic ethanol exists as a wholly alternative source of bioenergy. Cellulosic, or second generation feedstocks, are comparatively an untapped resource that can exist bilaterally to corn ethanol. Forest residues or lignocellulosic plants such as corn stover (corn cobs, leaves, husk, and stalk), miscanthus, wheat straw, sugarcane bagasse, and switchgrass are favored potential biofuel resources. Bioenergy from these feedstocks is inherently non-competitive with traditional agriculture, easily incorporated existing distribution and transportation infrastructure, and based ideally on perennial, high yielding crops that have minimal nutrient demands (McLaughlin and Kszos, 2005; Parrish and Fike, 2005). There are concerns over the commercialization of cellulosic ethanol regarding land use change for cultivation, environmental impacts, economic feasibility, net energy yield, and capacity to reduce greenhouse gas emissions. Eutrophication, eco-toxicity, photochemical smog, human toxicity, and acidification potential have all been reported to increase with biofuel use (Bai et al., 2010; Dayland and Ciliz, 2016; Von Blottnitz and Curran, 2007; Yang, 2013).

Evaluation of cellulosic feedstocks, as conducted through an LCA, consists of defining goal & scope, developing a life cycle inventory, impact assessment analysis, and interpretation. The steps to complete a LCA are conducted within the research objective to define and analyze the life cycle of sugarcane bagasse and switchgrass derived ethanol. First, sugarcane bagasse will
be evaluated based upon the pilot scale design at the former Stan Mayfield Biorefinery in Perry Florida and accompanying techno-economic analysis in Gubicza et al. (2016). The biorefinery was designed to be highly-efficient, producing more electricity than it uses, and minimizing processing steps. Sugarcane bagasse is made available as waste from the adjacent sugar mill and refined to ethanol using what is theorized as potentially less resource consumptive process. However, an environmental analysis was not conducted to support that and it is a limited resource in the United States. The process is then extended to switchgrass as it has been subjected to substantial government funded research and might be the ideal energy crop for domestic implementation with broad growth ability, yields, and economic potential. It is theorized that the biochemical hydrolysis will be conducted in the same fashion. Both feedstocks have a slightly different lifecycle that, compared to corn ethanol, may be more or less competitive environmentally.

A life cycle analysis was conducted for sugarcane bagasse and switchgrass at different blend ratios using SimaPro v8.5 and EcoInvent v3.4. Each life cycle was defined by the product stages and foreground processes within. A system boundary created to identify the stages that solely contribute to ethanol production. Policy requires that advanced and cellulosic ethanol fulfill the quota of the RFS2. In order to meet the emissions standards set and understand the broad scale environmental impacts it is essential to conduct a life cycle analysis. A sustainable, renewable bioenergy market for cellulosic biofuels will have evaluated the life cycle of each feedstock. In the case of sugarcane bagasse, there will be minimal land requirements and agricultural hotspots. It will be more successful than corn if the biorefinery demands are less than the corn agricultural inputs. With regard to switchgrass, if minimal demands, high yields, and stand length offset biorefinery inputs then impacts will be minimized. The impact assessment
and interpretation of each feedstock will be evaluated and compared to identify, high-impact processes (hotspots), areas for feasible technological improvement, or system modifications that limit emissions trade-offs. The results of this analysis will reflect on the established EISA and RFS2 and offer suggestion to further policy development.

2. Sugarcane Bagasse

2.1 Sugarcane Bagasse Introduction

In its most simplistic design, bioenergy has the qualitative appearance of a climate neutral process; plants absorb carbon dioxide through respiration and it is re-emitted during combustion. This generalization is often made, but may be inaccurate due to limited research in land use change, soil organic carbon uptake, and life cycle analysis (Bonin and Lal, 2012; Morales et al., 2015). Sugarcane has long been one of the most common ethanol producing crops. In Brazil, 40% of the world’s sugarcane is produced, and 55% of that is used for ethanol production (Janssen and Rutz, 2011). Ethanol refining of sugarcane is considered to be highly successful because of the amount of readily fermentable sugars. However, like corn-derived ethanol, sugarcane is an intensive crop in terms of land production, fertilizer demand, and pesticides. It is a tropical, sub-tropical, grass that is adaptable to climate and altitude but susceptible to diseases (Webb, 2014). Although it is a perennial crop, sugarcane can decrease in yield over time and will be replanted in high-demand, mechanized agricultural sectors (Baucum, 2007). Harvests can occur manually after a burndown but this process has been accelerated with mechanization (Bezerra, 2016). A burndown is a common agricultural practice of killing off weeds or active-growth using a full spectrum herbicide. The sugarcane is then milled, a chopping process that releases the sugar juices from the stalks, shortly after harvesting to prevent biomass degradation.
The juices are refined to powdered, granulated, or brown sugar in a drying and crystallization process.

Numerous byproducts can be produced from sugarcane including sucrose, blackstrap molasses, and bagasse. Bagasse is the remaining plant content after the sugarcane stalks have been milled, crushed, shredded and/or ground. For every three tonnes of sugarcane produced, approximately one tonne of bagasse is produced (Huntrods et al., 2017; Thambiraj and Shankaran, 2016). Typical uses for bagasse include production of electricity, combined heat and power, and paper pulp. In 2011, U.S. Sugar Corporation produced 773,000 tons of raw sugar, 41 million gallons of molasses, and 200,000 megawatts of electricity (Salisbury, 2012). It is biomass that is high in lignocellulose, a complex polysaccharide (cellulose and hemicellulose), that must be hydrolyzed to monomeric sugars prior to fermentation. Broadly it is 50% cellulose, 25% hemicellulose, and 25% lignin (Parameswarna, 2009). As a waste residue, it can be used to produce cellulosic ethanol rather than first generation, sucrose based, sugarcane ethanol.

In the US, sugarcane is grown mostly in Florida and Louisiana with less than 10% being from Texas. Historically, Hawaii was also a successful sugarcane producer until labor problems and land prices defunct the industry in 2016. Florida has established a strong sugarcane market due to it high nitrogen soil, water resources, and year-round warm-humid climate that makes it the highest domestic producing state (Salisbury, 2012). Forty nine percent of the harvested sugarcane land is in Louisiana accounting for 222577.103 ha (USDA NSF CIPM, 2014). It set records in 2018 with approximate yields of 992.895kg/ha (Delta Farm, 2018). Still, 20% of domestic sugarcane is imported to fulfill US demand (Baucum, 2007). Although there are environmental concerns, especially about wetlands degradation in sensitive areas like the Everglades, sugarcane cultivation will continue due to the regional economic importance. Albeit
spatially limited and the current utilization of bagasse reduces feedstock availability, these areas may be able to support a cellulosic ethanol facility that contributes to ethanol feedstock diversity.

2.2 Methods

Life cycle analysis (LCA) aggregates the environmental impact categories based on the ‘cradle to grave’ premise. It is a measurement tool to assess environmental performance, or risk assessment, for industrial systems that, on an interdependent schematic, begin at raw material acquisition and ends at waste disposal (Morales et al., 2013). This attributional life cycle analysis of sugarcane ethanol is based on current potential technologies and reasonable practices. Lifecycle stages for sugarcane bagasse include feedstock acquisition, ethanol refining, and use-combustion (figure 2.1). The cultivation process for sugarcane bagasse is not necessary because it is considered a waste product from sugarcane manufacturing. All the environmental impact associated with cultivation is allocated to the refined sugarcane output, not the bagasse. Bagasse is collected at the sugarcane refinery and transported to the ethanol refinery. The ethanol is then combusted during vehicle operation as de facto waste stage rather than the bagasse’s previous onsite use for electricity or combined heat and power generation. A life cycle inventory was prepared to support the analysis using EcoInvent version 3.4, literature, and the ethanol refinery design proposed by Gubicza et al., (2016). There are no operational sugarcane bagasse ethanol facilities in the United States, but it has been explored on pilot scales such as the Stan Mayfield Biorefinery at Perry, Florida. The goal of this life cycle analysis is to demonstrate the benefits of the biorefinery proposed in Gubicza et al., (2016) are coincident with minimal environmental impacts for sugarcane bagasse feedstocks. Results will be expanded to consider processes hotspots, comparisons with other feedstocks, and policy implications.
When feedstock is considered a waste residue, establishment and maintenance can exist outside of the system boundary (Daylan and Ciliz, 2016; Daystar et al., 2015). Because the system boundary excludes cultivation as bagasse is a waste product, many of the regional implications associated with energy cropping are limited. All environmental impact of agriculture is allocated to the refined sugar. Electricity mixes, fuel efficiencies, and vehicle emissions were selected, and modified, to focus the study region in the United States. Both E15 and E85 scenarios, 15% and 85% ethanol respectively blended with fossil fuel, were designed in SimaPro version 8.5. Sugarcane bagasse product was preexisting and not modified from the EcoInvent database. The transportation, biorefinery, and use-combustion stage are designed based on literature. The product, or life cycle stages, are designed independently based on mass them aggregated as an assembly based on the functional unit.

A corn life cycle was created to compare to bagasse as it is the dominant domestic source of ethanol. Modifications were made from EcoInvent version 3.4 to ensure that the comparison
was for similar system boundaries with regional applicability. A small volume of enzymes were added to the corn biorefinery as they are used to facilitate the breakdown of starches into glucose and they were not otherwise included (Wang et al., 2012). All of the natural gas (MJ) included was converted to Midwest Regional Organization medium voltage (kWh) electricity to ensure that each biorefinery system operation was comparable and not influenced by differing energy sources. Transportation is already embedded in the corn ethanol process as multi-modal and it was not removed as it likely reflects the average of the real-world circumstances. Storage is implicitly included as it is assumed that the dry mill methodology is a faster process that requires less long-term storage of voluminous biomass such as bagasse.

The functional unit is based on 1-km driven in a passenger car as defined by 40 Code of Federal Regulations (CFR) 86.1803-01, 49 CFR 523.2. Although energy and mass are sometimes used, the purpose, or function, of the ethanol is to operate the vehicle. It is one of the most commonly used functional units in comparing transportation fuels. Quantification of all inputs and outputs through the cellulosic ethanol system depend on the context of how product is being valued. When ethanol is being compared to other cellulosic fuels, energy content may be more applicable. In comparison, when assessing within the transportation fuel market, driving distance applies. All impact scores will reflect the reference unit, accounting by mass, energy, volume, 1-km driven, MJ ethanol, or liter of ethanol. All output terms from unit processes will be quantified according to the designated functional unit (Marjorie et al., 2015). The fuel efficiency was based on domestic use.

EcoInvent version 3.4 is the primary database used in this study. Although originally developed for Switzerland and Western Europe, it has been expanded to include global average data and unit processes adapted to the United States. Rest of World (RoW) and Global (GLO)
processes are both acceptable global averages. RoW includes uncertainty data as do many of the unit processes in the EcoInvent database. The United States Life Cycle Inventory (USLCI) is included in SimaPro 8 and there is a preexisting switchgrass ethanol process based on the Hsu, *et al.* (2010) and National Renewable Energy Laboratory (NREL) that is based on assumptions for production in 2022. It is limited with respect to output parameters and functionality with more developed impact assessment methods such as ReCiPe. The analysis conducted at NREL assumes that improvements in production and processing will result in efficiencies, reduced environmental impact, and economic feasibility. During review, the USLCI design includes ‘Dummy’ inputs with limited elementary emissions that may limit the scope of an impact assessment. There is global acceptance to EcoInvent and a strong international community that supports its validity. Although USLCI is appropriate in the United States, modification of EcoInvent may produce stronger analytical results.

The impact assessment was calculated using ReCiPe 2016 Midpoint (H) method. It has three cultural perspectives: Individualist, Hierarchist, and Egalitarian. The former being the most optimistic and latter being most conservative based on the precautionary principal. Hierachist (H) was selected as the default as it is encountered most in scientific models (Pre Consultants, 2016). The midpoint method is a problem-oriented approach that covers eighteen indicators; climate change, stratospheric ozone depletion, ionizing radiation, ozone formation-human health, fine particulate matter formation, ozone formation-terrestrial ecosystems, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic ecotoxicity, human non-carcinogenic ecotoxicity, land use, mineral resource scarcity, fossil resource scarcity, and water use. Despite the higher number of impact categories in the midpoint method, there is less extrapolation than endpoint methods.
The wide range of impacts will allow for more precise analysis of the implications of bioethanol and targets science-based audience rather than policy-makers. Also, the life cycle evaluated is diverse with multiple product stages that should cover a wider range of impact categories. A sensitivity analysis is conducted by altering biorefinery electricity inputs from the regional energy mix that are technologically feasible to eliminate. Removing energy inputs will make it possible to identify impact contributions directly related to ethanol production inputs.

Normalization is the process by which complex reference units, created during characterization and used in the impact assessment, are divided in order to compare potential impacts. Often this will result in per capita impact to determine the average impact per person-year. This unit shows the extent of a problem in terms of damage as impact per daily average life years (DALY). Sometimes this can help with regionalization of a problem as the denominator is the number of person in the area. The result is that, for example, a comparison can be made between damage for global warming and eutrophication. ReCiPe 2016 does not permit normalizing data as it has not been published yet. As the study is refined, updated, and new versions of SimaPro are released with ReCiPe 2016 updates, normalization should be conducted and results reevaluated.

The Life cycle analysis conducted herein is guided by the International Standards Organization (ISO) 14040:2006, Life Cycle Assessment: Principles and Practice by the United States Environmental Protection Agency in conjunction with the National Risk Management Research Laboratory, and Life Cycle Analysis Guidance with SimaPro (Curran, 2006; Daylan and Ciliz, 2016; Goedkoop, 2016; International Standardization Organization 14040:2006). Provided these parameters are followed, it will be possible to measure potential environmental
trade-offs, identify hot-spots, and determine the environmental implications from commercial scale production of sugarcane bagasse ethanol.

2.3 Sugarcane Bagasse Data & Inputs

a. Transportation Logistics

Only a single transportation process is accounted for in the feedstock acquisition stage. All of the agricultural impact is allocated to refined sugarcane and outside the system boundary for sugarcane bagasse feedstock. Round-trip travel distance for bagasse between the sugarcane mill and biorefinery is assumed to be 50km in order to decrease transit time and cost. Distances between facilities can vary, ranging from 25km to 150km (Bai et al., 2010; Fu et al., 2003). However, the distance assumes that a biorefinery would be constructed within a reasonable proximity to available feedstocks and has therefore been minimized. Implementing further transport distances will decrease environmental performance (Bai et al., 2010; Fu et al., 2003; Obydenkova, 2017). Diesel trucks, based on EURO 3 standards, similar to USEPA Tier 2 emissions, with 16-32 tonne carrying capacities are utilized. Isolating feedstock acquisition as a single process prevents displacing any impact to the biorefinery. In the assembly stage, transportation is adjusted to kg/km of transportation. Additional storage for bagasse is not necessary. Storage needs are available, and therefore allocated, to the sugarcane. If the sugar mill is capable of production and storage between growing seasons so should the biorefinery.

b. Biorefinery

The biorefinery design is based on the advanced simultaneous saccharification and fermentation (SScF) proposed in Gubicza et al., (2016) (figure 2.2, table 2.1). SScF process integration is intended to reduce material handling and improve yields. It is broken down into two processes based on the product stages. A fermentation broth process and distillation process. Fermentation includes sugarcane bagasse chopping, dilute phosphoric acid steam explosion, and
addition of the enzyme cellulose. Tap water is used four times during fermentation and has been modeled as such, rather than a cumulative amount, in order to preserve the integrity of the mass-balance. Water is used both as vapor steam and liquid in the fermentation process. A drying agent common to ethanol refining, magnesium sulfate, is added in order to increase yeast tolerance. Sodium metabisulfite reduces the toxicity resultant from dilute acid pretreatment and supplement fermentation. The fermentation broth is distilled by two stripper columns and dehydrated by molecular sieve. Ethanol is then further treated by rectifier to increase the concentration of the ethanol to 99.8%. Of note is the dilute phosphoric acid steam pretreatment and stillage process synthesis. The dilute phosphoric acid is intended to provide a less acidic stillage and require lesser grade alloys in the biorefinery. Post-ethanol recovery, stillage is used both onsite and transported offsite.

Figure 2.2 Sugarcane Bagasse Biorefinery Process Flow

Presented in Gubicza et al., the biorefinery methodology uses a phosphoric dilute-acid steam pretreatment with a self-sustaining energy supply. This process uses lesser metals, simplifies mixing and loading, limits chemicals inputs, and increases yields. Steam and electricity is generated by burning solid stillage, biogas, sludge, and using a process steam turbine system. Remaining liquid stillage is not modeled as a waste but substituted as a nitrogen field input for increased crop yields.
<table>
<thead>
<tr>
<th>Operations</th>
<th>Unit</th>
<th>Bagasse</th>
<th>10 Year Total</th>
</tr>
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<tr>
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<td>684460</td>
</tr>
<tr>
<td>Tap Water</td>
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<tr>
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<td>kg</td>
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<tr>
<td>Tap Water</td>
<td>kg</td>
<td>47501</td>
<td>475010</td>
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<tr>
<td>Tap Water</td>
<td>kg</td>
<td>18658</td>
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<tr>
<td>Enzyme Cellulase</td>
<td>kg</td>
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<td>7700</td>
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<tr>
<td>Tap Water</td>
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<td>Ammonia</td>
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<td>Magnesium Sulfate</td>
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<td>29515</td>
</tr>
<tr>
<td>Sodium Sulfite</td>
<td>kg</td>
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<td>10300</td>
</tr>
<tr>
<td>Electricity SH, MRO</td>
<td>kWh</td>
<td>9530</td>
<td>95300</td>
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<tr>
<td>Electricity FS, MRO</td>
<td>kWh</td>
<td>3740</td>
<td>37400</td>
</tr>
</tbody>
</table>

Table 2.1: Biorefinery Inputs for Sugarcane Bagasse

Distillation stillage is separated to a liquid and solid portion. Both are considered coproducts. Solid stillage is used onsite for combined heat and power. It is assumed that the facility can produce enough electricity to sustain operation with exception to energy needed for steam generation during pretreatment. Electricity was added to account for heating water for steam generation. Any electricity is based on Midwest Reliability Organization mix, medium voltage. It is assumed that the stillage, due to the reduced acidity, can be sold as fertilizer and is outside the system boundary. Therefore, all the environmental impact is allocated to the ethanol. Stillage produced during rectification is combine with acidic flash steams and drying vapor for onsite anaerobic digestion and aerobic treatment. The generated biogas and sludge is also used
for combine heat and power. The process flow does produce water for municipal waste treatment that satisfies the mass balance.

c. Deviations from Gubicza et al. (2016)

Minor deviations have been made from the Gubicza et al. (2016) design. Under the techno-economic evaluation, the biorefinery was collocated with a sugarcane manufacturing plant. Assumptions by Gubicza et al. (2016) are often made speaking to the efficiency within the process where all wastes including lignin stillage can produce all the necessary steam and electricity (Bai et al., 2010; Daylan and Ciliz, 2016; Murphy and Kendall, 2015; Gubicza et al., 2016). Less conservative research suggests that the process will be capable of producing more energy than it requires (Bai et al., 2010; Murphy and Kendall, 2015). It was reasonable under that scenario to utilize stream from the adjacent plant and not account for any transportation of bagasse. In the interest of creating a realistic life cycle for waste residues, it is necessary to account for electricity, water, and transportation inputs. Although, sugarcane has been milled, chopped, or pressed for juice extraction an additional chopping process was included in the biorefinery to ensure proper biomass size for optimal pretreatment. Due to the interest in process integration and synthesis, unnamed gases emitted during fermentation are assumed them to be similar to carbon dioxide. This assumption avoids favoring any greenhouse gas or requiring precise knowledge of the emissions associated with the biorefinery process. Only the full mass of chemical inputs is known while magnesium sulfate and sodium metabisulfite are named.

Chemical input was divided between both compounds in order to not favor either in the analysis.

d. Functional Unit & Combustion

United States Environmental Protection Agency (USEPA) uses a fossil fuel based test fuel without ethanol or oxygenates. However, USEPA uses a standardized laboratory test
procedures to determine fuel efficiency that accounts for ethanol and ‘real-world’ conditions. When determining efficiency of USEPA test fuel, fuel economy test values are reduced by 10% to account for ethanol, hills, wind, or road conditions (USEPA Fuel 2012; USEPA Highlights, 2018). To determine fuel needs for E15 and E85, 10% was added to model year (MY) 2016 for theoretical fuel efficiency. A real-world E0 was calculated by decreasing the theoretical efficiency by 7%. As a baseline ethanol blended fuel efficiency is then reduced 3% for every 10% ethanol. Adjusted fuel economy on MY 2016 is 10.50 km/L (24.7 mi/gal). After the above adjustments and accounting for the proper amount of ethanol within the blended fuel, .01155kg and .08415kg were required for E15 and E85 respectively to move a passenger vehicle 1-km.

Creating the functional unit of 1-km driven requires both fuel and refinery efficiency. The mass-balance derived from the input-output tables (Table 2.1) in Gubicza et al., (2016) indicated a ratio of 0.120 kg ethanol/kg biomass. This differs from the 0.241 kg ethanol/kg biomass, 305 L/tonne, in the narrative of Gubicza et al., (2016) assumed to be the ethanol output capability of the facility. The discrepancy is a result of the 50% water-weight of the natural bagasse input accounted for in Table 2.1. The dry-mass input still yields a ratio of .241 kg ethanol/kg biomass. To adequately generate enough ethanol for the functional unit, the ratio of .120 kg ethanol/kg requires .0958kg and .6987kg of bagasse for respective fuel varieties. Although each process was created using mass inputs, the functional unit is applied to the product stages as they are assembled.

Within the assembly, fuel combustion is added as operation of a passenger car. This varies from a typical product life cycle waste stage or disposal scenario because it is not a traditional a disposal route. To properly create the combustion scenario, there was modification to the EcoInvent operation, passenger car process. The EcoInvent process uses a 5% ethanol
blend that is derived from low-sulfur petrol and ethanol 99.7% from biomass. The blend was modified to utilize sugarcane bagasse at distillation instead of generic, ethanol from biomass. The input amounts for petrol and ethanol within the operation process vary based on USEPA efficiencies for E15 and E85 ethanol percentages. The output is 1-km driven.

2.4 Sugarcane Bagasse Results

E15 and E85 made from sugarcane bagasse were analyzed independently as sankey diagrams (figure 2.3, 2.4). These diagrams illustrate life cycle emissions of a single impact category by using proportional arrow width as flow quantity. The scope of the sankey diagrams uses a 1.45% emissions cut-off rule. Without agricultural production, the primary contributors to global warming (kg CO2-eq) are dependent on the fuel blend. In the E15 scenario, combustion during vehicle operation over 1-km appears to be the largest contributor to climate change (figure 2.4). When compared to E85, .282kg CO2-eq more emissions are generated overall. A 96% increase occurs from E15 or 51% of the E85 scenario. This is caused by transition from a predominantly conventional fuel blend to mostly ethanol. The upstream processes of fossil fuel in E15 generate .244kg CO2-eq that is mostly associated with fossil fuel refining followed by crude oil transport. The opposite is true for E85. A more diverse set of unit processes including enzymes, sodium sulfite, and electricity used during fermentation produce .374kg CO2-eq as the dominant contributor to global warming. Global warming alone, the blend ratio determines the hotspots. In order to evaluate each fuel over different impact areas, the impact assessments of each were compared (figure 2.5, table 2.2).
Figure 3: ReCiPe Midpoint (H) V1.13 / World Recipe H Normalization, Climate change for E15 Sugarcane Bagasse Fuel
Figure 4: ReCiPe 2016 Midpoint (H) V1.01 / Characterization, Global warming (kg CO2 eq) Sugarcane Bagasse Fuel
Figure 2.5: ReCiPe 2016 Midpoint (H) V1.01 Comparing Sugarcane Bagasse E15, Sugarcane Bagasse E85
<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>Bagasse E15</th>
<th>Bagasse E85</th>
</tr>
</thead>
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<tr>
<td>Global warming</td>
<td>kg CO2 eq</td>
<td>0.295579796</td>
<td>0.578308621</td>
</tr>
<tr>
<td>Stratospheric ozone depletion</td>
<td>kg CFC11 eq</td>
<td>1.31033E-07</td>
<td>4.22152E-07</td>
</tr>
<tr>
<td>Ionizing radiation</td>
<td>kBq Co-60 eq</td>
<td>0.010062509</td>
<td>0.03624023</td>
</tr>
<tr>
<td>Ozone formation, Human health</td>
<td>kg NOx eq</td>
<td>0.000348084</td>
<td>0.000670264</td>
</tr>
<tr>
<td>Fine particulate matter formation</td>
<td>kg PM2.5 eq</td>
<td>0.00288345</td>
<td>0.001108665</td>
</tr>
<tr>
<td>Ozone formation, Terrestrial ecosystems</td>
<td>kg NOx eq</td>
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<td>0.00069575</td>
</tr>
<tr>
<td>Terrestrial acidification</td>
<td>kg SO2 eq</td>
<td>0.000703229</td>
<td>0.002112846</td>
</tr>
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<td>Freshwater eutrophication</td>
<td>kg P eq</td>
<td>3.85722E-05</td>
<td>0.000230005</td>
</tr>
<tr>
<td>Marine eutrophication</td>
<td>kg N eq</td>
<td>1.39971E-05</td>
<td>9.68821E-05</td>
</tr>
<tr>
<td>Terrestrial ecotoxicity</td>
<td>kg 1,4-DCB</td>
<td>0.361260099</td>
<td>0.971060525</td>
</tr>
<tr>
<td>Freshwater ecotoxicity</td>
<td>kg 1,4-DCB</td>
<td>0.00228313</td>
<td>0.010756617</td>
</tr>
<tr>
<td>Marine ecotoxicity</td>
<td>kg 1,4-DCB</td>
<td>0.00362151</td>
<td>0.015462814</td>
</tr>
<tr>
<td>Human carcinogenic toxicity</td>
<td>kg 1,4-DCB</td>
<td>0.003580224</td>
<td>0.017066111</td>
</tr>
<tr>
<td>Human non-carcinogenic toxicity</td>
<td>kg 1,4-DCB</td>
<td>0.08783837</td>
<td>0.390694081</td>
</tr>
<tr>
<td>Land use</td>
<td>m2a crop eq</td>
<td>0.010164718</td>
<td>0.071400722</td>
</tr>
<tr>
<td>Mineral resource scarcity</td>
<td>kg Cu eq</td>
<td>0.000211409</td>
<td>0.000667687</td>
</tr>
<tr>
<td>Fossil resource scarcity</td>
<td>kg oil eq</td>
<td>0.092139508</td>
<td>0.096571521</td>
</tr>
<tr>
<td>Water consumption</td>
<td>m3</td>
<td>0.063483871</td>
<td>0.032600123</td>
</tr>
</tbody>
</table>

Table 2.2: ReCiPe 2016 Midpoint (H) V1.01 Characterization Sugarcane Bagasse E15 compared to Sugarcane Bagasse E85

Higher concentrations of ethanol yielded unfavorable results in seventeen of eighteen impact categories including the largest differentials in land use, marine eutrophication, and freshwater eutrophication. Electricity from coal and lignite, used during fermentation product
stage, is associated with 54.3% of the freshwater eutrophication. Potato growth from enzyme production accounts for over 60% of marine eutrophication. Land use is driven by enzyme use and their upstream processes including potato growth and potato starches.

The impact assessment categories with the largest percentage difference between feedstocks are those most sensitive to increasing the quantity of required fermentation broth inputs. Only water consumption is less for E15 because 96.3% of the water is used in the background processes associated with conventional fuel. The fuels were similar in their fossil resource scarcity (kg oil-eq) with a near even transference of impact between convention fuel production and fermentation broth. Terrestrial ozone formation (kg NOx-eq) is the second closest impact category, of which, E15 is approximately 55% of E85. Each blend contributes their highest output to terrestrial ecotoxicity (kg 1,4-DCB). Enzyme production and sodium sulfite are the highest contributors to the broth in its contribution to terrestrial ecotoxicity. Upstream processes such as copper and building construction, potato starches, are also noteworthy contributors. Results of E85 and E15 bagasse ethanol fuels blends must be compared to the defender, corn ethanol.

Corn ethanol for both blend ratios produces more kg CO₂-eq during operation of the vehicle than either sugarcane bagasse fuel scenario. For example, based on the non-percentage indicators in the sankey diagrams, at combustion, bagasse E85 emits .202kg CO₂-eq. Which is .006kg CO₂-eq less than the corn E85. However, there are more kg CO₂-eq emitted during the life cycle of the higher ethanol fuel blends for both corn and bagasse feedstock (figure 2.6, table 2.3). Again, there a similar problems as noted when comparing bagasse fuel blends. Increased fermentation inputs produce greater impacts than those associated with conventional fuel production. Compared to biochemical hydrolysis of bagasse, the corn dry-mill process has
minimal inputs. Corn agriculture is a hotspot in first generation E85 life cycle, emitting .118kg CO₂-eq. of the total .157kg CO₂-eq. This is still less than 50% of CO₂-eq emitted by the ethanol fermentation product stage of E85 bagasse. Comparing all bagasse and corn blends, corn has the highest impact to stratospheric ozone, marine eutrophication, land use, and water consumption. Each impact associated with E85 is driven by various and diverse field inputs used in the preexisting corn process. Marine eutrophication and stratospheric ozone are reduced using sugarcane bagasse E15 rather than corn E15. The field inputs for corn represents 98% and 78% respectively of those impact categories. Corn has at least 55% or more of the impact that is expected from sugarcane bagasse for terrestrial ecotoxicity, mineral resource extraction, and ozone formation. Regardless of fuel blend, energy demand from MRO electricity mix contributes environmental impact to biorefinery process albeit much higher with increased ethanol demand.
Figure 2.6: ReCiPe 2016 Midpoint (H) V1.01 Comparing Sugarcane Bagasse E15, Sugarcane Bagasse E85, Corn Ethanol E85, Corn Ethanol E15
## Impact category | Unit | Corn E85 | Corn E15 | Bagasse E15 | Bagasse E85
--- | --- | --- | --- | --- | ---
Global warming | kg CO₂ eq | 0.37079546 | 0.267097598 | 0.295579796 | 0.578308621
Stratospheric ozone depletion | kg CFC11 eq | 2.1579E-06 | 3.6928E-07 | 1.31033E-07 | 4.22152E-07
Ionizing radiation | kBq Co-60 eq | 0.01772413 | 0.007521083 | 0.010062509 | 0.03624023
Human health | kg NOx eq | 0.00051224 | 0.000326394 | 0.000348084 | 0.000670264
Fine particulate matter formation | kg PM2.5 eq | 0.00040941 | 0.000192369 | 0.000288345 | 0.001108665
Terrestrial ecosystems | kg NOx eq | 0.00053516 | 0.000355737 | 0.000377779 | 0.00069575
Terrestrial acidification | kg SO₂ eq | 0.00121568 | 0.000580088 | 0.000703229 | 0.002112846
Freshwater eutrophication | kg P eq | 9.405E-05 | 1.99117E-05 | 3.85722E-05 | 0.000230005
Marine eutrophication | kg N eq | 0.00049857 | 6.91313E-05 | 1.39971E-05 | 9.68821E-05
Terrestrial ecotoxicity | kg 1,4-DCB | 0.73548908 | 0.328926764 | 0.361260099 | 0.971060525
Freshwater ecotoxicity | kg 1,4-DCB | 0.00416913 | 0.001378965 | 0.00228313 | 0.010756617
Marine ecotoxicity | kg 1,4-DCB | 0.00507291 | 0.002195446 | 0.00362151 | 0.015462814
Human carcinogenic toxicity | kg 1,4-DCB | 0.0051596 | 0.001945997 | 0.003580224 | 0.017066111
Human non-carcinogenic toxicity | kg 1,4-DCB | 0.05776551 | 0.042142291 | 0.08783837 | 0.390694081
Land use | m² a crop eq | 0.20050712 | 0.027885203 | 0.010164718 | 0.071400722
Mineral resource scarcity | kg Cu eq | 0.00059918 | 0.000202007 | 0.000214009 | 0.000667687
Fossil resource scarcity | kg oil eq | 0.05220528 | 0.086050024 | 0.092139508 | 0.096571521
Water consumption | m³ | 0.084765596 | 0.063483871 | 0.032600123

Limiting inputs to conduct sensitivity analysis would alter biorefinery ethanol production efficiency (kg ethanol/kg biomass) and is not reasonable given the reliance on the Gubicza et al., (2016) design. Changing the ethanol output would require adjustments to the chemical and enzymatic inputs. Electricity was added to account for steam generation as part of this LCA despite the assumption in Gubicza et al., (2016) that there would be spare electrical energy available to be sold to the grid. Sensitivity analysis was conducted by removing all additional energy inputs and assuming that the biorefinery was self-sustaining as suggested initially by
The assumption is based on the fact that the proposed facility was able to utilize process steams from the adjacent sugar mill, and combined heat and power, to produce excess electricity for sale to the grid. In this scenario, separated from the sugar mill, the biorefinery is assumed to be able to produce, at minimum, enough electricity to sustain itself.

The sankey diagram for E15 shows that global warming impact from fermentation is reduced from 17.4% to 12.9% (figure 2.7, table 2.4) when contribution from MRO electricity is no longer included. E85 sugarcane bagasse sourced fuel becomes more balanced (figure 2.8), 56.3% to 43.3%, between fermentation and vehicle operation as the fermentation impact is reduced to 0.263kg CO2-eq from 0.374kg CO2-eq. However, corn ethanol at equal ratio still contributes less to global warming. The difference is consistent with the fact that the fermentation broth produces greater amount of CO2-eq than the combine the agricultural and biorefinery processes of corn.

Across most impact categories there are only minor, within 10%, reductions for E15 fuel produced at a self-sustaining facility. The minimal reduction is a result of the high conventional fuel content and lack of agricultural processes. A self-sustaining E85 bagasse fuel continues to be better than corn in marine and stratospheric ozone depletion. Stratospheric ozone associated with electricity from hard coal while the smallest change yielding only an 8% reduction in kg CFC11-eq. However, it improves beyond corn in freshwater eutrophication as well due to the decrease in lignite mining. When compared directly with traditional E85 bagasse scenario the most dramatic reduction is seen as a 64.9% less freshwater eutrophication. There was 30% reduction in human non-carcinogenic toxicity. Removing electricity for sensitivity analysis exacerbates the influence of enzyme use and potato production therein the sankey diagrams. Based on the influence of the biorefinery component on the LCA results, a best case scenario
would compare corn E85 to bagasse E15 within the self-sustaining facility (figure 2.9). There would be reductions for most impact categories with exception to fossil resource scarcity and human non-carcinogenic toxicity. Fossil fuel resource scarcity is based on mineral resource extraction causing an overall decrease in global surplus ore potential after extraction. Blended fuel in that scenario is to the disadvantage of the overall life cycle emissions of fossil resource scarcity. The results of the sensitivity analysis confirm that there is a measurable, consistent, decrease in most impact categories but cellulosic fuels continue to have substantial contribution from ethanol conversion.

Figure 2.7: ReCiPe 2016 Midpoint (H) V1.01 / Characterization, Global warming (kg CO2 eq) Sugarcane Bagasse E15 Self-Sustaining Facility
Figure 2.8: ReCiPe 2016 Midpoint (H) V1.01 / Characterization, Global warming (kg CO2 eq) Sugarcane Bagasse E85 Self-Sustaining Facility
<table>
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<th>Unit</th>
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<th>Bg E85**</th>
<th>Bg E85</th>
<th>Corn E15</th>
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<tr>
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<td>Stratospheric ozone depletion</td>
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<td>kg NOx eq</td>
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<td>kg NOx eq</td>
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<td>0.0005496</td>
<td>0.000696</td>
<td>0.000356</td>
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<td>0.000378</td>
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<td>kg SO2 eq</td>
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<td>0.00178972</td>
<td>0.002113</td>
<td>0.00058</td>
<td>0.000659</td>
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<tr>
<td>Freshwater eutrophication</td>
<td>kg P eq</td>
<td>9.405E-05</td>
<td>7.8514E-05</td>
<td>0.00023</td>
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<td>Marine eutrophication</td>
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<td>8.7239E-05</td>
<td>9.69E-05</td>
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<td>1.27E-05</td>
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<td>0.91571728</td>
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<td>Freshwater ecotoxicity</td>
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<td>Marine ecotoxicity</td>
<td>kg 1,4-DCB</td>
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<td>0.00913575</td>
<td>0.015463</td>
<td>0.002195</td>
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<td>Human carcinogenic toxicity</td>
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<td>0.00880079</td>
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<td>0.001946</td>
<td>0.002446</td>
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</tr>
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<td>Human non-carcinogenic toxicity</td>
<td>kg 1,4-DCB</td>
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<td>0.27163442</td>
<td>0.390694</td>
<td>0.042142</td>
<td>0.071497</td>
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</tr>
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<td>Mineral resource scarcity</td>
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<td>Water consumption</td>
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<td>0.18765269</td>
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<td>0.0326</td>
<td>0.084766</td>
<td>0.063405</td>
<td>0.063484</td>
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</tbody>
</table>

Table 2.4: ReCiPe 2016 Midpoint (H) V1.01 Characterization Corn E85, Corn E15, Bagasse E15, Bagasse E85, Bagasse E85 Self Sustaining Facility, Bagasse E15 Self Sustaining Facility (**Self-Sustaining)
2.5 Sugarcane Bagasse Discussion & Conclusion

Despite the optimism around cellulosic fuels, its’ success remains unsettled. Numerous techno-economic analyses seek to strengthen the case for potential investment while environmentalists dissent against fossil fuels. The technology for biochemical hydrolysis is not new but it has been plagued by both economic and efficiency feasibility issues. Thus, use of waste products, such as bagasse and stover, as an ethanol feedstock is highlighted because it is inexpensive, readily available, and produced on large scales. Eliminating field production satisfies the demands for environmentalists and economists alike. The agricultural production of sugarcane in United States has diminished and any efforts to use the remaining bagasse are regionally limited. Under that limited scope, the potential still would exist for a small scale, localized facility, or expansion to regions more likely to grow expansive sugarcane. Still, this life
cycle assessment demonstrates that sugarcane bagasse derived ethanol does not achieve the reduced environmental impact it is theorized to provide.

The first product stage in the bagasse lifecycle was identified as transportation. Assumed to be 25km, this may be an underestimate. Transportation contributes to numerous processes in the network but .0379tkm of the .0633tkm are attributed to biomass transportation. Although, only operation (including upkeep and mileage) of the truck is taken into account, the contribution demonstrates the potential for dramatically larger impact should distances reach 50km or more. This could be reduced using clean diesel retrofits or newer trucks with higher emissions standards to increase feasible transportation distances. A sugarcane refinery may not sustain the facility independently. Therefore, further transportation may be required in order to locate a biorefinery in a central location to numerous feedstock sources or an established regional management regime. Other considerations may need to be made variations for in-truck storage of stillage or biomass. It may be more feasible increase the distances for one biomass, while utilizing an alternative mixed feedstock (waste residues and energy crops) refinery technologies to provide year-round quality biomass with reduced transportation distances.

Initial analysis of bagasse revealed that the ethanol concentration in the fuel has a distinct impact in the emissions over 1-km driven. Fuels with more ethanol are more intensive in their fermentation inputs. Although somewhat intuitive, in comparing bagasse blends the primary source of emissions shifts between conventional fuel and fermentation. Balancing emissions with a different blend would control field and fuel hotspots but, with regard to overall output for most impact categories, corn ethanol has less environmental impact. One of the highest touted benefits is that there might be reduced greenhouses gases or ‘carbon neutral’ potential of using bagasse, but that is not evident. The results differ from Kadam, (2002) which utilized similar product
stages of transport, ethanol production, and use of electricity generated onsite but compared the ethanol to emissions generated from open-field burning. With respect to climate change, bagasse ethanol performs worse than corn and it does not meet advanced or cellulosic criteria for biofuel generation. Assumptions may have contributed to these results such as the enzymes discussed in Gubicza et al. (2016) are a specific variety that may not be relative to those in EcoInvent. However, Peterson et al. (2014) concluded that the SScF process, although advanced, had the greatest environmental impact due to the intensive use of processing chemicals which is consistent with excessive enzyme and chemical use contributions found. Further, specific quantities of chemicals magnesium sulfite and sodium metabsulfite were not provided.

Regional evaluation is not permitted because the results are an aggregation of all processes. However, there may be a larger footprint attributed to land use and water resource consumption at the regional level. To consider is that corn growth requires irrigation and productive land that is not required by bagasse. Although, sugarcane itself is a high demand crop, it does not preclude the implementation of smaller scale biorefinery designs should it be economical and environmentally equitable. Impact is not finite, but in areas producing corn for fuel terrestrial ecotoxicity and water consumption can be evaluated. Expansion and intensification of corn ethanol may exacerbate input demands to facilitate the competitiveness of other feedstocks including bagasse. In a hypothetical scenario, corn stover used for ethanol production would allocate agricultural impacts to the corn for use as food. Although the agricultural impact would be reduced, the result would be only a trade-off because the biorefinery would need to be adjusted for biochemical hydrolysis which may be equally as disadvantageous as the SScF method proposed. The design, while advanced, still suffers from technological limitations.
The amount of stillage produced varies based on feedstock-specific pretreatment, hydrolysis, fermentation, and distillation. As the efficiency of ethanol conversion improves, the overall amount of stillage available for power generation and fertilization will decrease. This analysis does not evaluate energy balance or environmental impact of stillage but environmental performance across multiple impact categories was improved when removing electricity. It should be investigated to confirm that sufficient energy is produced for a self-sustaining biorefinery if solely relying on stillage as an energy source. Proper characterization of the stillage is necessary to evaluate environmental impact associated with land application and disposal. Assuming the fertilizer has economic value, it could remain outside the system boundary when sold or, if properly characterized, be accounted for when disposed of.

Ethanol from sugarcane bagasse is not an ideal ethanol feedstock when considering the environmental impact associated with fermentation. Future research should prioritize reduced inputs in hydrolysis. Removing electricity, reducing enzyme, and chemical loading are all hotspots that can be reduced at fermentation. Cellulosic ethanol is promising for fuel production due to the availability of feedstocks, ease of refining, and untapped economic potential but without demonstrating environmental benefits compared to the defender (corn), it will not fulfill the criteria established by the renewable fuel standard. Continued evaluation across regional scales may improve efficiency but there should be continued investment in innovative refinery technologies.

Domestic policy has prioritized the categories ethanol (first generation, advanced, cellulosic) and the amount that should be produced but not the feedstock. Sugarcane bagasse is available on a highly limited, regional basis in the United States and the industrial process likely already seeks to utilize the bagasse for electricity generation. That is not to say it cannot be
explored. There are several policy and economic pathways to expand ethanol from bagasse. An increase in exports could drive domestic production of sugarcane which, in turn, would increase the feedstock availability. Policy incentives or subsidies could be made available to sugarcane producers in order to diversity the ethanol fuel market protecting against climate change or poor biomass availabilities. Also, should the regional energy mix come to include renewable electricity that becomes cheaper than the cost to refine ethanol, it would be more lucrative to produce ethanol than use bagasse for onsite combine heat and power.

3 Switchgrass
3.1 Switchgrass Introduction

Switchgrass (*panicum virgatum*) is a native North American herbaceous bunchgrass that grows across a significant portion of the United States and Canada. California is the only non-native state for switchgrass growth in the continental United States (USDA Release, 2012). Anthropocentric uses of switchgrass include high quality livestock feed (hay), erosion control, phytoremediation, and biofuel. Growth occurs rapidly during the summer where the stem can reach five to twelve feet depending on cultivar, soil properties, and climatic conditions (OSU, 2016; USDA Release, 2012). Switchgrass cultivars vary across the United States but are typically generalized between lowland and upland ecotypes; the former being smaller, with lower water and nitrogen demands (Wright Historical, 2007). Shallow, deep, dry, wet, and poorly drained soils are all capable of sustaining the crop (Douglas, et al., 2009; USDA Planting, 2012). Growth is not exclusive to prime agricultural soil; areas including shores, riverbanks, marshes, woodlands, and prairies with soil pH between 5.0 – 8.0 are all suitable (OSU, 2016; USDA Planting, 2012; Wolf and Fiske, 2009). Stands typically survive ten to fifteen years after securing establishment between year one and three (Douglas, et al., 2009; Wright Promising.
Some environmental concerns associated with first generation bioethanol can be mitigated or eliminated when using second generation feedstock like switchgrass.

Ecologically, switchgrass fields can serve as habitats and protection for multiple grassland fauna including birds and rabbits (USDA Release, 2012; Wolf and Fiske, 2009). Seeds provide food for pheasants, quail, turkeys, doves, and songbirds while post-harvest stalks provide winter cover (Hartman, et al., 2011; USDA Release, 2012; Wolf and Fiske, 2009). Roots often extend greater than 9 feet in depth aiding in drought resilience, increase carbon sequestration capability, and minimize soil erosion (Liebig et al., 2005; Wright Historical, 2007). Water resource consumption is reduced by backwater hedge flow and rain fed switchgrass management schemes (Monti, 2012). Land use change from vulnerable, degraded, overused fallow land can increase regional biodiversity and restore soil properties (Hunt and Forster, 2006). Any nutrient runoff from minor manure or fertilizer application is shown to be reduced because of increased infiltration of switchgrass soils (Monti, 2012). Site specific management tools are potentially capable of handling biodiversity issues (Blottnitz and Curran, 2007). Maximizing benefits hinges on maintaining informed regional practices that were built on life cycle impacts and long-term design.

At the cost of billions of dollars, significant government sponsored research has been conducted over decades to isolate switchgrass as a ‘model’ species for cellulosic ethanol (McLaughlin and Kszos, 2005; Wright Historical, 2007). Despite extensive research, there is substantial variation amongst potential yields, processes, and input requirements. This study used peer-reviewed literature in creating a base case scenario that reflects a reasonable proposal for field implementation in the United States. Assuming ethanol is a passive product, excluding combustion, improvement should be made by examining materials used, minimizing inputs, and
utilizing co-products. A complete LCA of switchgrass ethanol is necessary to comprehensively assess environmental impacts under improving technological refining processes and management decisions.

3.2 Switchgrass Methods

Switchgrass bioethanol remains predominantly under research and pilot design phases with only three, small, mixed use, facilities of minor commercial-scale (Brown and Brown, 2013; Hoekman, 2009; Lu et. al., 2015; Schnoor, 2011; Turhollow, 2010; UK, 2013; U.S. Ethanol, 2016). To conduct an environmental analysis, life-cycle stages must first be determined and aggregated as contiguous schematic from cultivation through waste stage combustion (figure 3.1). These stages are to be represented in a realistic manner; operating under potential, best-practice field management, refining technology with research supported background processes, and infrastructure logistics. A life cycle inventory will support the analysis using primary data of foreground processes based on literature and the ethanol refinery design from Florida State University and Gubicza et al., (2016). Based on results from the impact assessment, data will need to be interpreted to identify hotspots and potential best management practices compared to current conventional bioenergy practices. To stimulate societal and economic drivers to diversify the transportation fuel market, stabilize prices, mitigate the skepticism hindering its expansion, and provide long term energy security, environmental analysis of switchgrass ethanol is necessary.
Switchgrass has three lifecycle stages: agriculture production, ethanol production, and use-combustion. Agriculture production is the first stage that includes soil/land preparation, crop planation, chemical application, harvest, and onsite storage that are combined under three-unit processes. To account for year-to-year differences during establishment and the typical ten-year stand term, the production stage has three variations; year zero/year 1, year 2, and years three to ten. Each year is assembled with 50km transportation by truck, modified to domestic terms from 16 tonne lorry which is similar to USEPA Tier 2 emissions. This distance assumes 25km to the biorefinery with switchgrass and a return trip with liquid stillage. The biorefinery includes only two unit processes because there are only two unique intermediary flows. However, the
simultaneous saccharification and cofermentation (SScF) process includes pretreatment, seed culturing, liquefaction, and fermentation, included in the study LCA. The broth is then distilled to yield ethanol and stillage coproducts. It is assumed that switchgrass and ethanol yields are static for all scenarios with only methodological or inputs changes.

Similar to the bagasse scenario, the functional unit is for 1-km driven as defined by 40 CFR 86.1803-01, 49 CFR 523.2. The fuel efficiency was based on domestic use USEPA MY 2016. US processes in EcoInvent version 3.4 are used where available or modified from RoW and GLO datasets that represent global averages when regional applicability is unavailable. Impact assessment was conducted using ReCiPe (H) 2016.

3.3 Data & Inputs
a. Land Selection and Occupation

The management practices of switchgrass are designed to reduce the energy, cost, and agrochemical use. Land selection is modeled as half a hectare each of non-use grasslands and fallow cropland. This is intended to mimic utilizing a mix fallow/marginal grasslands and land potentially available in the Conservation Reserve Program (CRP) if annual harvesting of perennial grasses were approved. Such a program was intended to reduce the amount of in-production agricultural land. However, it is assumed that switchgrass offers similar soil property benefits to that of native grasses. Also, it may be advantageous to use fallow, marginally-productive, or grasslands to minimize the effect of indirect land use change and intensity of modification (Schmer et al., 2014). Land use transformation will be for a total of one-hectare permanent, non-irrigated crop. A non-irrigated crop would be a conservative emissions estimate for land-use change that has been largely underestimated or unaccounted for. Land is occupied over ten years and errors in utilizing fallow, unimproved land into agricultural production rather
than utilizing operational farmland. Marginal soils are not suitable for corn without extensive soil inputs. Processes and inputs are unique to varying productivity over ten growth years. All agricultural product stages have an output of switchgrass, chopped, at farm.

The carbon dioxide from air and then the relative available energy in the biomass is proportional to values based on USLCI NREL 2022. Feedstock yields are much higher than yields in the NREL study database, but it is assumed that the carbon intake of the biomass would not be highly variable given the same feedstock. Carbon dioxide from air will account for sequestration of carbon in soil and biomass. Reflected in the LCA, *biomass from air* will account for some reduction of global warming potential in the impact assessment. The biomass from air is not necessarily result in an emission such as other inputs. It is categorically defined as an ‘Input from Nature’ in SimaPro. This input reflects that an object is extracted from a natural resource without inclusion of anthropocentric demands like energy, fuel, or infrastructure. Energy available in biomass would be used for energy balancing or a functional unit based on energy. However, it is assumed that there is enough energy being provided in the life cycle (i.e., production stage) and any excess energy would be emitted as heat or available to sell back to the grid.

b. Year Zero and One Agricultural Production Stage

Year zero and one were aggregated for the LCA. Different inputs are required but there is no biomass output during year zero to represent a product stage. Land preparation impact can be minimized by using no-till options, but disking or tillage could be considered depending on soil types (Douglas *et. al.*, 2009). To prepare the land, the cover crop is mowed by a rotary mower. Mowing will reduce overgrown plots to facilitate a glyphosate burndown and tillage. Chemical burndown uses 2.24 kg glyphosate applied by boom sprayer (Jacobson, 2014; Monsanto, 2011).
Seed plantation is facilitated by rolling and a drill-press sowing method (Christensen and Koppenjan, 2010; Douglas et. al., 2009; Monono et al., 2013; USDA Planting, 2012). Full yields and establishment may take up to three years (Monono et al., 2013). Productively steadily increases annually over the first three years after only attaining 30% and 70% of the optimal during the first two.

c. Years Subsequent to Agricultural Establishment

Year three to ten are all assumed to reach 9571.43kg (Mitchell and Schmer, 2012; Thakrar, 2017; USDOE Quarterly, 2017). It is projected that yields will improve over time (Daystar et al., 2015). In the current state of switchgrass agriculture and limited long-term, field scale studies a more conservative estimate of current or near-state feasibility is appropriate. Year two, and three through ten include slight differences in field practice. Each has increases in carbon dioxide intake from air and energy in biomass due to increasing yields. Ammonium nitrate is applied in each year after establishment. Between year two and three, low levels of fertilization, potentially as granular urea or ammonium nitrate, can be used for establishment but this may increase weed competition (Ashworth et al., 2015; Sadeghpour et al., 2014). Maintained biomass yields typically use between 0-100kg/ha of nitrogen per year, but to minimize impacts 50-67kg/ha has been shown to be effective (Ashworth et al., 2015; Bai et al., 2010; Guretzky et al., 2011; Pedrosa et al., 2014; Sykes et al., 2016; Wang, 2015). Nitrogen can be applied at higher rates up to 150kg but overall value in yields may diminish (Duffy, 2008). It is assumed 67kg is ammonium nitrate (35-0-0) in applied by broadcast spreader. The mow-windrow-bale-load design, onsite storage, chopping, and transportation are the same in every year.
d. Feedstock Logistics

Feedstock logistics define the harvesting practice and efforts necessary to transport the aggregated feedstock. In one-cut systems, harvests occur after the first killing frost due to 27% to 60% greater biomass yields (Garland, 2008; Schmer et al., 2014). Multi-cut systems are disadvantageous due to higher harvest emissions and cost (Hsu et al., 2010; Martelli and Bentini, 2015). Harvests are conducted in a mow-windrow-bale-load design. The agricultural infrastructure in place only requires modification to practice rather than capital cost of new equipment (McLaughlin and Kszos, 2005; Mitchell and Schmer, 2012). Switchgrass is mowed by rotary cutter but it is assumed to be a combine mower-conditioner for field drying using a crimp-crush method. After drying, the crop is then windrowed to facilitate baling. The baling process occurs in-field as round bales that are then collected in a bale loading process. Harvesting in round bales aligns with typical cropping methods and equipment but square baling increases field, storage capacity, and transportation efficiency (Martelli and Bentini, 2015; Ownley et al., 2013). Bales are 500kg with dimensions of 0.9144m x 1.2192m x 2.4394m and stored onsite in a shed design with timber construction, closed on three sides (Duffy, 2008). The shed was based on full yield over a hectare, approximately 20 bales, divided over the ten year stand. Screening determined the shed applied to year zero and one caused it to become a major contributor to multiple impact categories. Therefore, it was distributed across the length of the stand. Preservation of feedstock quality is vital to maintain year-round supplies with storage terms approaching six months (Martelli and Bentini, 2015). Prior to transportation to the biorefinery the switchgrass is chopped for pretreatment in an industrial chopper to improve transportation efficiency.
Only a single transportation process is accounted for in this life cycle. Depending on the regional management plan, which has yet to be established, there can be more or less transportation stops or modes including preprocessing, regional storage, fossil fueling refinery or mixture location, and bulk distribution center. Hsu et al., (2010) relies on a separate feedstock preprocessing facility unrelated to the farm or refinery. As many as seven transportation stops have been assumed to occur in the process (Daylan and Ciliz, 2016). Over compensating for transport, such as 150km, creates impact assessment results bias toward transport as conducted in (Fu, 2003). Auxiliary transportation considerations such as ethanol to regional storage or blending facility are inconsistent and would be offsetting in comparing blendstock fuels. Single stage transportation is included to preserve the linear nature of biomass feedstock acquisition and biorefinery product stages that may vary compared to conventional gasoline. In effect, this would skew the impact analysis low if any future cellulosic feedstocks comparisons were not based on the same design. Transportation for switchgrass is consistent with the bagasse logistics. Round-trip travel distance between the farm and biorefinery for switchgrass is assumed to be 50km using a 16-32 tonne truck.

e. Biorefinery

Construction of the cellulosic fermentation plant (biorefinery) is proportional to the 1kg input from grasses at fermentation plant process in EcoInvent version 3.4. It includes all capital requirements and infrastructure, including processing equipment, required. Switchgrass will be refined in the enzymatic hydrolysis methodology based on Gubicza et al., (2016) similar to the sugarcane bagasse scenario. The process does vary based on the mass-balance for the scenario due to the temporal variation in yields (table 3.1). The switchgrass input for each year is proportional to the sugarcane bagasse inputs required to produce the amount of fuel to travel 1-
km. The design is consistent with the bagasse scenario with exception to the use of stillage. Solid stillage, sludge, and biogas continue to be used for combine heat and power generation while liquid stillage is not sold but utilized for fertilization of switchgrass. The combine heat and power is assumed to be sufficient for auxiliary operations at the facility with exception to MRO grid electricity for steam generation during fermentation. Stillage coproducts offer the capacity for field fertilization via liquid stillage without synthetics and avoid energy costs with onsite production via combine heat and power utilizing solid stillage. Liquid stillage is highly variable by feedstock and process chemical used in hydrolysis (Baral et al., 2017). Although, there can be concerns regarding heavy metal leaching and potential toxicity in untested feedstocks (Wilkie, 2000). ‘Fertiigation’, termed for stillage use in the field, has increased yields with chemical, biological, and physical soil benefits due to its nitrogen, phosphorus, potassium, and other nutrients (Mutton et al., 2001).
Table 3.1: Switchgrass Biorefinery Inputs

Gubicza et al., (2016) describes efforts to use limited chemicals and dilute, less caustic acids, partially in consideration of preserving the stillage nutrient value for refinery to farm use. The liquid stillage is considered to be “high nitrogen” and as such has been assumed to be stillage in concentrate. Liquid stillage concentrate can reach 5.83kg/m³ (Mutton et al., 2001).

The intent of this unique fermentation process may be to create higher nitrogen liquid stillage but the information is not provided. The stillage nitrogen content was determined for each production year and modeled as an avoided product for ammonium nitrate. An avoided product subtracts from the life cycle environmental impact of the designated product. Each year in which fertilization occurs, the environmental impact of synthetic ammonium nitrate will be slightly reduced by the amount of nitrogen in the stillage. A liquid vacuum tanker typically used for manure spreading is used for distribution.
f. Functional Unit

The switchgrass ethanol life cycle assessment uses the same functional unit of 1-km designed in the bagasse scenario. Assemblies were created in order apply the functional unit and combine agricultural production, transportation, fermentation, distillation, and operation of passenger vehicle for E15 and E85. Because of the yearly variation in agricultural production, yield, and inputs switchgrass ethanol are evaluated on a full ten year stand. A single year of equal ratio fuel could be compared to annual corn or bagasse ethanol, but it will not reflect reduced agricultural inputs over time that act as potential benefits. Whereas corn and bagasse duplicates the same process, switchgrass uses more agriculture inputs in some years than others. Corn, bagasse, and switchgrass at E85 in year three would not include any impact of chemical burn down or land use changes for switchgrass. An assembly was created for a ten-year stand of switchgrass E15 and E85 fuels to compare to corn and bagasse over similar timeframes.

3.4 Switchgrass Results

Sankey diagrams reveal similar results for global warming (kg CO$_2$-Eq) for each individual E15/E85 year with minor tradeoffs between year one, two, and subsequent years because of changing agricultural processes (figure 3.2, 3.3). Although the agricultural inputs decrease in year two, they are increased in the biorefinery, evidenced by each year producing approximately 0.32kg CO$_2$-Eq. Majority of the emissions from each year are attributed to petroleum in the fuel blend producing 0.244kg CO$_2$-Eq. For higher blend fuels in year three, there is shift in global warming potential away from petroleum to field and fermentation. This is consistent as described in the sugarcane bagasse scenario. That shift comes with an increase of 0.439kg CO$_2$-Eq. Over a ten year stand, E15 fuel combustion accounts for 50% or more of the impact in six impact categories and 96.2% of water consumption due to upstream background processes. Conversely, fermentation broth contributes 72.58% and 87.86% to marine and
freshwater eutrophication respectively. Fermentation broth for E85 and fuel combustion for E15 have the highest influence across all impact categories except for land use which is largely associated with year zero and one product stage (figure 3.4, 3.5). Hotspots within E15 are amplified in the E85 scenario with exception to transference of impact away from petroleum.

Figure 3.2: ReCiPe 2016 Midpoint (H) V1.01 / Characterization, Global warming (kg CO2 eq) Switchgrass Year 3 E15

Figure 3.3: ReCiPe 2016 Midpoint (H) V1.01 / Characterization, Global warming (kg CO2 eq) Switchgrass Year 3 E85
Both ten-year switchgrass fuel blend life cycles contribute the highest output to terrestrial ecotoxicity, global warming, and human non-carcinogenic toxicity. However, overall quantitative output does not equal damage and cannot be compared across impact across categories without normalization. The largest change appears to be between E15 and E85 was for land use and marine eutrophication. Land use change increases for E85 more than seven times because of the amount of switchgrass required in the blend ratio. It is associated with the agricultural productivity and land occupation needed to produce the proper amount of switchgrass. The ethanol increase does not linearly affect impact categories unilaterally but human non-carcinogenic/carcinogenic toxicity, mineral resource scarcity, marine ecotoxicity, and freshwater/eutrophication do show aspects of such a relationship. Potato production for enzyme development drives marine and freshwater eutrophication to more than seven times in E15. E85 has higher outputs for every category except water consumption (table 3.2). Using a 1% cut-off comparing water consumption process contribution, the decrease was primarily linked to hydropower in the electricity mix used during petroleum fuel manufacturing. Fossil resource scarcity for E15 is still 72.5% of E85 despite the decrease in petroleum use. Coal and lignite used in electricity generation during fermentation of E85, make the impact higher for fossil fuel scarcity. Overall lowest quantitative outputs were for stratospheric ozone depletion (kg CFC11 eq). The low ozone emissions are attributed to the ‘negative impact’ generated by the avoided product ammonium nitrate from the stillage.
In order to compare available feedstocks with switchgrass, sugarcane bagasse and corn were evaluated on ten-year scales and equal fuel ratios (figure 3.6-3.7, table 3.3-3.4). Common in both scenarios is corn has the highest impact for stratospheric ozone (corn, nitric acid, seed), marine eutrophication (corn, seed), and water consumption (hydropower in fuel manufacturing). Switchgrass has a higher impact in the other fifteen impact categories. Bagasse is second highest emitter compared to corn and switchgrass for all impact categories except stratospheric ozone as there is no synthetic fertilizer allocated to it. Switchgrass E15 produces 1.37kg 1,4-DCB (terrestrial ecotoxicity), or 29.4%, more than corn and 1.04kg 1,4-DCB more than bagasse. Terrestrial ecotoxicity quadruples for switchgrass when increased to E85. Operation of the vehicle, nitric acid for fertilizer, copper, heavy fuel oil, and potato production have the highest switchgrass emissions contributing to terrestrial ecotoxicity. These upstream processes are linked to onsite structures, construction of the fermentation plant, fuel oil used for energy production.
during fossil fuel manufacturing, and enzyme use. Terrestrial acidification increase with ethanol content resulting from sulfur dioxide in sodium sulfite production. Switchgrass uses .21m³ less water than corn but slightly more, .0006m³, then bagasse. Corn feedstock water use is associated with the electricity mix, pesticides, and irrigation. More kg CO₂-Eq is emitted by switchgrass than bagasse and corn as a result combustion and fermentation broth. Bagasse performs best in impact categories most influenced by agricultural processes such as ozone, eutrophication, and land use.

Figure 3.6: ReCiPe 2016 Midpoint (H) V1.01 Comparing Corn 10 Year E15, Sugarcane Bagasse 10 Year E15, and Switchgrass E15
<table>
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<th>Impact category</th>
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<th>Corn E15</th>
<th>Bagasse E15</th>
<th>Switchgrass 10 Year E15</th>
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<tr>
<td>Global warming</td>
<td>kg CO2 eq</td>
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<td>2.955797964</td>
<td>3.209184597</td>
</tr>
<tr>
<td>Stratospheric ozone depletion</td>
<td>kg CFC11 eq</td>
<td>3.69E-06</td>
<td>1.31033E-06</td>
<td>2.42768E-06</td>
</tr>
<tr>
<td>Ionizing radiation</td>
<td>kBq Co-60 eq</td>
<td>0.075211</td>
<td>0.100625091</td>
<td>0.116707446</td>
</tr>
<tr>
<td>Ozone formation, Human health</td>
<td>kg NOx eq</td>
<td>0.003264</td>
<td>0.003480837</td>
<td>0.00398514</td>
</tr>
<tr>
<td>Fine particulate matter formation</td>
<td>kg PM2.5 eq</td>
<td>0.001924</td>
<td>0.002883449</td>
<td>0.003372261</td>
</tr>
<tr>
<td>Ozone formation, Terrestrial ecosystems</td>
<td>kg NOx eq</td>
<td>0.003557</td>
<td>0.003777791</td>
<td>0.004290413</td>
</tr>
<tr>
<td>Terrestrial acidification</td>
<td>kg SO2 eq</td>
<td>0.005801</td>
<td>0.007032287</td>
<td>0.008325388</td>
</tr>
<tr>
<td>Freshwater eutrophication</td>
<td>kg P eq</td>
<td>0.000199</td>
<td>0.000385722</td>
<td>0.000470487</td>
</tr>
<tr>
<td>Marine eutrophication</td>
<td>kg N eq</td>
<td>0.000691</td>
<td>0.000139971</td>
<td>0.000168893</td>
</tr>
<tr>
<td>Terrestrial ecotoxicity</td>
<td>kg 1,4-DCB</td>
<td>3.289268</td>
<td>3.612600992</td>
<td>4.659277378</td>
</tr>
<tr>
<td>Freshwater ecotoxicity</td>
<td>kg 1,4-DCB</td>
<td>0.01379</td>
<td>0.022831295</td>
<td>0.031021373</td>
</tr>
<tr>
<td>Marine ecotoxicity</td>
<td>kg 1,4-DCB</td>
<td>0.021954</td>
<td>0.036215102</td>
<td>0.048204249</td>
</tr>
<tr>
<td>Human carcinogenic toxicity</td>
<td>kg 1,4-DCB</td>
<td>0.01946</td>
<td>0.035802243</td>
<td>0.047605677</td>
</tr>
<tr>
<td>Human non-carcinogenic toxicity</td>
<td>kg 1,4-DCB</td>
<td>0.421423</td>
<td>0.878383696</td>
<td>1.185135837</td>
</tr>
<tr>
<td>Land use</td>
<td>m2a crop eq</td>
<td>0.278852</td>
<td>0.101647175</td>
<td>0.803502963</td>
</tr>
<tr>
<td>Mineral resource scarcity</td>
<td>kg Cu eq</td>
<td>0.00202</td>
<td>0.002114093</td>
<td>0.003275874</td>
</tr>
<tr>
<td>Fossil resource scarcity</td>
<td>kg oil eq</td>
<td>0.8605</td>
<td>0.92139508</td>
<td>0.973128062</td>
</tr>
<tr>
<td>Water consumption</td>
<td>m3</td>
<td>0.847656</td>
<td>0.634838709</td>
<td>0.635450014</td>
</tr>
</tbody>
</table>

Table 3.3: Table 7: ReCiPe 2016 Midpoint (H) V1.01 Comparing Corn 10 Year E15, Sugarcane Bagasse 10 Year E15, and Switchgrass 10 Year E15
Figure 3.7: ReCiPe 2016 Midpoint (H) V1.01 Comparing Corn E85, Sugarcane Bagasse E85, and Switchgrass E85
<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>Corn E85</th>
<th>Sugarcane E85</th>
<th>Switchgrass 10 Year E85</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming</td>
<td>kg CO2 eq</td>
<td>3.7079546</td>
<td>5.783086207</td>
<td>7.629186532</td>
</tr>
<tr>
<td>Stratospheric ozone depletion</td>
<td>kg CFC11 eq</td>
<td>2.158E-05</td>
<td>4.22152E-06</td>
<td>1.23622E-05</td>
</tr>
<tr>
<td>Ionizing radiation</td>
<td>kBq Co-60 eq</td>
<td>0.1772413</td>
<td>0.362402297</td>
<td>0.479573536</td>
</tr>
<tr>
<td>Ozone formation, Human health</td>
<td>kg NOx eq</td>
<td>0.0051224</td>
<td>0.006702639</td>
<td>0.010376844</td>
</tr>
<tr>
<td>Fine particulate matter formation</td>
<td>kg PM2.5 eq</td>
<td>0.0040941</td>
<td>0.011086654</td>
<td>0.014647995</td>
</tr>
<tr>
<td>Ozone formation, Terrestrial ecosystems</td>
<td>kg NOx eq</td>
<td>0.0053516</td>
<td>0.006957504</td>
<td>0.010692323</td>
</tr>
<tr>
<td>Terrestrial acidification</td>
<td>kg SO2 eq</td>
<td>0.0121568</td>
<td>0.021128457</td>
<td>0.030549607</td>
</tr>
<tr>
<td>Freshwater eutrophication</td>
<td>kg P eq</td>
<td>0.0009405</td>
<td>0.002300051</td>
<td>0.002917623</td>
</tr>
<tr>
<td>Marine eutrophication</td>
<td>kg N eq</td>
<td>0.0049857</td>
<td>0.000968821</td>
<td>0.001179534</td>
</tr>
<tr>
<td>Terrestrial ecotoxicity</td>
<td>kg 1,4-DCB</td>
<td>7.3548908</td>
<td>9.710605254</td>
<td>17.33638469</td>
</tr>
<tr>
<td>Freshwater ecotoxicity</td>
<td>kg 1,4-DCB</td>
<td>0.0416913</td>
<td>0.107566168</td>
<td>0.167236672</td>
</tr>
<tr>
<td>Marine ecotoxicity</td>
<td>kg 1,4-DCB</td>
<td>0.0507291</td>
<td>0.154628137</td>
<td>0.241977546</td>
</tr>
<tr>
<td>Human carcinogenic toxicity</td>
<td>kg 1,4-DCB</td>
<td>0.051596</td>
<td>0.170661108</td>
<td>0.256657455</td>
</tr>
<tr>
<td>Human non-carcinogenic toxicity</td>
<td>kg 1,4-DCB</td>
<td>0.5776551</td>
<td>3.906940814</td>
<td>6.141846978</td>
</tr>
<tr>
<td>Land use</td>
<td>m2a crop eq</td>
<td>2.0050712</td>
<td>0.714007222</td>
<td>5.827527501</td>
</tr>
<tr>
<td>Mineral resource scarcity</td>
<td>kg Cu eq</td>
<td>0.0059918</td>
<td>0.006676869</td>
<td>0.015141267</td>
</tr>
<tr>
<td>Fossil resource scarcity</td>
<td>kg oil eq</td>
<td>0.5220528</td>
<td>0.965715206</td>
<td>1.34262644</td>
</tr>
<tr>
<td>Water consumption</td>
<td>m3</td>
<td>1.8765269</td>
<td>0.326001235</td>
<td>0.330454925</td>
</tr>
</tbody>
</table>

Table 3.4: ReCiPe 2016 Midpoint (H) V1.01 Comparing Corn 10 Year E85, Sugarcane Bagasse 10 Year E85, and Switchgrass 10 Year E85

Sensitivity analysis was conducted by removing electricity for steam generation as detailed in the sugarcane bagasse scenario. All impact categories for switchgrass decrease when the facility is assumed to be self-sustaining (figure 3.8, table 3.5). Freshwater eutrophication is reduced more than any other category for both cases because of coal in the MRO energy mix. Stratospheric ozone, terrestrial ecotoxicity, land use, and water consumption all receive less than a 3% reduction for E85. The effect of self-sustaining facility is more dramatic in E85 because more energy inputs are required to produce more fuel. Compared to E15, the self-sustaining reduction is apparent, the high percentage of fossil fuel drives the impact assessment. When compared to other fuels, ionizing radiation, fine particulate matter, freshwater eutrophication, and human carcinogenic toxicity are reduced by 30% for E85 self-sustaining. Results for E85 from switchgrass are still not favored compared to corn E85. There is a reduction associated with
categories influenced by electricity generation but it does not alleviate the biorefinery enzyme
demand. This was mimicked by E15 corn to E15 switchgrass. The self-sustaining facility for E85
has less impact ionizing radiation, fine particulate matter formation, and freshwater
eutrophication than a bagasse facility that would require electricity.

Figure 3.8: ReCiPe 2016 Midpoint (H) V1.01 Sensitivity Analysis: All
Switchgrass Scenarios
### Impact category

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>Switchgrass 10 Year E15</th>
<th>Switchgrass 10 Year E15**</th>
<th>Switchgrass 10 Year E85</th>
<th>Switchgrass 10 Year E85**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming</td>
<td>kg CO2 eq</td>
<td>3.209184597</td>
<td>3.066760462</td>
<td>7.629186532</td>
<td>6.591525441</td>
</tr>
<tr>
<td>Stratospheric ozone depletion</td>
<td>kg CFC11 eq</td>
<td>2.42768E-06</td>
<td>2.38031E-06</td>
<td>1.23622E-05</td>
<td>1.20171E-05</td>
</tr>
<tr>
<td>Ionizing radiation</td>
<td>kBq Co-60 eq</td>
<td>0.116707446</td>
<td>0.097206941</td>
<td>0.479573536</td>
<td>0.33748501</td>
</tr>
<tr>
<td>Ozone formation, Human health</td>
<td>kg NOx eq</td>
<td>0.00398514</td>
<td>0.003799222</td>
<td>0.010376844</td>
<td>0.009022302</td>
</tr>
<tr>
<td>Fine particulate matter formation</td>
<td>kg PM2.5 eq</td>
<td>0.003372261</td>
<td>0.002764384</td>
<td>0.014647995</td>
<td>0.010219181</td>
</tr>
<tr>
<td>Ozone formation, Terrestrial ecosystems</td>
<td>kg NOx eq</td>
<td>0.004290413</td>
<td>0.004103196</td>
<td>0.010692323</td>
<td>0.009328314</td>
</tr>
<tr>
<td>Terrestrial acidification</td>
<td>kg SO2 eq</td>
<td>0.008325388</td>
<td>0.007911471</td>
<td>0.030549607</td>
<td>0.027533931</td>
</tr>
<tr>
<td>Freshwater eutrophication</td>
<td>kg P eq</td>
<td>0.000470487</td>
<td>0.000276431</td>
<td>0.002917623</td>
<td>0.001503782</td>
</tr>
<tr>
<td>Marine eutrophication</td>
<td>kg N eq</td>
<td>0.000168893</td>
<td>0.00015654</td>
<td>0.001179534</td>
<td>0.001089533</td>
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<tr>
<td>Terrestrial ecotoxicity</td>
<td>kg 1,4-DCB</td>
<td>4.659277378</td>
<td>4.5838381</td>
<td>17.33638469</td>
<td>16.81987462</td>
</tr>
<tr>
<td>Freshwater ecotoxicity</td>
<td>kg 1,4-DCB</td>
<td>0.031021373</td>
<td>0.025059727</td>
<td>0.167236672</td>
<td>0.123801842</td>
</tr>
<tr>
<td>Marine ecotoxicity</td>
<td>kg 1,4-DCB</td>
<td>0.048204249</td>
<td>0.040099411</td>
<td>0.241977546</td>
<td>0.18292804</td>
</tr>
<tr>
<td>Human carcinogenic toxicity</td>
<td>kg 1,4-DCB</td>
<td>0.047605677</td>
<td>0.037017968</td>
<td>0.256657455</td>
<td>0.179518471</td>
</tr>
<tr>
<td>Human non-carcinogenic toxicity</td>
<td>kg 1,4-DCB</td>
<td>1.185135837</td>
<td>1.032622831</td>
<td>6.141846978</td>
<td>5.03681297</td>
</tr>
<tr>
<td>Land use</td>
<td>m2a crop eq</td>
<td>0.803502963</td>
<td>0.80204889</td>
<td>5.827527501</td>
<td>5.816933545</td>
</tr>
<tr>
<td>Mineral resource scarcity</td>
<td>kg Cu eq</td>
<td>0.003275874</td>
<td>0.003195215</td>
<td>0.015141267</td>
<td>0.014553613</td>
</tr>
<tr>
<td>Fossil resource scarcity</td>
<td>kg oil eq</td>
<td>0.973128062</td>
<td>0.938458397</td>
<td>1.34262644</td>
<td>1.090033259</td>
</tr>
<tr>
<td>Water consumption</td>
<td>m3</td>
<td>0.635450014</td>
<td>0.634710506</td>
<td>0.330454925</td>
<td>0.325067097</td>
</tr>
</tbody>
</table>

Table 3.5: ReCiPe Midpoint (H) V1.01 Sensitivity Analysis: All Switchgrass Scenarios (**Self-Sustaining)

3.5 Switchgrass Discussion & Conclusion

Switchgrass provides unique opportunities as an energy crop. An untapped economic resource, ecologically beneficial, and less demanding than its biofuel competitors, switchgrass occupies a unique niche for bioenergy research. However, the validity of any such statements are contingent on potential. Many of the same concerns for sugarcane bagasse exist for switchgrass. This analysis confirms that even in an advanced, highly efficient, biorefinery design, the current inputs demands for and type of enzymes and chemicals consumed are too great to fulfill policy
demands of advanced or cellulosic biofuels. Similar hotspots were seen in as drivers in hydrolysis Gerbrandt et al. (2016). (Transportation logistics remain speculative as the demands are based on a regional management paradigm that does not exist. A biorefinery of commercial scale for bagasse or switchgrass has yet to compete with the ease and yield of corn ethanol. There is no established market for these cellulosic energy feedstocks and therefore the crop is not produced on such a scale. Although there are short falls, research continues to attempt to satisfy the potential of switchgrass and in doing so should merge the social, economic, and environmental measurements of biofuels.

Impact assessment for switchgrass was higher for majority of the impact categories. It is common that multiple impact categories including eutrophication, smog, ozone depletion, toxicity factors, acidification are reduce compared to fossil fuels while greenhouse gas emissions decrease (Daylan and Ciliz, 2016; Daystar et al., 2015; Fu, 2003). However, the role of agricultural production off the feedstock is seen as the driver in most cases rather than upstream enzyme production or biorefinery demands. There should be room for improvement across a multitude of inputs. Both enzymes and chemicals in the biorefinery should be targeted as hotspots. There is also substantial contribution from the upstream background processes. As such, the facility should seek to ensure that it is self-sustaining with regard to electricity needs. The need for a self-sustaining facility via combined heat and power is vital to the success of the plant (Gerbrandt et al., 2016; Hsu et al., 2010; Morales et al., 2015). Copper was found to impact terrestrial ecotoxicity for both switchgrass and bagasse due to construction of the onsite storage shed for switchgrass and cellulosic fermentation plan. The agriculture production of switchgrass continued to be overshadowed by the biorefinery processes. Land use change could have been reduced by selecting solely land that was potentially going to be used for CRP. The land that
would otherwise become CRP would still be removed from out of traditional agricultural production. In this scenario, it would be used for switchgrass with a land use change from annual-intensive agriculture to non-irrigated perennial grasses. Further, the assumption of extensive production was made in the effort to account for underestimated land use change factors or more aggressive farming methods that were unaccounted for specifically. It is likely that, at minimum, land use change could be reduced by model variation.

The biorefinery process was initially designed for sugarcane bagasse. With a different composition it is likely that further research scale testing would be required to confirm LCI inputs necessary for switchgrass. It is ideal that a process designed specifically for switchgrass could be more efficient. Also, energy modeling has not been done to ensure self-sustaining scenario. As conducted, stillage offsets a minor amount of ammonium nitrate but it is unclear how the composition would affect the impact assessment. In the scenario that the stillage is properly characterized, there is potential that the impact assessment could be either better or worse. Notably in the area of stratospheric ozone. If the stillage does contain nitrogen at concentrations higher than proposed, a higher amount of ammonium nitrate would be avoided. Thereby reducing, at minimum, stratospheric ozone which is not necessary a target area to compete with corn. However, an unfavorable result of characterization could include liquid stillage with metals, elevated pH, or lead to excessive nutrient loading to soil that would likely decrease yields and increase impact.

Reliance on EcoInvent can reduce the accuracy of the life cycle. There were multiple aspects of the biorefinery methodology that were intended to be site-specific that are challenging to account for. The enzymes identified may not be equal, or as production intensive, as those in EcoInvent. As one of the most driving hotspots across multiple impact categories, the ability to
reduce enzyme impact would inherently make second generation feedstocks potentially competitive with corn. By using a dilute phosphoric acid steam pretreatment, it was proposed that the fermentation plant could use using less precious or demanding alloys in during the refining process. During a review of the cellulosic fermentation plant process, there were limited metals inputs that that could have been altered or removed. Inherent database and modeling issues are not uncommon but future life cycle inventories can be improved to reflect a variability prospective bioenergy among systems.

In establishing common system boundaries, it was possible to examine the environmental impact associated with various feedstocks for ethanol production. Each feedstock presented utilized a unique set of field inputs, as applicable, that when paired with an appropriate biorefinery could be compared. Although unfavorable for biomasses that were suspected to have decreased life cycle emissions, the research demonstrates that biorefinery inputs must be reduced, stillage properly characterized, and life cycle assessment reevaluated. Although outside the scope of life cycle assessment, it is feasible that, with regard to soil properties or ecosystem services, there may still be benefits to cellulosic biofuels. A commercial system of cellulosic biofuels will be evaluated on more than environmental impact, but also in conjunction with social and economic tenants that define sustainability.

Switchgrass remains outside of the realm of environmental sustainability. Policies might be created in order to facilitate improved life cycles. Due to the scale and yields of switchgrass, it can be grown under a regional management paradigm. The plans could be required, recommended, or wholly separate from the RFS. Regional implementation will ensure sufficient biomass availability for a biorefinery that is centrally located. This would minimize transportation distances and allow for use of share-cropping technology. Centralized storage,
square bale harvesting machinery, and an agricultural paradigm to can minimize inputs, maintain yields, and reduce risk assumed by farmers given policy support. Further, the biorefineries should be incentivized or required to be self-sustaining because exterior electricity drove multiple impact categories. Optimizing regional management plans will bring new economic potential to areas such as the former ‘rust belt’ with available land that could be improved by a new economic sector. This study can be expanded for both sugarcane bagasse and switchgrass. Uncertainty data was included but Monte Carlo analysis has not been conducted. This should be explored in further studies or future review. A life cycle analysis is living research that can constantly be improved by modifying processes to reflect real-world likeness or technological improvements.
Citations


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Wright, L. L. "Promising resources and systems for producing bioenergy feedstocks: Switchgrass Production in the USA." *Bioenergy, International Energy Agency, Oak*


Appendix A: Characterization ReCiPe 2016 (H) Midpoint
SimaPro Database Manual, 2018

Climate change
The characterization factor of climate change is the global warming potential, based on IPCC 2013 report. For the Individualist perspective 20 year time horizon was used, for Hierarchist 100 years and for Egalitarian 1000 years. Climate-carbon feedbacks are included for non-CO2 GHGs in the Hierarchist perspective. The unit is yr/kg CO2 equivalents.

Ozone depletion
The characterization factor for ozone layer depletion accounts for the destruction of the stratospheric ozone layer by anthropogenic emissions of ozone depleting substances (ODS). The unit is yr/kg CFC-11 equivalents.

Ionizing radiation
The characterization factor of ionizing radiation accounts for the level of exposure for the global population. The unit is yr/kBq Cobalt-60 equivalents to air.

Fine particulate matter formation
The characterization factor of particulate matter formation is the intake fraction of PM2.5. The unit is yr/kg PM2.5 equivalents.

Photochemical ozone formation, terrestrial ecosystems
The characterization factor is determined from the change in intake rate of ozone due to change in emission of precursors (NOx and NMVOC). The unit of ecosystem ozone formation potential is yr/kg NOx equivalents.

Photochemical ozone formation, human health
The characterization factor is determined from the change in intake rate of ozone due to change in emission of precursors (NOx and NMVOC). The unit of human health ozone formation potential is yr/kg NOx equivalents.

Terrestrial acidification
The characterization factor for terrestrial acidification is Acidification Potential (AP) derived using the emission weighted world average fate factor of SO2. The unit is yr/kg SO2 equivalents.

Freshwater eutrophication
The characterization factor of freshwater eutrophication accounts for the environmental persistence (fate) of the emission of P containing nutrients. The unit is yr/kg P to freshwater equivalents.

Marine eutrophication
The characterization factor of marine eutrophication accounts for the environmental persistence (fate) of the emission of N containing nutrients. The unit is yr/kg N to marine equivalents.

Human toxicity and ecotoxicity
The characterization factor of human toxicity and ecotoxicity accounts for the environmental persistence (fate) and accumulation in the human food chain (exposure), and toxicity (effect) of a chemical. The unit is yr/kg 1,4-dichlorobenzene (1,4-DCB) emitted.

*Land use*
The amount of land transformed or occupied for a certain time. The unit is m²*yr.*

*Water use*
The factor for the water use is the amount of fresh water consumption. The unit is m³ water consumed. Mind that in current implementation this impact category does not include regionalized characterization factors. They may be included in the future, when factor for all the regions will be developed.

*Mineral resource scarcity*
The characterization factor for mineral resource scarcity is the surplus ore potential. The unit is kg Copper (Cu) equivalents. The characterization factor of fossil resource scarcity is the fossil fuel potential, based on the higher heating value. The unit is kg oil equivalents.
Supplemental Figures

ReCiPe 2016 Midpoint (H) V1.01 Corn E15 compared to Sugarcane Bagasse E15
Global warming
Stratospheric ozone depletion
Ionizing radiation
Fine particulate matter
Terrestrial acidification
Ozone formation, Human health
Terrestrial ecotoxicity
Terrestrial eutrophication
Marine eutrophication
Terrestrial ecotoxicity
Marine ecotoxicity
Human carcinogenic toxicity
Human non-carcinogenic toxicity
Land use
Mineral resource scarcity
Fossil resource scarcity
Water consumption

ReCiPe 2016 Midpoint (H) V1.01 Corn E85 compared to Sugarcane Bagasse E85
Global warming
Stratospheric ozone depletion
Ionizing radiation
Ozone formation, Human health
Fine particulate matter
Ozone formation, Terrestrial acidification
Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Human carcinogenic toxicity
Human non-carcinogenic toxicity
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Human carcinogenic toxicity
Human non-carcinogenic toxicity
Land use
Mineral resource scarcity
Fossil resource scarcity
Water consumption

ReCiPe 2016 Midpoint (H) V1.01 Sugarcane Bagasse E15 compared to Sugarcane Bagasse E15 Self-Sustaining
Global warming
Stratospheric ozone depletion
Ionizing radiation
Ozone formation, Human health
Fine particulate matter
Ozone formation, Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Human carcinogenic toxicity
Human non-carcinogenic toxicity
Land use
Mineral resource scarcity
Fossil resource scarcity
Water consumption

ReCiPe 2016 Midpoint (H) V1.01 Sugarcane Bagasse E85 compared to Sugarcane Bagasse E85 Self-Sustaining
ReCiPe 2016 Midpoint (H) V1.01 Sugarcane Bagasse E15 10 Year compared to Switchgrass E15
Global warming
Stratospheric ozone depletion
Ionizing radiation
Ozone formation, Human health
Fine particulate matter
Ozone formation, Terrestrial acidification
Freshwater eutrophication
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Human carcinogenic toxicity
Human non-carcinogenic toxicity
Land use
Mineral resource scarcity
Fossil resource scarcity
Water consumption

ReCiPe 2016 Midpoint (H) V1.01 Switchgrass E15 compared to Switchgrass E15 Self-Sustaining
Global warming
Stratospheric ozone depletion
Ionizing radiation
Ozone formation, Human health
Fine particulate matter…
Ozone formation, Terrestrial…
Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Human carcinogenic toxicity
Human non-carcinogenic…
Land use
Mineral resource scarcity
Fossil resource scarcity
Water consumption

ReCiPe 2016 Midpoint (H) V1.01 Switchgrass E85 compared to Switchgrass E85 Self-Sustaining
Global warming
Stratospheric ozone depletion
Ionizing radiation
Ozone formation, Human health
Fine particulate matter formation
Ozone formation, Terrestrial acidification
Terrestrial acidification
Terrestrial agroecosystems
Terrestrial ecotoxicity
Freshwater eutrophication
Marine eutrophication
Marine ecotoxicity
Human carcinogenic toxicity
Human non-carcinogenic toxicity
Land use
Mineral resource scarcity
Fossil resource scarcity
Water consumption

ReCiPe 2016 Midpoint (H) V1.01 Corn E85 compared to Switchgrass E85
Global warming
Stratospheric ozone depletion
Ionizing radiation
Ozone formation, Human health
Ozone formation, Terrestrial
Ozone formation, Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Human carcinogenic toxicity
Human non-carcinogenic toxicity
Land use
Mineral resource scarcity
Fossil resource scarcity
Water consumption

ReCiPe 2016 Midpoint (H) V1.01 Corn E85 v. Bagasse Self-Sustaining
Switchgrass E85 self-sustaining v. Switchgrass E85 Self-Sustaining