LIFE CYCLE ANALYSIS OF RESIDUAL WOODY BIOMASS-BASED BIOFUEL

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AFEX	ammonia fiber expansion
BDT	bone dried tons
CO	carbon monoxide
CO2	carbon dioxide
CRF	cumulative Radiative Forcing
CY	cubic yards
FRS	fermentation residual solids
GHG	greenhouse gas
GI	gigajoule
GIS	geographic information system
GREET	greenhouse gases, regulated emissions, and energy use in transportation
GW	global warming
GWP	global warming potential
IPK	iso-paraffinic kerosene
ISO	International Standards Organization
LCA	life cycle assessment
LCI	life cycle inventory
MBS	mild bisulfite
NH3	ammonia
NOx	nitrogen oxide
PM	particulate matter
SO2	sulfur dioxide
SOT	state of technology
SPORL	sulfite pretreatment to overcome recalcitrance of lignocellulose
SSL	spent sulfite liquor
TEA	techno-economic assessment
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
VOC	volatile organic compounds
WoTW	Woods-to-Wake
WTW	Well-to wake

EXECUTIVE SUMMARY

The overall Life Cycle Assessment (LCA) activities undertaken during the NARA project can be broadly divided into three different categories: (i) LCA of feedstock logistics, (ii) LCA of marketable intermediary product (sugar) and (iii) woods to wake LCA of bio-jet fuel. From the residual feedstock logistics analysis, which includes biomass collection, handling and in-woods preparation, the results show that road conditions play an important role in determining the most efficient residue collection system along these LCA metrics. As we go further from paved roads, highly more sophisticated residue collection techniques (like biomass bundling or mobile chipper operations) present greater environmental advantage over the base system (i.e., grinding at centralized landing). The cradle-to-gate assessment of a proposed sugar production facility analyzed the overall LCA of sugar made from woody biomass using MBS pretreatment across all seven impact categories, with specific focus on potential global warming and eutrophication impacts. The study found that the eutrophication impact (0.000201 kg N equivalent) is less than the impacts from conventional beet and cane sugars, while the global warming impact (0.353 kg CO_2 equivalent) falls within the range of conventional processes. The results of this LCA can be used for various other forms of sugar based bio-energy products (like, ethanol, butanol, etc.) sourced from residual woody biomass. Finally, the overall woods-to-wake LCA was undertaken for two distinctly different production scenarios. In the first scenario, an IPK only production facility was evaluated, where all the lignin is converted into energy using a backpressure turbo generator. The second model evaluated the production of IPK along with two co-products, activated carbon and marketable lignosulphonate. Utilizing a 'Woods-to-Wake' (WoTW) Life Cycle Assessment (LCA) approach, which is comparable to a Well-to-Wake (WTW) LCA for petroleum based aviation fuel, in these papers, the environmental implications of feedstock recovery, production, and utilization of residual woody biomass based biojet fuel are assessed. These papers also present a comparative assessment of the environmental implications of substituting petroleum based jet fuel with that of residual woody biomass based biojet fuel. For the IPK only production scenario, the results reveal that the WoTW global warming impact of residual wood based bio-jet fuel represent a 78% improvement over the WTW global warming impact of petroleum-based jet fuel. For the IPK along to multiple co-products production scenario, the results reveal that the WoTW global warming impact of residual wood based bio-jet fuel represent more than an 100% improvement over the WTW global warming impact (i.e., net negative global warming impact) of petroleum-based jet fuel, after considering the long term carbon storage and displacement credits associated with activated carbon and lignosulphonate.

INTRODUCTION

Interest in the biochemical conversion of non-merchantable woody biomass (especially harvest slash) into biofuels and other usable energy products is continually growing (Ganguly et al., 2014; Dutta, Daverey, & Lin, 2014; Sunde, Brekke, & Solberg, 2011). One of the reasons for this increased interest is that as countries seek ways to reduce GHG emissions, renewable forest based bioenergy is seen as an appealing alternative to fossil fuels (Berndes et al., 2013). In the US, the significance of converting residual forest biomass into biofuels goes beyond fossil fuel displacement. Typical forest harvest operations in the US, especially along the western part of the country, leave a considerable volume of unused woody biomass in the forest in the form of treetops and branches (Gholz et al., 1979). Given the limited economic feasibility of extracting these harvest residues, the residual woody biomass is typically piled and burned in the forest as prescribed burns (Oneil et al., 2010; Pierobon et al., 2014; Springsteen et al., 2011). Moreover, the lack of a reliable market for woody biomass has reduced the economic incentives to conduct forest thinning activities, resulting in the steady accumulation of woody biomass in forests which have reached hazardous levels (Hessburg & Agee, 2003; Kloor, 2000). This increasing volume of woody biomass has contributed to the increase in the number of catastrophic wildfires that have occurred in the western US over the past decade. The burning of woody biomass in forests (both prescribed burns and wildfires) is a major source of greenhouse gas emissions in the western US (Littell et al. 2009; Peterson, Hyer, and Wang 2014). Woody biomass burning results in emissions of various compounds, including carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), volatile and semivolatile organic compounds (VOC and SVOC), particulate matter (PM_{10} and $PM_{2.5}$), ammonia (NH_3), sulfur dioxide (SO_2) and methane (CH_4) (Wiedinmyer et al. 2006). While some of the emitted chemicals, such as CO_2 and CH_4, are potent agents of global climate change (IPCC 2013), biomass burning also adversely affects local and regional air quality, with acute negative impacts on human health at the local and regional levels (Anenberg et al. 2012).

One strategy for the increased utilization of thinning and post-harvest residual woody biomass is its conversion to advanced second generation drop-in fuels. Conversion of the residual biomass into biofuel will not only remove slash piles from forests, which mitigates the negative environment impacts of decaying or burning (Jaafar and Loh 2014; Preston et al. 2011), but it will displace fossil fuels, thereby reducing our reliance on petroleum-based fuels. Renewable second generation (from non-food sources) jet fuel is a practical solution for the aviation industry looking for an alternative carbon-reduction strategy that requires no aircraft or engine modifications (Daggett et al. 2007; IATA 2014). Despite the potential environmental benefits of using forest residuals, the economic feasibility of extracting residuals from the forest is limited due to a combination of low market demand and high collection and transportation costs (Cambero et al., 2015; Shabani, Akhtari, & Sowlati, 2013). Recently, the use of clean renewable fuels has been encouraged since the Energy Independence and Security Act was signed into law in 2007, providing meaningful economic opportunity for the reduction of foreign oil dependence and greenhouse gas emissions (Energy Independence and Security Act of 2007, 2007). The US Energy Information Administration (EIA) requires that the overall greenhouse gas emissions of cellulosic bio-fuel must be 60% lower than the carbon emissions generated during the production of petroleum-based jet fuel in order to meet public procurement guidelines (EPA, 2011). It has been suggested that the replacement of fossil fuels with biofuels produced from forest residues and forest thinning could substantially reduce greenhouse gas emissions (Lippke et al., 2012).

Common Methodology across LCA Tasks

To estimate the overall environmental impact associated with recovering residual woody biomass to produce bio-jet fuel, as well as any net reduction in emissions to the atmosphere achieved by displacing fossil fuels, the Life Cycle Assessment (LCA) method is used. Life Cycle Assessment (LCA) is an internationally recognized methodology to assess the environmental impacts of a product or activity (a system of products) over its entire life cycle. LCA has evolved into an internationally accepted method for analyzing the complex environmental impacts of a product (Puettmann, Wagner, & Johnson, 2010).

All the LCA analysis listed in this report follows the ISO 14040 and 14044 standard (ISO 2006a; ISO 2006b) for the overall LCA framework. The environmental impacts were assessed using TRACI 2.1 (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) (Bare, 2011). The following impact categories were included: global warming, smog, acidification, eutrophication, carcinogenics, non-carcinogenics, respiratory effects and ecotoxicity. The life cycle inventory analysis and impact assessments were conducted using SimaPro 8. As per the IPCC Fifth Assessment Report, this paper reports the 100 year impact for the global warming potential (IPCC, 2013).

Tasks 1-3 in this report contain information that has been published or accepted in peer-reviewed journals.

TASK 1: LCA OF LOGISTICS

Task Objective

The procedures of collecting woody biomass for alternative energy generation have been studied worldwide over the past years (Lindholm, Berg, & Hansson, 2010; Brechbill, Tyner, & Ileleji, 2011; Johnson, Lippke, & Oneil, 2012). The environmental and economic impacts resulting from collecting and transporting woody biomass to energy facilities have been reflected in a number of studies (Kizha et al., 2015; Zamora-Cristales et al., 2013). Different equipment used in the biomass collection process can influence the overall economic and environmental impacts due to variations in productivity, and the distance between the site and bioenergy facility is an influential factor (Butnar et al., 2010; Johnson, Lippke, & Oneil, 2012). However, most of the previous studies have included the delivering process of residues to bioenergy facility as one of the components within a larger-scaled energy production chain and have mostly focused on the economic costs of transportation instead of the environmental impacts such as GHG emissions (Maung et al., 2013; Archer & Johnson, 2012). Transportation logistics were not evaluated specifically in addition to chemical process during bioenergy production. Some studies have been concerned about the potential location and geographical settings of bioenergy pretreatment facilities, for example, (Sultana and Kumar 2012) used GIS to optimize the location of bioenergy facilities that require the lowest transportation costs. However, such studies did not consider the types of equipment or vehicles required through the process, which are key impact factors in the bioenergy production process. Furthermore, limited number of studies has taken factors such as road conditions and distances into account when evaluating the impacts of wood-based energy production, particularly on how different types of road should be distributed for transportation.

Efficiently delivering loose residues to pretreatment facilities requires processing at the forest sites. That is, transforming large and loose pieces of residues into smaller particles for transportation by chip vans or trucks with trailer. Common processing methods of residues include chipping and grinding. Another processing method is bundling, where a bundler is used to bundle up the residues for easier transportation without requiring additional equipment such as grinders. Although the goal of using a grinder or chipper is to produce small-sized particles, they can have various advantages and disadvantages. By comparison, mobile chippers are often considered to be more energy efficient, and due to smaller sizes, they usually provide higher accessibility to limited access forest sites (Bisson & Han, 2016). The downside of using mobile chippers is that they usually require cleaner forest residues, while grinders are comparatively less sensitive to material quality. Bundling is an innovative option for efficiently transporting harvest residue from forest site to a biomass processing facility. This process involves a bundler to compress loose woody biomass into bundles to provide better delivery efficiency. Depending on the moisture content and distance of transportation, the results of using the bundling technique for forest residue processing are mixed in terms of economic costs and environmen-tal trade-offs. From an economic perspective, although the initial cost of bundling may be higher compared to conventional techniques such as chipping, transport of bundle would eventually become more cost efficient than transport of loose chips as the transport distance increases (Johansson et al., 2006).

There are various processes for collecting biomass for energy generation, and the choices of equipment and machinery used in these processes may significantly affect the potential GHG impacts. This study will be focusing on the environmental impacts, especially GHG emissions, instead of economic impacts providing a basis for selecting residue collection sites from an environmental prospective that is mainly based on road conditions.

The primary objective of this study is to provide information on the potential environmental impacts of forest residue-based energy generation during various processing and transportation process scenarios, and assess the effect of different road conditions and distances and their role in residue transportation to better understand the appropriate processing system under various site conditions. In this study, the environmental impacts of several residue processing and transportation systems in the Pacific Northwest region is modeled using a life cycle assessment approach. Life Cycle Assessment (LCA) is a tool for estimating the potential impacts associated with a product, process, or service. Previous works on woody biomass feedstock have provided a foundation for this research (Eranki & Dale, 2011; Ravula, Grisso, & Cundiff, 2008).

Methodology

System Scenario Description

Three residue processing and transportation scenarios are compared in this study. These scenarios are originally developed by Zamora-Cristales et al. (2013), where these scenarios were used to estimate the economic costs of the transportation logistics associated with forest slash pile processing, accounting for the time and labor costs involved in the process. The initial transportation modeling utilized actual operations in the western Oregon and Washington, USA. In that paper the authors have analyzed one harvest unit that contained all necessary features in relation to road access and pile location that allowed us to illustrate all model capabilities and analyze the results. Accordingly, the results of this study directly relates to the analysis that was performed in a harvest unit located about 27 km east of the city of Sutherlin in southwest Oregon, United States (43°25’34”N, 123°3’37”W).

System 1: Bin truck with stationary grinder at centralized landing (Benchmark; Figure LCA-1.1)

The system involves transporting residues from slash piles to a secondary landing where the residues are processed into chips using a stationary grinder. The processed residues are transported to a local bioenergy facility for pretreatment using a chip van. Two excavator loaders are required to load the bin truck and the grinder. Two transportation stages are involved in this system scenario, where residues are transported to the centralized landing during the 1st stage and processed chips are delivered to the facility during the 2nd stage.

The purpose of the establishment of a centralized landing is to provide an accessible open space for residue processing since slash piles are often scattered around the forest with limited access. A centralized landing can also reduce the mobilization costs. The use of a stationary grinder to process the collected residues at once is also considered to be more efficient. This is the most common harvest residue collection practice in the Pacific Northwest and hence is considered the benchmark scenario.

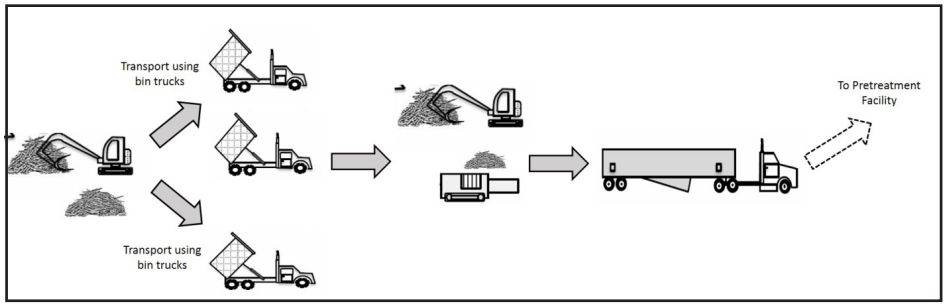


Figure LCA-1.1. System 1: Bin truck with stationary grinder at centralized landing. Chip van is used for hauling processed residues.

System 2: Bundling in forest with electric grinder at facility (Figure LCA-1.2)

The purpose of a bundling system is to combine residues into multiple bundles using a bundler so they can be transported to a bioenergy facility. The bundles are processed at the facility with an electric grinder instead of on the site with a diesel grinder. The advantage of this system is the ability to reduce fossil fuel consumption from the diesel grinder. The use of logging trailer makes it possible to access difficult road conditions within the forest site, which eliminates the need for additional vehicles such as the bin truck. However, the bundler may add an additional stage to the residue collection process, and therefore contribute to higher fuel consumption.

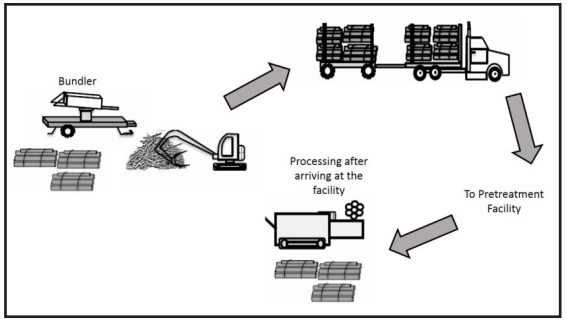


Figure LCA-1.2. System 2: Bundling in forest and processed with electric grinder at facility. Bundles are processed with electric grinder at the facility.

System 3: Mobile chipper with set-out trailer (Figure LCA-1.3)

The system involves using a mobile chipper to process the residues at the loca-tion of each slash pile. The processed residues are loaded into the set-out trailer directly from the chipper and are hauled by a truck to the bioenergy facility. The size of trailers can range from 32 to 45 feet long on steep terrain, and the actual accessibility of the trailers depends on the way they are coupled (Zamora-Cristales & Sessions, 2015). For the system scenario described here, two 32-feet trailers, each with a capacity of 100 cubic yards (CY), are used and are hauled by a double trailer chip van. This system eliminates the need to establish a centralized landing and reduces the fuel consumption from bin trucks. However, the system requires trailer access closer to the slash piles, and the mobile chipper might not be as efficient as the stationary grinder and is unable to process particles such as small rocks that are mixed in the residue. Often the material must be sorted before it can be chipped to identify the cleanest and largest material.

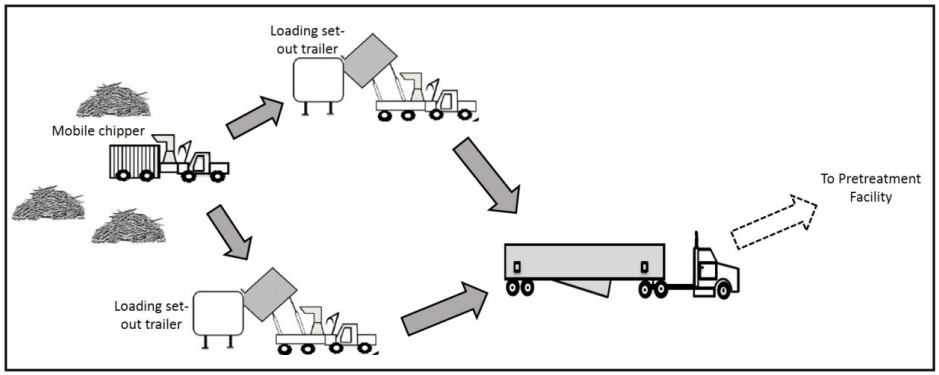


Figure LCA-1.3. System 3: Mobile chipper with set-out trailer. Logging truck with trailers is used for hauling.

Results

In the analysis, the proportion of paved highway and gravel road distance emerged as an important factor in the environmental impact assessment of forest residues. In System 1, the variation in GWP occurred during the 1st and 2nd stage transportation where the distance of gravel road increased respectively from 15% to 55% on a 10% increment. As the distance travelled on gravel road by both the chip van and the bin truck increased, the transportation stages contributed more to the overall emissions produced in this system. A similar trend occurred in Systems 2 and 3. As the proportion of the distance travelled on gravel road increased, the contribution to GWP, acidification and eutrophication from transportation increased. Since the total distance between the pretreatment facility and the forest site was maintained constant at 50 miles one-way, the results implied that changes in the distances for different road conditions would affect the environmental impacts of residue processing and transportation. The significance of this effect depends on the extent of parts played by transportation.

It should be noted that a similar pattern of decline was found for Systems 2 and 3, although the impacts discussed in this study for System 3 was lower than those of System 2 overall. This may be due to similar stages of transportation used in the systems. Since Systems 2 and 3 only required a single stage of transportation instead of 2-stage transportation as in System 1, the overall emission produced from transportation was reduced to lower rates. This can be seen from the figures shown previously. For example, the highest GWP for System 1 was 56.9 kg CO_2 eq., while the highest GWP for System 2 was 47.7 kg CO_2 eq., and 41.4 kg CO_2 eq. for System 3.

Assuming the GWP produced by the equipment for all biomass collection operation scenarios is constant, all systems emit less GHG when the proportion of highway distance is longer. Although the fuel consumption of chip van on gravel road is higher than that of bin trucks, it is more efficient in transporting the same amount of residues due to its large capacity. In other words, by only looking at the performance of vehicles on gravel road, it would take fewer trips for the chip van to transport the same amount of residues compared with bin trucks. All systems performed better with greater proportions of highway distance. Since the total distance of dirt road was kept constant at 1 mile each way, the differences in GWP were mostly caused by the distance distribution of highway and gravel roads. For this study, the average speed limit for all vehicles traveling on gravel road is 15 mph, and the speed limit for traveling on highway is 45 mph. Therefore, the travel time for every BDT of residues is longer on dirt and gravel roads, which leads to lower efficiency.

Additionally, to investigate the effects of road conditions on the residue transportation process, several hypothetical scenarios were conducted under different distance distributions. For example, if the distance of paved highway started at 40% of the total 50-mile one-way distance and increased on a 5% increment until it reached 90%, the GWP for the grinder system showed a steeper declining pattern as the highway distance increased. The bundler system also indicated a declining pattern, but did not vary as much as the grinder system. Although in reality, the distance of dirt road usually does not exceed 2 miles (Mason et al., 2008), this hypothetical scenario provided a clear indication of road condition impacts on different processing and transportation systems.

In Western Washington and Oregon, where this study is located, most of the feedstock is sourced from industrial forests with established access to state highways. For this region, highway transportation dominates the overall haul distance of the woody feedstock. In this region, on an average, highway haul distance is greater than 85% as most of the primary landings are located within a couple of miles of the nearest highway. All the three proposed biomass collection systems have fairly similar (within 5% margin of error) environmental implications, with the benchmark scenario (which is the status quo) nominally superior over the bundling scenario. Hence, for well accessible industrial forest locations, the additional investment associated with in-woods biomass handling and processing (Systems 2 and 3) may not be necessary from an environmental perspective based on our knowledge. The economic costs and benefits of applying these system scenarios require further investigation. However, for natural regeneration forests located far away from the established highways, similar to eastern Washington, eastern Oregon, Montana and Idaho forests, the environmental gains associated with the advanced in-woods feedstock handling techniques are significant.

Moreover, some of the assumptions used for this analysis, including the moisture content of the residual biomass and baseline road conditions, are specific to the coastal PNW region. Given the higher rainfall and moisture content in the atmosphere, the moisture content of residual biomass in this region is generally higher than average. Moreover, most of the forests in this region are industrial plantation forests with better access to highways. These conditions play a significant role in determining the baseline scenario and the overall environmental impact. However, for the forests of the PNW region located east of Cascades, the conditions are very different with drier conditions and dominated by natural regeneration forests. Hence, the residual biomass in this region will likely have lower moisture content and located further away from paved highway.

Conclusions/Discussion

One of the concerns of producing bioenergy from forest residues is to make the bioenergy production process more environmentally feasible. Residual feedstock collection, in-woods processing, and transportation are not only relevant for the economics of residual biomass based bio-energy, but play a significant environmental role in the overall process. The results of this study clearly indicate that road conditions and in-woods biomass handling play an important role in determining the environmental impacts. As the paved highway transportation is the most efficient, the closer the feedstock source is to the highway the better is the associated environmental impact of feedstock processing and transportation. Given the same overall distance travelled, the deeper we go inside the forest to collect the residue, the greater environmental impact gets associated with the collection process. This is true for all the three systems presented in this research study.

The research results further reveal that not all the three systems are equally sensitive to the reduction in the proportion of highway distance. The benchmark scenario, which uses bin trucks to collect the loose residue and processes them in a central landing (System 1; Figure LCA-1.1), is most sensitive to the reduction in the proportion of highway hauling distance. With System 1, the environmental impacts deteriorate steeply with residue collection scenarios for deeper forest feedstock locations, given the inefficient in-woods loose residue handling and transportation. However, both the 'bundler' and the 'mobile chipper' systems (i.e., Systems 2 (Figure LCA-1.2) and 3 (Figure LCA-1.3)), demonstrate greater environmental performances with deeper in-woods residue collection, as compared to System 1. For all road types, the mobile chipper system (i.e., System 3) is clearly the environmentally favorable in-woods residue processing and transportation system.

TASK 2: LCA OF MARKETABLE INTERMEDIARY PRODUCT (SUGAR)

Task Objective

A critical step in the conversion process is the release of fermentable sugars from the cellulosic biomass for downstream processing (Agbor et al., 2011; Eggeman & Elander, 2005; Lloyd & Wyman, 2005). This is done with pretreatment techniques that degrade lignin structures in the wood allowing access to the polysaccharides for hydrolysis. Obtaining fermentable sugars is a key step in the conversion process because sugar yields significantly affect downstream fuel products (Mood et al., 2013; Lloyd and Wyman, 2005). Additionally, sugars are a critical diverging point in many biochemical conversion pathways (also capable of being converted into chemicals like esters and carboxylic acids that are expensive to make in the petroleum industry).

Established pretreatment processes that liberate fermentable sugars from cellulosic biomass include dilute acid, ammonia fiber explosion, steam explosion, and hot water treatments (Eggeman & Elander, 2005; Gao et al., 2011; Tao et al., 2011; Nwaneshiudu et al., 2015). These conventional methods have been characterized extensively for their economic and environmental sustainability (Eggeman & Elander, 2005; Tao et al., 2011). Mild bisulfite (MBS) pretreatment is an emerging technique showing similar sugar releasing efficiencies, while also offering the added advantage of utilizing well-known pulping technologies (Gao et al., 2013). MBS pretreatment is a calcium bisulfite-based method similar to Kraft pulping or SPORL (Sulfite Pretreatment to Overcome Recalcitrance of Lignocellulose) processes where sulfurous acid is used to degrade the lignin fibers in cellulosic biomass (Gao et al., 2013). Similarities to the conventional Kraft pulping process (low pH) gives SPORL-like processes (high pH) such as MBS an edge in development.

Zhou et al. (2013) report that SPORL's advantage over other emerging techniques is its simple scale-up potential because existing infrastructure from pulping plants directly feeds into the development of the process. They also report the increased sugar yield of SPORL processes due to favorable interactions between sulfonated pulp moieties and enzymes in enzymatic hydrolysis. However, these sulfite processes also create significant amounts of aqueous ligno-sulfonates, furfurals, and other organic byproducts that must be assessed for their environmental impacts (Gao et al., 2013; Zhou et al., 2013).

Comprehensive techno-economic assessments (TEA) and impact analysis on emerging pretreatment technologies are critical to inform feasibility of plant design and can also influence policy/venture capital interest concerning the technology (Sunde et al., 2011; Mielenz, 1997; Nguyen et al., 1996). The National Renewable Energy Laboratory (NREL) has led the way by conducting full-scale techno-economic and environmental assessments on proposed bioethanol facilities that convert corn stover into alcohol, iso-butanol, and other fuel grade compounds (using dilute acid pretreatment, not MBS). Other works have also looked extensively at green-house gas (GHG) emissions and energy use of various pretreatment technologies (Tao et al., 2011; McKechnie et al., 2015; Pourbafrani et al., 2014). However, a full environmental assessment of MBS pretreatment of woody biomass has yet to be done on a facility that produces sugar as its main product.

The goal of this study was to develop a life cycle impact assessment of soft-wood-based sugar syrup produced at 60 % concentration. We model a process that converts a generic blend of forest residuals using the MBS pretreatment technique. The primary focus of this assessment was the environmental impacts of one such sugar depot located in the PNW. This was built based on the TEA and plant design of the 2011 NREL sugar production model incorporating the MBS pretreatment technique.

Methodology

The functional unit used in this analysis is 1 kg of sugar product from forest residuals. The pretreatment, hydrolysis, and separation processes were modeled in ASPEN Plus at an industrial scale. Data for biomass pre-processing, enzyme production, wastewater treatment, and the boiler were generated outside the ASPEN model (US-LCI database, NREL report). The TRACI impact assessment method was used within the SimaPro 8 platform to quantify the life cycle environmental impacts.

System boundary

To quantify GHG emissions from the production of sugar, a cradle-to-gate system boundary was adopted. "Cradle" was defined as the source of waste/residual woody biomass (slash piles) at the forest landing, where only the burdens of the operations to grind and transport the slash pile were included. The residual contaminants left in the concentrated sugar product were outside the scope of this study. The amount of solids sent to the boiler to generate energy was estimated using specified metrics from the NREL 2011 model. The proposed geographic region for the study was the PNW. The cut-off rule used is 95 % on a mass basis and the duration of the study is over a one-year period.

Feedstock zone, biomass transportation and pre-processing

The life cycle inventory (LCI) of biomass feedstock entering the processing plant is based on the assumption that 845,000 BDT of harvested residues is fed into the biomass processing plant on an annual basis. Based on preliminary estimates (by NARA industrial consultants), it is assumed that 9 % of the biomass gets screened out (fines and rejects) of the process, and approximately 770,000 BDT of woody biomass enters the pretreatment process. The remaining 75,000 BDT of fines go to the boiler unit to be burned as hog fuel. Given the feedstock requirement, the LCI associated with the specific feedstock (FS-10—Douglas Fir/Ponderosa Pine mixture)

depends on two features: (1) the feedstock zone, including the geographical region and forest types under consideration, and (2) associated feedstock logistics and in-woods processing. The woody biomass feedstock zone used in this study includes the eastern Washington, northern Idaho, and western Montana region (hereafter referred to as the "inland west region"). The chosen logistics benchmark scenario indicates that the loose residues are transported from the primary landing to the secondary landing in a 30-cubic yard (CY) dump truck, where they are chipped using a large chipper. Residuals must be transported from a primary to secondary landing (where the chipper and direct loader are located) because the 120 CY chip vans cannot navigate the forest spur road. The chipped residues are directly loaded into a 120 CY chip van and transported to the pretreatment facility. Given the target annual feedstock requirement and the estimated availability of harvest residues in the region, an average distance of 75 miles is estimated from the primary landing to the processing facility (Pierobon et al., 2014). It should be noted that although the feedstock LCA is reported in bone dry units, a 35 % feedstock moisture content is assumed when calculating truck capacity and associated fuel consumption. Finally, the feedstock handling at the pretreatment facility includes getting bales of chipped woody biomass onto an electrically powered conveyor belt, on which the wood is screened and fed into the plant.

Mild bisulfite pretreatment

After feed handling and screening, the wood chips are fed into a batch pretreatment reactor that uses electricity, high-pressure steam (above 207 °C and 17 atm), and reagents (calcium bisulfite, sulfurous acid, water, and oxygen). The calcium bisulfite and sulfurous acids are created onsite by two stage reactions. Firstly, sulfur (S) powder is burned at ~1400 °C producing sulfur dioxide (SO_2). The heat generated from this reaction will be used to create steam that heats the biomass digestion reaction.

Secondly, limestone [$Ca(CO)_3$] is then reacted with the sulfur dioxide to produce calcium bisulfite, sulfurous acid, and CO_2. These two reagents along with water and oxygen are reacted with the biomass in a digester for 4–14 h at a pH of ~2 before being sent by conveyor to be washed. After the wash, the supernatant is collected as spent sulfite liquor (SSL), while the wet pulp is flashed and sent into enzymatic hydrolysis tanks.

Enzyme production

The process model in the 2011 NREL report (Humbird et al., 2011) accounted for the production of the Cellulase enzyme. As stated in the report, this scheme entailed using a T. reesei-like fungus to create the Cellulase enzyme. An aerobic fermentation is model using a feedstock of glucose and fresh water (Nguyen et al., 1996). Media and a small amount of purchased cellulase are used to induce cellulase production. Created cellulase enzymes are then sent into enzymatic hydrolysis tanks. However, for this environmental assessment, data for the Novozyme cellulase enzyme production process was used directly from the US-LCI database. Enzymes from Novozymes (the Denmark-based enzyme production company) are made in house using a production scheme similar to that model in the NREL report.

Enzymatic hydrolysis

Enzymes and reagents (water, lime) are added to eight enzymatic hydrolysis batch reactors where they are left to sit for 72 h (lime for pH adjustment). Enzyme input into the unit is approximately 0.66 TPH (tonne per hour). Reagents, water, and lime are added to each batch reactor and are typically stirred for increased sugar yields (~80 % conversion rate).

Separation

Lignin solids in the sugar slurry are separated out by centrifuge, and the remaining liquid is then recombined with the washed ligno-sulfonate "red liquor" stream. The resulting output stream is then concentrated with a three-stage triple effect evaporator operating at three pressure stages. This creates a concentrated 60 % sugar product stream with 40 % being water and other aqueous contaminants, 1 kg of which serves as the functional unit for the assessment. The gas evaporate waste is condensed back into a liquid and sent to the wastewater treatment facility.

Wastewater treatment

Wastewater treatment is adapted from the closed-loop system used in the modified NREL model (Humbird et al., 2010), using proportions of the input and output streams as well as the electricity usage of the unit. This treatment process uses digestion, anaerobic/aerobic treatment, as well as filtration. The process is assumed to recycle all of the process water with no discharge of wastewater outside the system boundaries. Waste streams of biogas go into the boiler, while the brine waste is discharged.

Boiler

The boiler process is adapted from the NREL process design consisting of a stoker-fired boiler that burns biogas, sludge (from water treatment), fines (screening), and lignin cake (from separation) towards generation of electricity that can be fed back to the energy grid. Burning of these components generates steam that is used in a steam turbine. For this process, reasonable estimates were used for its efficiency and outputs based on the NREL process design. Proportions were taken from the inputs and outputs of the NREL design and used to estimate outputs for the MBS process (the significant assumption being that the inputs from the MBS process are similar to that of dilute acid).

Results

The ASPEN Plus data were integrated into SimaPro by simply adjusting all input and output streams to the functional unit of 1 kg of sugar product. Environmental impacts were calculated across categories: global warming (GW), eutrophication, acidification, smog formation, ozone depletion, carcinogens, non-carcinogens, respiratory effects, and ecotoxicity. We focus on the eutrophication and GW impacts because of their significance to the proposed sugar plant and the assumptions made for the model (CO_2 and water discharge). GW impacts are tied to the

significant amount of carbon dioxide produced in the process, and eutrophication is strongly influenced by the large amount of contaminated water which could be released by the system. The potential health and air quality impacts for three prominent but ancillary categories (smog, acidification, and ecotoxicity) were also addressed.

Global warming

A comparison of global warming potential (GWP) for our model system is shown in Figure LCA-2.1. The bar graph in the figure is calculated in kilogram carbon dioxide equivalent (kg CO_{2eq}) and normalized to the sugar product output. The figure shows the calculated GWP of the major processes in sugar production including biomass pre-processing, MBS pretreatment, enzyme production, enzymatic hydrolysis, wastewater treatment, and boiler.

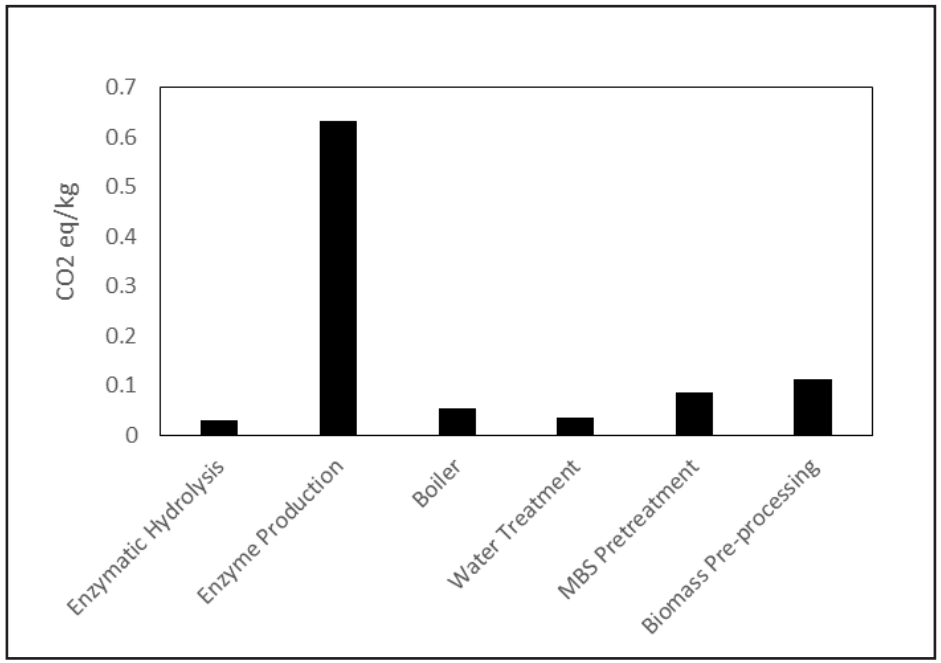


Figure LCA-2.1. Process contribution to global warming. Six main units of the sugar process are shown with their corresponding GW impacts (measured in CO_2 equivalents/kg)

We see from the figure that the greatest contributors to the GWP of the proposed facility are biomass pre-processing and MBS pretreatment. The biomass pre-processing GWP is mainly influenced by the diesel-range fuels used to prepare and transport the forest residuals before arriving at gate. These may change depending on the possible logistical options for forestry operations and transportation scenarios available. The MBS pretreatment process, which has the highest GW impact, is predominantly influenced by the high-pressure steam used for the process. Figure LCA-2.1 also shows the less impactful unit processes to GW (boiler, enzymatic hydrolysis, enzyme production, and water treatment). Modeling the biogas and dirty water as inert (because they feed back into the system) means that most of the GW impact of the process is coming from the electricity usage. The enzyme production and boiler (burning hog fuel and lignin cake) units have the least GHG emissions. The LCI for cellulase from the US-LCI database only shows a marginal release of carbon dioxide into the environment. A majority of the boiler's impact is primarily due to the electricity used by the turbo generator. Lastly, impacts from enzymatic hydrolysis can be attributed to the medium pressure steam and other reagents (quicklime, water, etc.) required for the process.

The overall GW impact of the sugar product leaving the production facility was assessed. The resultant stream does not account for any of the burdens from the aqueous contaminants (sulfonated lignin, furfural, acetic acid) that remain in the concentrated sugar product stream. The sugar stream along with the aqueous contaminants is to be supplied to an external alcohol production facility, as is proposed in the NREL corn stover model. The value of the GWP of 1 kg sugar product is calculated to be 0.353. This number includes the displacement credit taken from the grid-bound electricity being produced by the boiler. We assess the reasonableness of this value by comparing it to other values reported in the literature for similar technologies. Although very limited, some values were obtained for the specified system (biomass to sugars only). Thomas et al. (2012) yield a GWP value of 0.522 for its super critical sugar production process. Tao et al. (2011) show a broader range of GWP between 0.9 and 2.5 kg CO_{2eq}/kg sugar for a wide gamut of pretreatment technologies (NREL 2011 SOT, AFEX, dilute acid, etc.). We see that the MBS and super critical water values are lower than those from these other sugar production processes. Accounting for the added displacement credit from the sold electricity, we see that we get a value of 0.518 for our MBS process, which is similar to the super critical process. A number of factors including impact assessment methods and modeling assumptions could explain these differences in resulting GWP.

Eutrophication

Assessing eutrophication impacts on local and global bodies of water is critical for the proposed sugar production. This work focuses on a proposed nth plant facility, so we assume a stock of well water to start the process. We assume that most of the water is being treated, recovered, and recycled back into the system at a rate of 490 tonnes per hour, meeting a significant portion of the process's water requirements.

Recycled water is redistributed back into the system based on individual water requirements of each unit process. Figure LCA-2.2 shows the six major processes and their eutrophication impacts, calculated in terms of gram per unit nitrogen (N) equivalents (TRACI—Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts). Biomass pre-processing and MBS pretreatment are processes that contribute the most to impacts in the eutrophication category. The high eutrophication impact of the biomass pre-processing unit is caused by the associated burdens of the diesel-range fuels used by the machinery and trucks that

process/transport the biomass. The same reasoning can also be used to describe the MBS pretreatment process impact; outside of the start-up water requirements that are simply recycled and re-used within the system, the process also uses water to wash the sulfur treated biomass and within heat exchangers for cooling. These all contribute to the observed impacts because water soluble sulfur-based moieties as well as other chemicals (acetic acid, ammonia, and furfurals) are present in these aqueous streams, which could have significant impacts if released into local bodies of water. The other processes (wastewater treatment, enzymatic hydrolysis, boiler, and enzyme production) seem to have relatively low eutrophication impact in the sugar production process. Of the four listed, enzymatic hydrolysis and wastewater treatment have the next greatest impact on eutrophication. This could be due to the water used to wash the sulfonated pulp and the possibility that "dirty water" (containing ammonia and nitrogen-based compounds) to be discharged into local streams and rivers. We also see that the impact of the wastewater treatment unit is marginal compared to the MBS and hydrolysis processes, even though a significant amount of water is being processes by the unit. This is because our assumed wastewater treatment process emits only brine (table salt) to the environment, unlike the boiler that emits ash and other nitrogen containing moieties. Additionally, the low impact of the water treatment facility is highly dependent on the assumption we made about the efficiency of the unit (our treatment unit being relatively similar to the NREL wastewater treatment process). In conventional pulping processes, the spent sulfite liquor (SSL) from the pretreatment process is not sent for treatment. Most processes find ways to use this stream. In the Kraft process, the "black or brown liquor" is treated with various chemicals to create more benign solids or are just disposed of in appropriate means (Jonsson et al., 2008; Wallberg et al., 2003). For more acidity processes like MBS, a "red liquor" is created also primarily composed of sulfonated lignin compounds. At the right concentration, the SSL can be sold as a cement additive (Konduri & Fatehi, 2015). This warrants further investigation as this stream accounts for a significant volume percentage of the "dirty water" beginning treatment in the process. The uses of spent sulfite liquor streams are still emerging and will need to be fully explored to determine its place in the growing biofuels and co-products literature.

The overall impact of the sugar product leaving the production facility was assessed within the eutrophication category. A normalized numerical value of 0.000201 kg N was obtained for the process. Due to a lack of eutrophication data from pretreatment technologies, these values were compared to beet and sugarcane products. The process modeled here is an order of magnitude lower than cane (0.00109 kg N) and beet (0.00488 kg N) processes. The difference may be due to a higher proportion of water and fertilizer used in sugar cane and beet production. This may illustrate the need for efficient use of land and water resources in these types of proposed sugar production facilities.

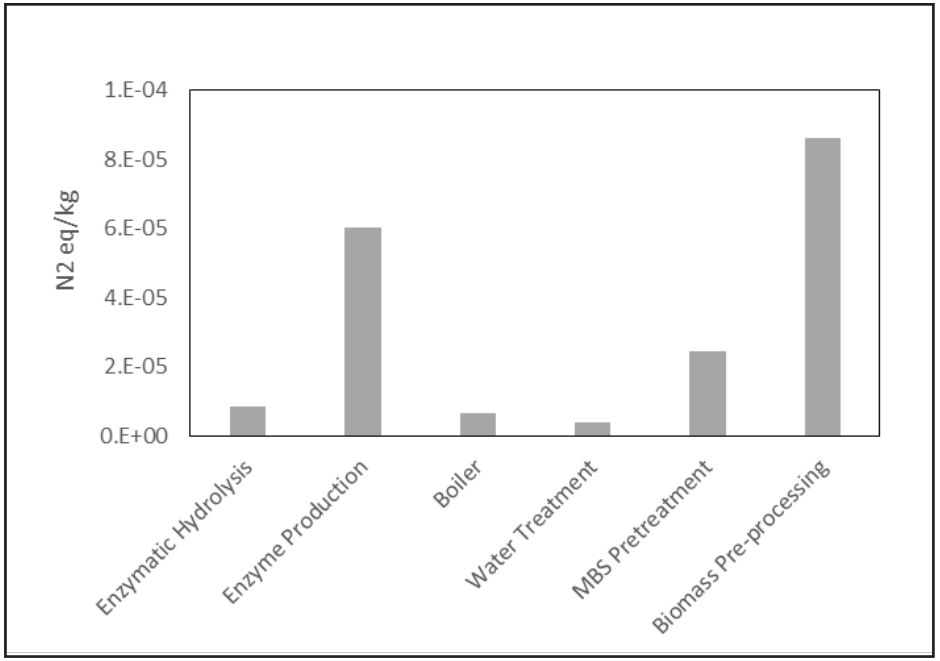


Figure LCA-2.2. Process contribution to eutrophication. Six main units of the sugar process are shown with their corresponding eutrophication impacts (measured in Nitrogen equivalents/kg).

Health and air impacts

Although not directly related to the bioconversion processes, three impact categories (smog, acidification, ecotoxicity) have significant impacts in the MBS sugar-making process. These impacts are shown to primarily come from the pretreatment and biomass pre-processing steps (processing and transportation of the woody biomass in the forest) with very slight impacts associated with fuels used in the processes. We also notice that for categories of ozone depletion, carcinogens, non-carcinogens, and respiratory effects, preprocessing processes and MBS pretreatment units carry a major part of the burdens (this does not include aspects that are unique to the conversion process). However, it is worth noting that under various conditions within the plant (for example, if evaporate streams were vented rather than condensed and sent to the wastewater treatment facility), these impact categories would be more integral to this kind of assessment.

Conclusions/Discussion

A "cradle to gate" life cycle analysis was conducted for sugar production from forest residue slash using MBS pretreatment. We analyze the process for its contributions to all impact categories within the TRACI assessment method, with specific focus on GW and eutrophication. Within the process, we found that the most impactful processes in both impact categories are the biomass pre-processing before it enters the plant site and the MBS pretreatment. This not only highlights the significant impact of more efficient transportation, but it also shows the environmental impacts of

grinders, chippers, and other harvesting machinery that run on diesel-range fuels. Within MBS pretreatment, we see that a majority of the impacts are attributed to the high-pressure steam being used in the process. Although the steam requirements could be met by the steam outputs of the sulfur and biomass boilers, we show here the uncredited impacts of MBS conversion relative to other processes as a worst-case scenario as well as to detail the overall needs of the MBS pretreatment. We also see that the sugar-making process carries burdens (within both categories) from reagents like water, steam and chemicals. Although the assumptions made in this work create a convenient closed-loop system to work with, we acknowledge that the large amount of water (which could potentially contain nitrogen-based compounds from the sugar production process) needed for the process may have a more significant impact in the eutrophication category. During the presented life cycle assessment of forest residual MBS sugar, we show that the GW impact (0.353 and 518 kg CO_2 eq) is lower than other pretreatment methods. We attributed this difference to the assumptions made about water treatment and lignin utilization. We also show that the impacts on eutrophication were significantly low when compared to beet and cane sugars. More importantly, due to the limited data on sugars products from cellulosic sources, this work highlights the possible impacts of a proposed sugar depot. Being assessed as a product, not just an intermediate, leaves much needed flexibility for emerging technologies within the ever-changing biofuels landscape. This work not only shows the importance of assessing the impacts of biomass to sugar production processes, but it also highlights the importance of water utilization and discharged. The strength of MBS and other acidic-based process will be strongly tied to the ability to utilize SSL streams from such systems, which seems very likely with MBS pretreatment.

TASK 3: WOODS-TO-WAKE LCA OF BIO-JET FUEL

Task Objective

A comprehensive Life Cycle Assessment (LCA) of forest residue based aviation fuel was performed using a 'Woods-to-Wake' (WoTW) approach which is aligned to the Well-to-Wake (WTW) analysis used in the Argonne Lab's GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) analysis (Argonne National Laboratory, 2012; Wang et al., 2012). One of the significant potential benefits of converting residual woody biomass to biofuel is to avoid burning them in prescribed burns. This study incorporates the benefits of the avoided environmental burdens associated with biomass burns, as a result of biomass conversion to biofuels, using the LCA approach. Hence, the overall objectives can be summarized as follows:

- perform a detailed Life Cycle Assessment (LCA) to evaluate the environmental impacts of using woody biomass as a feedstock for conversion into bio-jet fuel.
- incorporate the avoided environmental impacts associated with piling and burning the woody biomass within the forest into the LCA calculations.
- compare the LCA-based environmental impacts of the Woody Biomass-Based Jet Fuel to Petroleum-Based Jet Fuel.

Methodology

A comprehensive Life Cycle Assessment (LCA) of forest residue based aviation fuel is performed using a 'cradle-to-grave' approach where 'cradle' is defined as forest residues collected into slash piles and 'grave' is defined as the fuel combustion during flight in an aircraft. The product system is woody biomass based bio-jet fuel whose function is to fuel an aircraft during flight. The functional unit of the system is 1 GJ of energy produced by fuel combustion. The study is based on a production facility, which is scaled to produce 112,980 tons of IPK (bio jet fuel) using 700,000 bone dry metric tons of screened woody biomass. A simplified diagram of the system boundaries associated with the biofuel production process is shown in Figure LCA-3.1.

System Boundary

As shown in Figure LCA-3.1, the overall system boundary for developing the LCA of the bio-jet-fuel consists of the following components: (i) feedstock: (ii) biomass conversion: (iii) combustion in the jet engine. The individual components of the flow chart presented in Figure LCA-3.1 are explained in greater detail in the following sections. A mass allocation, between logs and residual biomass (tops and branches), is used for evaluating the upstream environmental burdens associated with the piled woody biomass at harvest landing. 100% of the burdens associated with all activities beyond the primary harvest landing are assigned to the biofuel processes.

Feedstock

This study assumes collection of residual biomass from the harvest landings to be used as the feedstock for bio-conversion to bio jet fuel. The overall biorefinery is scaled at 700,000 bone dry metric tons of screened woody biomass per year. Assuming, 9% rejects the yearly feedstock demand is modeled for 770,000 bone dry metric tons of residual woody feedstock per year, delivered to the screening facility. Given the logistical challenges in the case of forest residue based bio-fuel, feedstock collection and in-woods handling play a significant role in the overall environmental impact of the biofuel (Ganguly et al., 2014). Geographical location, regional vegetation, and topographical characteristics significantly affect the environmental impacts associated with collecting and transporting the woody residues from the forest landings to the biomass processing facility (Johnson et al., 2012). This study uses the environmental implications of producing woody biomass in the western Washington region. A mass allocation approach is used to account for upstream burdens associated with the feedstock (includes harvesting, forwarding and skidding operations). The assumptions presented in the following paragraph details the proportion used for mass allocation.

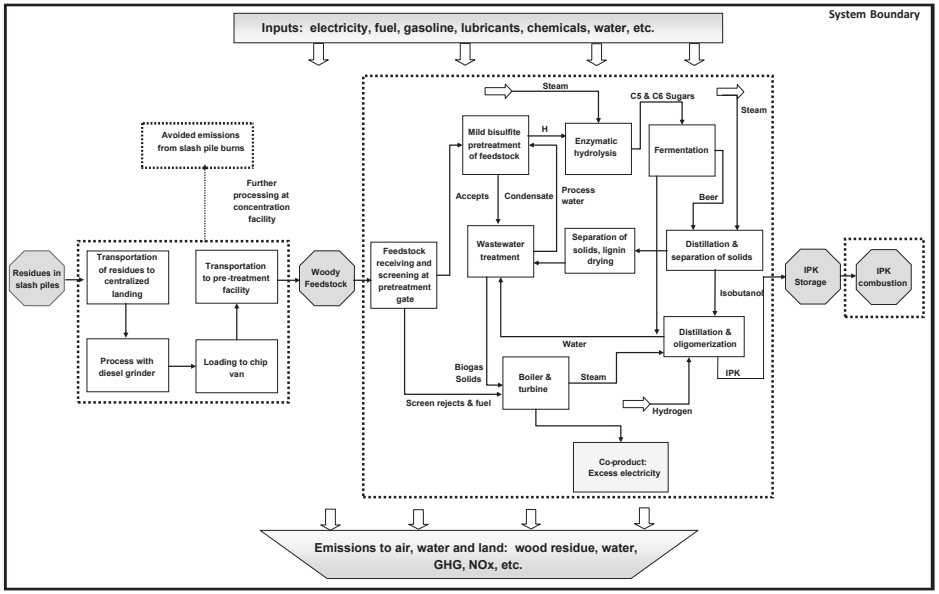


Figure LCA-3.1. Overall Scope of the Woody Biomass Feedstock

Woody slash piles at harvest landings are generated during harvest operations, with a significant portion of the residual biomass being scattered around the forest

floor during the harvest and skidding operations. Based on empirical time-motion studies, it is estimated that approximately 65% of the residual biomass gets accumulated into slash piles at the primary harvest landings (Perez-Garcia et al., 2012), the remaining 35% gets scattered on the forest floor. This research further assumes that 10% of the biomass in the slash pile is inadvertently left behind at the landing during the loading, chipping, and transporting of the biomass from the landing site to the biomass processing facility (Johnson et al., 2012). The residual woody biomass (a.k.a harvest slash) produced during commercial harvest operations in the Pacific Northwest is generally burned in the forest or left on the forest floor to decompose. Based on these conditions, it is estimated that only 58.5% of the total harvest residuals generated during the timber harvest operation are delivered to the pre-treatment facility for conversion into biofuel. Furthermore, according to the preliminary assessment of the feedstock quality, it is estimated that approximately 91% of the delivered feedstock material will pass through the screen and be sent to the pretreatment chamber, while 9% will be rejected and be used as fuel in the boiler (Chen et al., 2016). Based on the forest management practices, topography and existing road network in the inland west region, this paper adapts the feedstock logistics model developed by Zamora-Cristales, Sessions, Boston & Murphy, 2015, as presented in Tables LCA-3.1 and LCA-3.2. The harvest system and in-woods feedstock handling benchmark scenario data are presented in Table LCA-3.1. The transportation distance of the woody biomass from the harvest site to the processing facility on different types of roads is presented in Table LCA-3.2.

Table LCA-3.1. Equipment configuration.

Equipment	Capacity	Productivity [t h^{-1}]	Fuel consumption [l h^{-1}]
Forwarder	130 kW	31.4	29.9
Escavator loader	30 kW	36.2	25.6
Grinder	560 kW	45.4	96.5
Post-grinder loader	105 kW	45.4	21.3
Bin truck	30 m^3		
Chip van	100 m^3		

Table LCA-3.2. Benchmark scenario for road-type specific transportation distances.

Road type	Dirt	Gravel	Highway	Total
Avg. speed	(8 km h^{-1})	(24 km h^{-1})	(72 km h^{-1})	
One way haul km	1.6	10	68.4	80

The loose residues are transported from the primary landing to the secondary landing in a 30 m^3 bin truck, where they are processed using a stationary grinder (Johnson et al., 2012). In this scenario, the residuals are transported from the primary landing to the secondary landing where the grinder and direct loader are located because a 100 m^3 chip van cannot navigate the tight curves of the forest spur roads. The processed residues are directly loaded into the 100 m^3 chip van at the secondary landing and transported to the pretreatment facility. Based on the biomass availability conditions and the total biorefinery capacity, the average transportation distance from the primary landing to the biomass processing facility is 80 km. The feedstock is unloaded, screened and stored in metering bins at the pretreatment facility.

Biomass conversion and biofuel refinery

The analysis presented assumes an integrated biomass conversion facility, where the biomass storage, extraction of sugar from woody biomass and conversion of sugar into bio-jet fuel, are all undertaken at the same location. This study uses a mild bisulfite pre-treatment of the feedstock to liberate the C6 sugars and break down the lignocellulosic material which then is mixed with a cellulase enzyme and hydrolyzed to produce a fully saccharified sugar stream. The fermentable sugars are then converted to isobutanol (iBuOH) using a proprietary bio-catalytic fermentation and oligomerization process to produce bio-jet fuel (iso-paraffinic kerosene, IPK). Therefore, in this study the overall conversion of residual woody biomass to aviation biofuel is separated into four different sub-processes; (i) pre-treatment of residual woody biomass, (ii) enzymatic hydrolysis, (iii) fermentation and oligomerization to produce iso-paraffinic kerosene (IPK), and (iv) boiler, turbogenerator, wastewater treatment and utilities.

Pretreatment of biomass

The complex structure of lignocellulosic biomass (i.e. wood, wheat straw and corn stover) makes it difficult to break down the lignocellulosic material and liberate the C6 sugars to utilize the material in biofuel production (Humbird et al., 2011; Kaparaju et al., 2009). The composition of softwood harvest residue, which primarily includes tops and branches, is composed of 40-45% cellulose, 20-25% hemicellulose (including xylan, arabinan, galactan and mannan), 25-30% lignin (soluble and insoluble) and 8-10% bark and extractives. To dissociate the plant cell wall and remove the lignin in order to improve the accessibility of the enzymes and enhance

the digestibility of the cellulose in the hydrolysis process, a pretreatment stage is necessary (Cara et al., 2006; Chiaramonti et al., 2012; Fan et al., 2006). Accordingly, the feedstock is treated with calcium bisulfite ($Ca(HSO_3)_2$) at 145°C for a residence time of four hours to liberate the hemicellulose (C6) sugars and break down the lignocellulosic material in preparation for enzymatic hydrolysis. The pretreatment stage results in two streams being produced: the first stream, the pretreated pulp, contains the pulp solids and proceeds to the enzymatic hydrolysis department; the second stream, the spent sulfite liquor (SSL), contains primarily soluble sugars, extractives and lignosulfonate, and proceeds directly to fermentation.

Enzymatic hydrolysis

Microorganisms used to convert cellulose into biofuels have limited efficiency in digesting the material because of the complex structure of the polysaccharides constituting the cellulose stream. In order to improve the efficiency of the biofuel production, hydrolysis is generally applied at an industrial scale prior to fermentation (Lin & Hung, 2008). In the enzymatic hydrolysis the lignocellulosic material is mixed with a cellulase enzyme and hydrolyzed to decompose the macromolecules of polysaccharides contained in the pretreated pulp into simple monosaccharides units producing a fully saccharified sugar stream ready for fermentation. The enzymes are produced using purchased glucose and a filamentous fungi strain (Trichoderma reesei), induced with sophorose. The pulp stream from pretreatment (80°C, pH 1.8) is cooled to 50°C and pH is adjusted by lime to a pH of 5.0. The hydrolysis takes place over 72 hours and the released sugars are then used for fermentation into isobutanol.

Fermentation and oligomerization

The fermentable sugars are then converted to isobutanol (iBuOH) using a proprietary fermentation biocatalytic process; the Gevo, Inc. patented GIFT® process. The saccharified pulp biomass and the SSL stream are fermented separately. The fermentation process requires up to 48 hours at 34°C and a pH of 4.3. Beer produced during the fermentation process is then distilled to produce isobutanol. The separated and concentrated isobutanol is dehydrated using a catalyst to produce isobutene. The isobutene undergoes an oligomerization process using another catalyst and is fully saturated with hydrogen to produce iso-paraffinic kerosene (IPK). The IPK produced by this process meets the requirements of ASTM D7566-10a for hydro-processed synthesized paraffinic kerosene (SPK), a blendstock used in jet fuel (Peters & Taylor, 2013). The fermentation residual stillage (FRS) resulting from the fermentation of the saccharified pulp contains the unconverted insoluble solids. The stillage is conveyed to a lignin separator to separate and dewater the solids (mainly lignin) that are sent to the combustor. The SSL stillage is conveyed to the wastewater treatment.

Utilities: boiler, turbogenerator and wastewater treatment

The wastewater treatment process used in this analysis is a closed loop system consisting of anaerobic digestion, aerobic treatment, membrane bioreactor and reverse osmosis. The SSL stillage from fermentation and the water stream from lignin separation of the FRS stillage feed into the anaerobic digestion chamber. In anaerobic digestion, 91% of the organic component is destroyed and 86% gets converted to biogas (the remaining is converted to cell mass). In the aerobic treatment 96% of the remaining soluble organic matter is removed. The digested material is conveyed to a membrane bioreactor, which removes additional organic matter and to a reverse osmosis system for salt removal. Biogas, along with sludge from the anaerobic and aerobic treatment processes, is delivered to the boiler. A grate stoker-fired boiler burns the biogas, sludge, screen rejects, lignin and unconverted solids to generate high-pressure steam which is sent to a steam turbine. The boiler efficiency is assumed 80%. The system produces about 350,000 kg h-1 of steam at 454°C and 6.2 MPa. The turbine has two controlled extractions to deliver process steam with excess steam being condensed to produce electricity. Of the superheated steam produced, 21% is extracted from the turbine as high pressure steam at 1.4 MPa and 272°C to be used in the pretreatment stage and 54% is extracted as low pressure steam at 0.9 MPa and 236°C to be used in the remaining processes. The rest of the steam is condensed at -0.09 MPa and 46°C and pumped back to the boiler. A cooling tower supplies cooling water to the condenser and other processes. A total of 51 MW of electricity is produced by the system. Since the bio-refinery uses 43 MW, the system produces about 8 MW of excess electricity, which is sent to the local electricity grid and an energy credit is attributed to the IPK process.

IPK combustion

The model assumes that 6.818 kg of bone dry clean woody biomass (after screening out ash and fines) produces 1kg of IPK. In the analysis we assumed a calorific value of 43.1 MJ kg-1 for the petroleum based jet fuel of and of 43.2 MJ kg-1 for the bio-jet fuel (Hawkins & Johnston, 2016). Combustion emissions were estimated using the Ecoinvent database for intercontinental air freight since primary data for IPK combustion are not available (Ecoinvent, 2013).

Location of the bio-refinery

The location of the bio-refinery plays a significant role in the overall LCA analysis. There are a number of factors used in the analysis that are location specific, others are specific to the region. The annual feedstock demand for the facility is scaled at 700,000bone dry metric tons of screened woody biomass to produce 112,980 tons of IPK per year. The overall impact of feedstock collection, in-woods processing and transportation to the bio-refinery is heavily dependent on the location of the facility. The LCI data associated with electricity grid, diesel at the pump, baseline jet fuel, etc., are region specific (e.g., for electricity we used the 'Electricity, at eGrid, NWPP', which is recommended for PNW). For the analysis presented in this paper, we used a hypothetical location in Grays Harbor County in western Washington. This site is identified based on its proximity to the feedstock, sufficient for the bioconversion facility of the stated magnitude, and the availability of the support infrastructure and site suitable for building a facility of the proposed scale.

Results

Contribution analysis

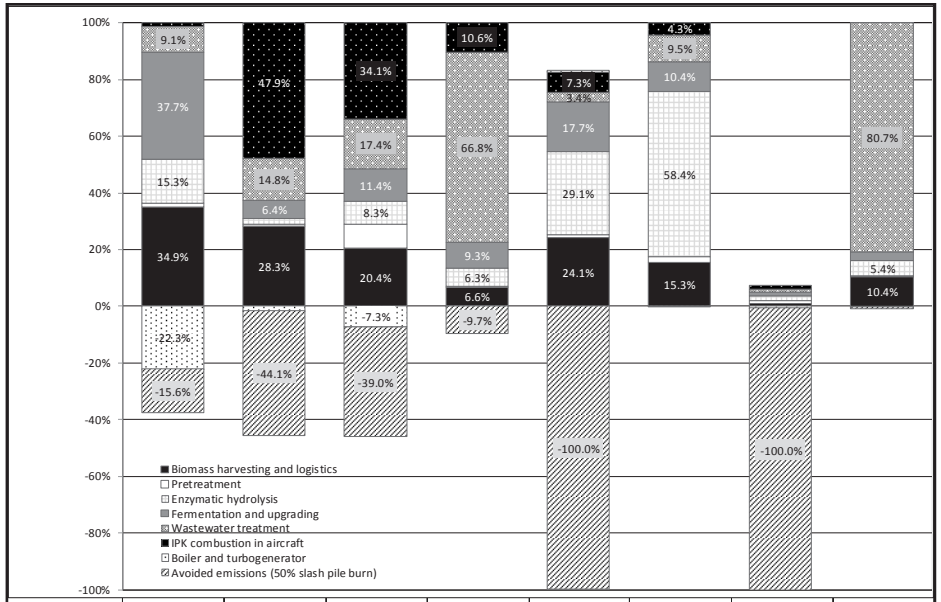
A complete contribution analysis for the woody biomass based bio-fuel sub-processes is presented in Figure LCA-3.2, for the eight TRACI Life Cycle Impact Assessment (LCIA) metrics. The contribution analysis is presented in a percentage scale along the y-axis, which runs from (+) 100% to (-) 100%. The individual TRACI impact categories are presented along the x-axis. To be able to have a perspective on the scale of the emissions, the actual values are also presented in the lower portion of the figure. As can be observed from the figure, some of the sub-processes have a net negative contribution to specific LCIA categories and some net positive. For example, the 'boiler and turbo-generator' process produces excess electricity, after feeding all of the steam and electricity requirements, resulting in a net negative impact in multiple categories, with significant net beneficial (i.e., net negative) impacts in global warming and acidification categories. To calculate the electricity credit, the '*Electricity, at eGrid, NWPP*' LCI data from the US-LCI database is used. The other sub-process with net beneficial environmental impact, with negative impact values in multiple categories, is the avoided emissions, which will be discussed later in this section.

Two of the LCIA categories, carcinogenics and respiratory effects, resulted in net negative value, even after factoring in all the emissions associated with biomass collection, in-woods processing and bioconversion. This is due to the significant negative values associated with the 'avoided emissions' process and highlights the net beneficial effect of avoiding the slash piles in the forests for developing value added impacts. One of the most important differences associated with open burns emissions (like, emissions from pile burns) and emissions from the tail pipe on an aircraft is the $PM_{2.5}$ concentration. As can be observed in the 'respiratory effects' column of the table associated with Figure LCA-3.2, the contribution of the total process related $PM_{2.5}$ emissions, including that of emissions from aircraft operation, operating machineries and transportation of the feedstock, is less than 5% than the avoided $PM_{2.5}$ emissions associated with not burning the slash piles. This specific beneficial effect is characteristic of 'residual' woody biomass based biofuel, and cannot be achieved in energy crop based biofuels.

The results show that fermentation and upgrading phase is the primary contributor to global warming potential, contributing to 37.7% of the GWP, whereas the feedstock collection and in-woods processing contributes 34.9% of the total GWP and enzymatic hydrolysis contributes 15.3%. This relatively high contribution associated with feedstock collection and processing, as compared to other biofuel LCAs (Solli et al., 2009), highlights the logistical challenges and higher impact associated with collection and in-woods processing of the residual feedstock.

All of the energy needs, steam and electricity, associated with the bioconversion process are internally produced within the 'boiler and turbo-generator' process. After producing enough steam and electricity to power the biorefinery, the residual woody biomass to IPK production process produces 15% excess electricity (which is transferred to the grid), which plays a significant role in achieving lower GWP impact. Here it may be noted that the relatively low GWP impact associated with pretreatment can be attributed to the fact that all of the steam required for the pretreatment process is internally produced by the 'boiler and turbo-generator' process, and these energy flows are contained within the system boundary.

According to international LCA standards and guidelines, the release of biogenic carbon dioxide is treated as carbon neutral and does not impact the GWP assessment (BSI, 2011; EPA, 2011; ISO, 2006a; ISO, 2006b; WRI & WBCSD, 2011). In case of woody biomass based bio-jet fuel, woody feedstock is the only source of carbon in the fuel, which is renewable, and is considered carbon neutral. The carbon neutrality assumption of biogenic carbon resulted in low contribution of bio-jet combustion in the overall GWP. After factoring in the net negative GWP impacts associated with the credit from the 'avoided slash pile burns' and the excess electricity, the overall GWP impact associated with the WoTW of 1 GJ of energy produced by fuel combustion is equal to 19.41 kilograms of CO_{2e}, not including the biogenic CO_2 emissions.



	$kg\ CO_{2\,eq}$	$kg\ O_{3\,eq}$	$kg\ SO_{2\,eq}$	$kg\ N_{eq}$	CTU_h	CTU_h	$kg\ PM_{2.5\,eq}$	CTU_e
	Global Warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity
Biomass harvesting and logistics	10.90	4.79	0.15	$9.02 \cdot 10^{-3}$	$1.50 \cdot 10^{-7}$	$1.47 \cdot 10^{-6}$	$3.10 \cdot 10^{-3}$	29.60
Pretreatment	0.45	0.12	0.06	$4.75 \cdot 10^{-4}$	$6.44 \cdot 10^{-9}$	$1.84 \cdot 10^{-7}$	$3.57 \cdot 10^{-3}$	0.57
Enzymatic Hydrolysis	4.78	0.33	0.06	$8.55 \cdot 10^{-3}$	$1.81 \cdot 10^{-7}$	$5.58 \cdot 10^{-6}$	$6.72 \cdot 10^{-3}$	15.35
Fermentation and upgrading	11.80	1.08	0.08	$1.27 \cdot 10^{-2}$	$1.10 \cdot 10^{-7}$	$9.98 \cdot 10^{-7}$	$4.90 \cdot 10^{-3}$	9.04
Waste water treatment	2.85	2.50	0.13	$9.10 \cdot 10^{-2}$	$2.10 \cdot 10^{-8}$	$9.07 \cdot 10^{-7}$	$2.88 \cdot 10^{-3}$	229.40
IPK combustion in aircraft	0.48	8.11	0.25	$1.45 \cdot 10^{-2}$	$4.52 \cdot 10^{-8}$	$4.14 \cdot 10^{-7}$	$4.73 \cdot 10^{-3}$	1.90
Boiler and turbogenerator	-6.97	-0.30	-0.05	$-1.43 \cdot 10^{-4}$	$4.39 \cdot 10^{-9}$	$7.15 \cdot 10^{-9}$	$-2.85 \cdot 10^{-3}$	-1.57
Avoided emissions (50% slash pile burn)	-4.87	-7.46	-0.29	$-1.32 \cdot 10^{-2}$	$-6.22 \cdot 10^{-7}$	$-8.22 \cdot 10^{-9}$	$-3.62 \cdot 10^{-1}$	-1.25
Total	**19.41**	**9.17**	**0.39**	**1.12**	$\mathbf{-1.04 \cdot 10^{-7}}$	$\mathbf{9.55 \cdot 10^{-6}}$	**-0.34**	**283.03**

Figure LCA-3.2. Contribution of the LCA phases to the overall impacts for 1 GJ of energy produced by IPK (no avoided impact).

As can be observed from Figure LCA-3.2, 'eutrophication' LCIA and 'ecotoxicity' LCIA are mostly caused by the wastewater treatment process which releases several compounds in water, such as phosphates, nitrates, furfural, acetic acid, lignosulfonic acid, soluble sugars, and dissolved gases (nitrogen dioxide and sulfur dioxide). Combustion of IPK in the airplane engine is the main contributor to the 'smog' LCIA criterion (47.9%) and is also an important contributor to the 'acidification' LCIA (34.1%). The other impacts associated with the combustion of biojet fuel include, 'eutrophication' impact (10.6%), 'carcinogenics' impact (7.3%) and 'non carcinogenics' impact (4.3%).

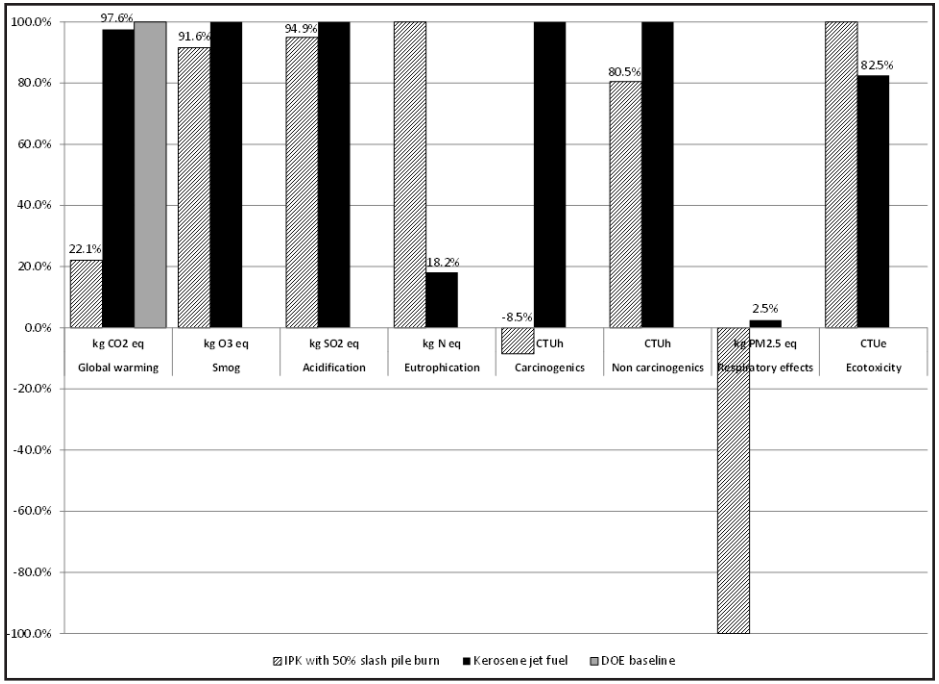


Figure LCA-3.3. Comparison of the LCA results for IPK with and without avoided emissions from slash pile burning and petroleum based jet fuel for a functional unit of 1 GJ.

Comparative analysis: environmental implications of the bio-jet fuel vs petroleum based jet-fuel

For the purpose of the comparative assessment, WoTW LCIA of bio-jet fuel is compared to WTW LCIA of petroleum-based jet-fuel (Figure LCA-3.3). In order to undertake the comparative assessment, a WTW LCA of petroleum based jet-fuel is undertaken using two different data sources. Given the US-LCI database does not have the inventory data associated with aircraft operation, the aircraft emission profile from the Ecoinvent database (Ecoinvent, 2013), a depository of European data, is used[1] for developing an LCI of the petroleum based fuel used in aircraft operation, the inventory data of Jet-A (the predominant petroleum based jet fuel) for Pacific Northwest is created by adapting the Ecoinvent processes to the PNW region, by using US-LCI data for all the sub processes and modifying the supply chain accordingly. The resultant process associated with petroleum based aircraft operation, for PNW, is modeled using Simapro 8.1. It may be noted, that though the U.S. Department of Energy's GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) software has a life-cycle model associated with aircraft operations, for the US, it focuses only on the greenhouse gases and the GWP impact assessment. The GREET software does not provide the necessary data associated with the non-GWP LCIA categories as identified in TRACI. The GWP impact category results

[1] The assumption used in this case is the emission profile of a jet aircraft should remain same independently from the source of the data.

obtained from Simapro are included along with the results obtained from GREET. In Figure LCA-3.3 the baseline petroleum based jet-fuel is indicated as '*DOE baseline*', corresponding to GREET 1.3 GWP associated with jet-fuel. It can be observed that the DOE baseline GWP number is similar (within 3%) of that modeled in Simapro using Ecoinvent data.

As compared to the DOE baseline, the overall GWP impact associated with woody biomass based jet fuel is 22.1% of that of the DOE baseline, which represents a 77.9% reduction in overall GHG emissions, using a 50% avoided slash burn scenario. From the contribution analysis it can be observed that the GWP reduction associated with the slash burn credit contributes to a reduction of 15.6% of the overall GWP impact associated with the WoTW assessment of the biofuel. This relatively low value of GWP credit is due to the fact that the avoided burdens associated with the large quantity of biogenic CO_2 emitted during the slash pile burning is not included in the analysis as per ISO and EPA guidelines. This reduction in the overall global warming potential is primarily due to the avoided CH_4 emissions, which are emitted during the slash pile burn. Hence, even without considering the avoided impacts associated with slash pile burning (i.e. 0 % avoided burn scenario), the GWP associated with bio-jet fuel is 26.5% of the petroleum based option, which would represent a 73.5% reduction in GWP. Hence, the overall reduction in GHG emissions associated with the residual biomass based jet fuel would meet the EISA mandated 60% reduction with or without the avoided slash burn credit.

Compared to fossil fuel, the use of IPK as jet-fuel is not only beneficial in terms of global warming, but also in terms of smog, acidification, and non-carcinogenics. Compared to fossil fuel, there is a net benefit (negative impact) for carcinogenics and respiratory effects. However, the use of IPK is substantially higher on the eutrophication and ecotoxicity impact categories. The conversion process from biomass to IPK releases phosphates to the water, which contribute to eutrophication. Furthermore, the conversion process also releases HCFC 140, dichlorobenzene, ethyl acetate, propanol and butanol into the air. Both the feedstock and the conversion phases are responsible for the release of heavy metals to the water, contributing to ecotoxicity.

Conclusions/Discussion

The WoTW/WTW comparative analysis of petroleum and residual biomass based jet fuel reveals that a 78% reduction of global warming potential can be achieved by substituting petroleum 100% based jet fuel with residual woody biomass based jet fuel. Within the biofuel production process, residual woody biomass recovery and in woods processing play a significant role in the overall carbon footprint of the bio-jet fuel, contributing to 35% of the overall GWP of bio-jet fuel. It may be noted that all the steam and electricity needs associated with the bio-conversion process is internally produced by utilizing the waste-stream, reducing the net GWP impact associated with the bio-conversion process. Moreover, the residual woody biomass to IPK production process produces 15% excess electricity (which is transferred to the local grid), after producing enough steam and electricity to power the biorefinery, which plays a significant role in achieving lower GWP impact.

Apart from the GWP, the key environmental benefits associated with residual biomass based bio-fuel are the avoided slash pile burns which result in beneficial local air quality impacts resulting from a significant reduction of the harmful carcinogens and pollutants from the air resulting in local health benefits. With reference to the LCIA metrics, this is indicated by the net negative 'carcinogenics LCIA' and 'respiratory effects LCIA'. The avoided slash pile burns also contributed to a reduction in the impact on 'non carcinogenics', 'photochemical smog' and 'acidification' LCA impact categories. These positive local environmental benefits make residual woody biomass a much more environmentally appealing feedstock for bio-energy production.

The results of the WoTW/WTW comparative analysis of petroleum and residual biomass based jet fuel reveal that not all LCA indicators favor the biojet fuel. Some of the LCA impact categories, including 'eutrophication' and 'ecotoxicity' impacts, were worse for the biojet fuel. Both water and air emissions of VOCs and heavy metals are primarily responsible for these higher impact factor scores. The next phase of this research aims at modifying the biomass pre-treatment and waste stream handling and treating procedures in order to minimize these emissions.

NARA OUTPUTS

Chen C., Zamora R., Ganguly I., Sessions J., Pierobon F. and Eastin I., (Accepted). Extending the LCA Concepts of Sustainable Forest Product Utilization: Modeling the Collection and Transportation Logistics of Forest Residues using Life Cycle Assessment, Journal of Forestry

Pierobon F., Ganguly I., Sifford C., Ravi V., Alvorado E., Eastin I. and Lamb B., 2016. Environmental impact assessment of prescribed fires incorporating air chemistry and pollutants dispersion in the Pacific Northwest. Oral Presentation presented at WFE, 2016

Ganguly I , Pierobon F.,, Sifford C., Ravi V., Alvorado E., Eastin I. and Lamb B., 2016. Avoided impacts of slash pile burning in the Pacific Northwest. Oral Presentation presented at FPS, 2016.

Ikechukwu C. Nwaneshiudu, Indroneil Ganguly, Francesca Pierobon, Tait Bowers, Ivan Eastin. (2016). Environmental Assessment of Mild Bisulfite (MBS) Pretreatment of Forest Residues into Fermentable Sugars for Biofuel Production, *Biotechnology for Biofuels*,

Ganguly, I. (2015). 'Woods-to-Wake' life cycle assessment of residual woody biomass based jet-fuel. Oral Presentation presented at the NARA annual meeting, Spokane, WA.

Ganguly, I. (2015). 'Woods-to-Wake' life cycle assessment of residual woody biomass based jet-fuel. (Extension: WEBINAR) Woods-to-Biofuels | Webinar Series, October 21, Live Broadcast from Seattle and uploaded on YouTube

Pierobon F., Ganguly I., Sifford C., Ravi V., Alvorado E., Eastin I. and Lamb B., 2015. Environmental impact assessment of prescribed fires incorporating air chemistry and pollutants dispersion in the Pacific Northwest. Oral Presentation presented at the ACLCA Vancouver, October 6-8, 2015.

Chen C., Zamora R., Ganguly I., Sessions J., Pierobon F. and Eastin I., 2015. Extending the LCA Concepts of Sustainable Forest Product Utilization: Modeling the Collection and Transportation Logistics of Forest Residues using Life Cycle Assessment. Oral Presentation presented at the ACLCA Vancouver, October 6-8, 2015.

Pierobon F., Ganguly I. and Eastin I., 2015. Comparative Life Cycle Assessment of NARA BioJet Fuel. Poster presented at the NARA Annual Meeting. Spokane, WA, September 15-17, 2015.

Chen C., Zamora R., Ganguly I., Sessions J., Pierobon F. and Eastin I., 2015. Life Cycle Analysis of the Logistics in Forest Residual Removal for Potential Bioenergy Production. Poster presented at the NARA Annual Meeting. Spokane, WA, September 15-17, 2015.

Sifford C., Ganguly I., Alvarado E. and Eastin I., 2015. Developing an Impact Assessment of Local Air Quality as a Result of Biomass Burns. Poster presented at the NARA Annual Meeting. Spokane, WA, September 15-17, 2015.

NARA OUTCOMES

KEY FINDING:

The findings in this section establish the environmentally beneficial role of residual woody biomass based bio jet fuel to be beyond the mitigation of global warming. A number of feedstock can achieve the GWP goals, but key environmental benefits associated with residual biomass based bio-fuel (a.k.a., NARA biofuel) are the avoided slash pile burns which result in beneficial local air quality impacts resulting from a significant reduction of the harmful carcinogens and pollutants from the air resulting in local health benefits. With reference to the LCIA metrics, this is indicated by the net negative 'carcinogenics LCIA' and 'respiratory effects LCIA'. The avoided slash pile burns also contributed to a reduction in the impact on 'non carcinogenics', 'photochemical smog' and 'acidification' LCA impact categories. These positive local environmental benefits make residual woody biomass a much more environmentally appealing feedstock for bio-energy production.

OTHER FINDINGS:

The research results establish the environmental footprint of woody biomass based sugar as one of the intermediary products. The research results also highlight the critical role of feedstock logistics especially in natural forests with challenging transportation facilities. The research results provide the necessary information for the forest managers to be able to opt for the best in-woods feedstock processing, based on forest location.

FUTURE DEVELOPMENT

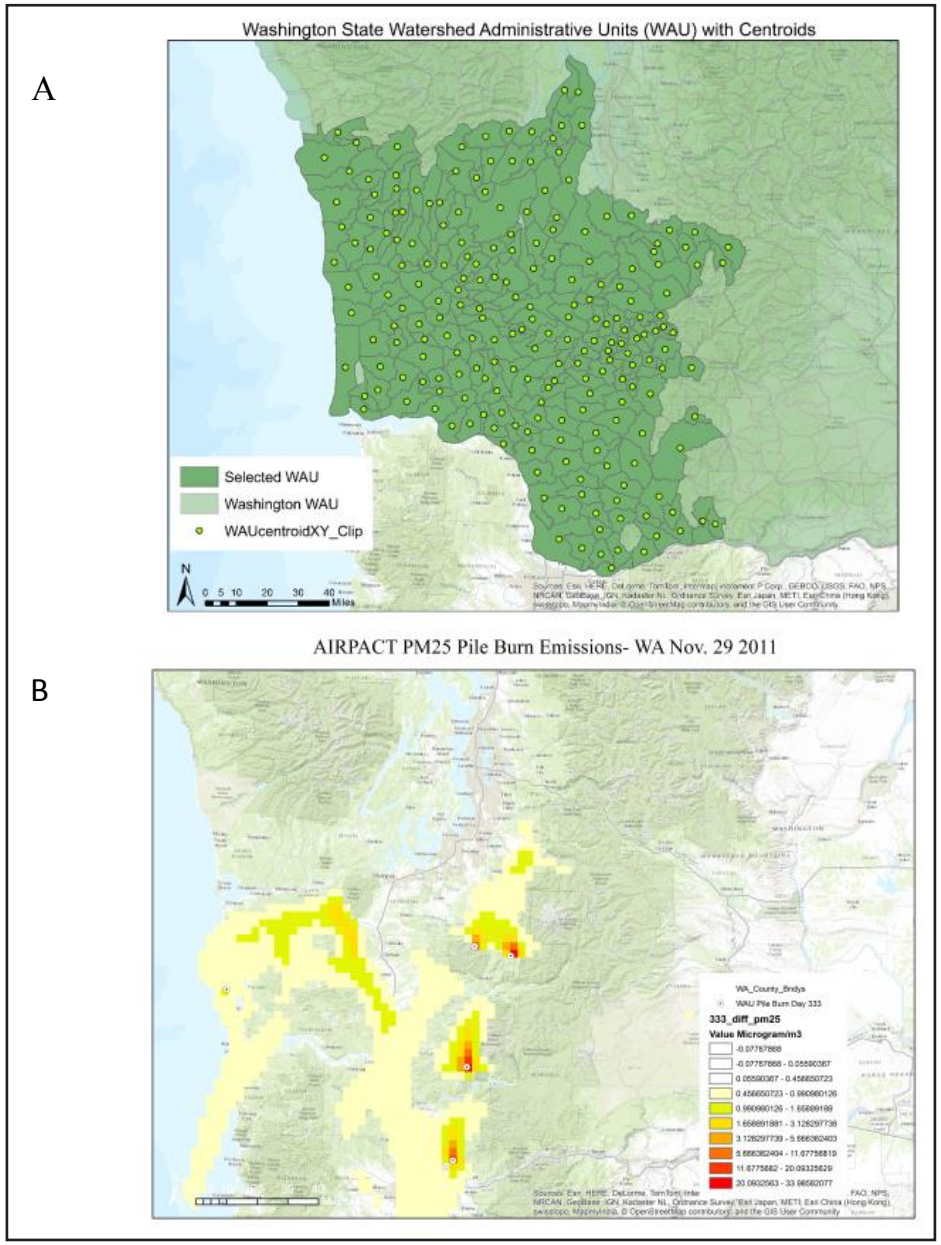


Figure LCA-FD-1. Timbershed distribution (A) and PM 2.5 plume emission from pile burns (B).

The research results presented in the following section are at various stages of being prepared for publication.

Air Quality

Preliminary studies were conducted to calculate the impact on human health as a result of prescribed fires in Washington State. The area of study (Figure LCA-FD.1A) included 214 Watershed Administrative Units (WAU) comprising of 11 counties and 3 timbersheds in southwest Washington. A total biomass supply of ~ 800,000 tons was modeled through the Washington State Biomass calculator and was assumed to be burned in 29 days in 2011. AIRPACT requires location coordinates for the pile burns so locations for the inputs were created in ArcMap. Fire emissions (such as CO_2 or $PM_{2.5}$) were evaluated based on load and combustion conditions using site-specific fire information contained in BlueSky. The pile sizes were modeled as: large (~50-60 tons/pile), medium (~20 tons/pile) and small (10 tons/pile). These sizes were used as inputs for Bluesky to estimate the emissions. BlueSky modularly links a variety of independent models of fire information, fuel loading, fire consumption, fire emissions, and smoke dispersion.

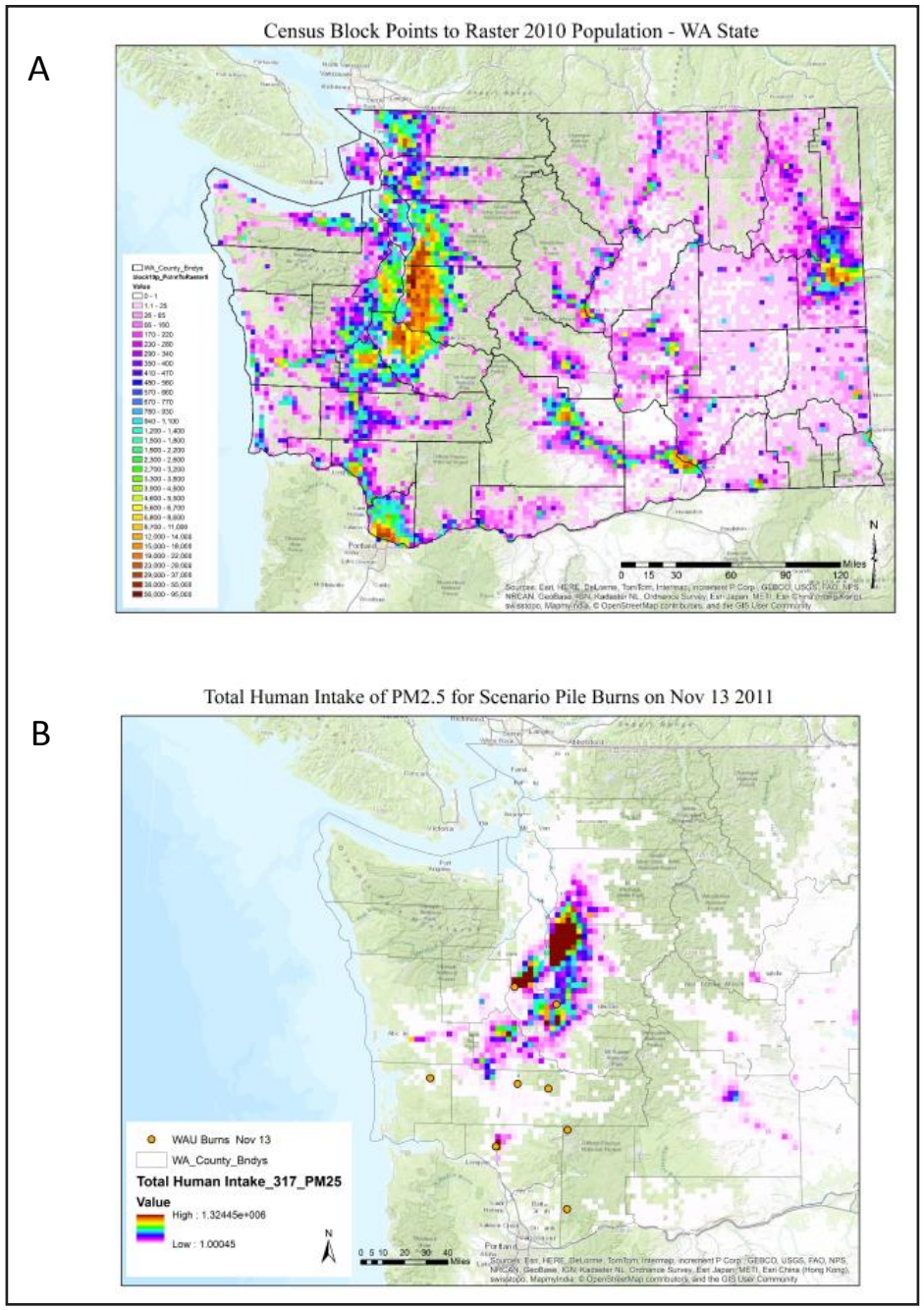


Figure LCA-FD-2. Population distribution (A) and smoke intake (B).

Using BlueSky outputs, dispersion and air chemistry models, the pollutants concentration in the atmosphere was calculated through AIRPACT (Figure LCA-FD.1B). Variables such as wind speed, temperature and precipitation affecting dilution, chemical reaction rates and the removal of pollutants through rain- out were included in the model. The total pollutants human intake (Figure LCA-FD.2A) was estimated by multiplying the pollutant concentrations by the human breathing rate, 13m^3/(pers·d), (USEtox 2.0), then by the total population for each pixel, assessed using census data (Figure LCA-FD.2B). Thee results were the estimated $PM_{2.5}$ intake by the underlying population and were compared to the WHO and EPA air quality thresholds.

Discussion and Conclusion

Results showed an increase in poor air quality in the direct vicinity of the pile burns mainly caused by $PM_{2.5.}$ Depending on the amount of slash burned and the weather, particulate matter also traveled great distances away from the pile burns, reaching densely populated areas such as Seattle and Tacoma, in addition to impacting smaller communities (LCA-FD.3A).

Particulate matter concentrations with the added pile burns exceed several air quality standards over the burn period, some concentrations reaching EPA “very unhealthy” air quality status.

Days when the total (baseline + prescribed burn) 24 hours $PM_{2.5}$ average (highest pixel value occurring anywhere in the state during that day) was greater than:

- 25 microgram/cubic meter (WHO guideline): exceeded 28 out of 29 days
- 35.5 microgram/cubic meter (US EPA guideline “Unhealthy for Sensitive Groups”): exceeded 23 out of 29 days
- 55.5 microgram/cubic meter (US EPA guideline “Unhealthy”): exceeded 13 out of 29 days
- 150.5 microgram/cubic meter (US EPA guideline “Very Unhealthy”): exceeded 2 out of 29 days
- 250.5 microgram/cubic meter (US EPA guideline - Hazardous): exceeded 1 out of 29 days

Additionally, results showed that 3 days of the 29-day pile-burning scenario accounted for 80% of the daily total impacted population affected by pile burn $PM_{2.5}$ concentrations that exceeded the WHO guideline of 25µg/m^3 (LCA-FD.3B).

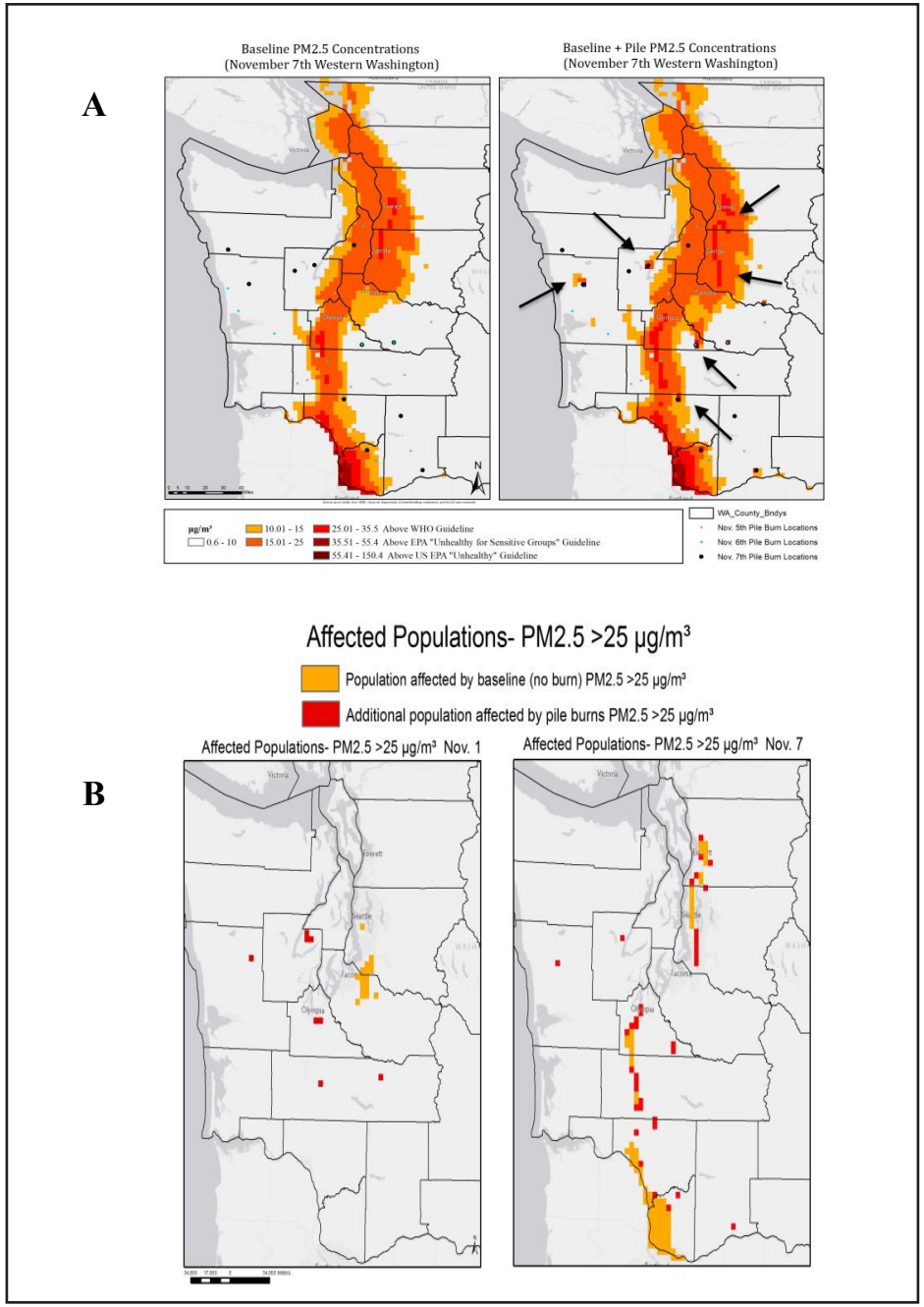


Figure LCA-FD.3. Airpact results obtained for PM 2.5 ambient air quality. A) Baseline PM2.5 concentrations shown with and without pile burns. B) Affected populations by burn and no burn air quality.

In conclusion, this study showed that emissions from slash pile burns are critical at the local level and that policies aimed at promoting alternative uses of biomass could dramatically reduce the impact on human health. In areas where slash pile burning cannot be avoided, best practices in fire management can be identified based on site specific factors, e.g. meteorological conditions, air chemistry, biomass supply, number of piles, size and shape, population density and site morphology. Since these factors are site specific, the application of this method to other regions would be beneficial to know how pile burning affects populations in other parts of the country.

Radiative Forcing Analysis

Objectives

This work aims to propose a methodology to calculate the impact on global warming of biogenic greenhouse gas emissions and sequestration through the Radiative Forcing analysis to determine the effect of introducing a temporal aspect in the biomass based bioenergy impact evaluation. The main biogenic contributions identified are: carbon sequestration, residues decomposition and combustion emissions. The goals of the study are: (i) perform a Radiative Forcing analysis of biogenic greenhouse gas emissions and sequestration of woody biomass bioenergy; (ii) compare the results of the Radiative Forcing analysis for a 50-year rotation period and for a 75-year rotation period and (iii) analyze the effect of the burning ratio in the Radiative Forcing analysis results.

Methodology

The methodology includes the following steps: i) calculation of the emission sources and sinks profiles over time for biomass growth, residues decomposition and combustion emissions; ii) Radiative Forcing analysis, which includes calculation of decay functions, radiative efficiency and Radiative Forcing; iii) application of the Radiative Forcing analysis to the emission profiles, which includes calculation of the emission profile matrices, application of the Radiative Forcing model and calculation of the cumulative effect.

Calculation of emission sources and sinks profiles

Biomass growth

A 75-year period of growth was calculated through the yield table of Douglas-fir plantations (with no thinning) in Inland Northwest Forests, which include northern Idaho, northeastern Washington and western Montana. Two case studies were considered, which assumed to completely harvest the forest respectively at year 50 and 75. In both cases of the total harvested biomass, it was considered that the merchantable biomass was used in the timber industry, while 75% of the residuals was recovered and used for energy production and the remaining 25% was left in forest to decompose. The forest growth was calculated for the whole tree (including stem, top, branches and bark) and the residues ratio was calculated at the year of

harvesting (last year of the rotation period, e.g. year 50). The growth was calculated as the difference of biomass between two subsequent years, divided by the time interval (equal to 1) and espressed in terms of carbon, assuming a carbon content of 50% of the total woody biomass (IPCC, 2006).

Combustion emissions

Greenhouse gases (CO_2, CH_4 and N_2O) emission values were taken from the Ecoinvent database "Wood chips, from forest, hardwood, burned in a furnace 300kW/CH". It was assumed that 100% of the carbon was transferred from solid biomass to the atmosphere to respect the mass balance between the different components of the system.

Residues decomposition

Residues decomposition was modeled through a first order decay equation:

$$C(t) = C_0 e^{-kt}$$

C(t) = biomass present at time t
C_0 = biomass present at time 0 (at the beginning of the evaluation period)
k = decay constant ; k = 1.57 (cite)
t = time

It was assumed that 5% of the total carbon was released as methane and the remaining 95% as carbon dioxide.

Calculation of the emissions profiles

The horizon time of evaluation of the emission profiles was 300 years. All the emission and sequestration sources were assigned to the time when they were released or absorbed and for the number of years they were released/absorbed for each GHG.

Calculation of the Radiative Forcing for a pulse of GHG

Decay functions

The impact of greenhouse gas (GHG) emissions to global warming is calculated through the Radiative Forcing (RF) concept, which is related to the relative abundance of that GHG in the atmosphere and on its Radiative Efficiency (RE). The relative abundance of the GHG in the atmosphere is measured through the decay functions, which tell how long a unit-pulse of GHG will stay in the atmosphere once it has been released due to the environment capacity to transform or remove it from the atmosphere. They depend on the GHG residence time in the atmosphere and its bulk concentration. The decay of a pulse of CO_2 with the time t is based on the revised version of the Bern Carbon Cycle Model and is given by (IPCC, 2013):

$$C_{CO_2}(t) = a_0 + \sum_{j=1}^{3} a_j e^{-t/\tau_j}$$

(a_0=0.2173; a_1=0.2240; a_2=0.2824; a_3=0.2763; τ_1=394.4 years; τ_2=36.54 years; τ_3=4.304 years).

The decay of a pulse of GHG (CO_2 excluded) follows a first order decay equation in function of the lifetime in the atmosphere (IPCC 2013):

$$C_{GHG_i}(t) = e^{-\frac{t}{\tau_i}}$$

τ_i = lifetime of the i-th GHG. The values of the GHGs lifetimes according to the 5th IPCC Report are τ_{CH4} = 12.4 years and τ_{N2O} = 121 years (IPCC 2013).

The lifetimes of different GHGs are listed in Table 8.A.1 of the IPCC 5th Report. The decays of a unit-pulse of CO_2, CH_4 and N_2O are shown in Figure LCA-FD.4.

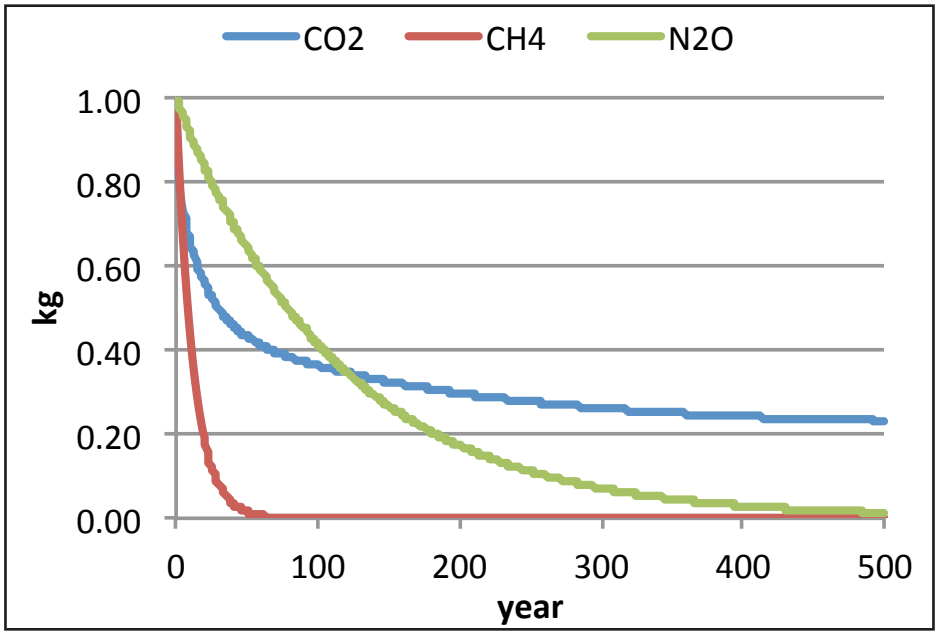


Figure LCA-FD.4. Decay of 1 kg pulse of CO2, CH4 and N2O.

Calculation of the Radiative Efficiency

The Radiative Efficiency (RE) is the RF per unit mass increase in atmospheric abundance of component i and is calculated for a perturbation of 1 unit to the background concentration. According to IPCC 2013, to convert the radiative efficiency values given per ppbv values to per kg, they must be multiplied by $(M_A/M_i)(10^9/T_M)$, where M_A is the mean molecular weight of air (28.97 kg $kmol^{-1}$), M_i is the molecular weight of species *i* and T_M is the total mass of the atmosphere, 5.1352 $*10^{18}$ kg.

Calculation of the Radiative Forcing for a pulse of GHG

The Radiative Forcing for a pulse of GHG was obtained by multiplying the decay function for a pulse of GHG by the Radiative Efficiency of the GHG for each time *t*.

$$RF_{GHG_i}(t) = RE_{GHG_i} \cdot C_{GHG_i}(t)$$

Emissions have a positive RF while sequestered carbon dioxide has a negative RF. The number of equations is equal to the number of GHGs included in the study. In this study, three RFs were calculated, one for each of the considered greenhouse gases CO_2, CH_4 and N_2O.

Application of the Radiative Forcing analysis to the emissions profiles

Calculation of the emission profiles matrices

To apply the RF analysis to the emission profiles, a matrix for each emission/removal source and for each greenhouse gas was defined (emission profiles matrices). In this study six matrices were calculated, one for CO_2 sequestration, three for burning emissions respectively of CO_2, CH_4 and N_2O and two for emissions of CO_2 and CH_4 from decomposition of residues. Each emission profile matrix included: in the rows, the years, and in the columns, the yearly emission/removal profiles. For example, for carbon sequestration, the first row and first column included the CO_2 sequestered by the forest at year 1, corresponding to the biomass growth of the forest for that year. The emission/removal profile was repeated from columns 2 to n, starting from row 2 to n and assigning to the remaining cells the value zero.

Application of the Radiative Forcing to the emission profiles

By multiplying each emission profile matrix by the Radiative Forcing of the corresponding greenhouse gas unit-pulse, the Cumulative Radiative Forcing (CRF) for the source j and GHG i was obtained:

$$CRF_{j,GHG_i} = M_{ij} \cdot RF_{GHG_i}(t) = \begin{pmatrix} y_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ y_n & \cdots & y_1 \end{pmatrix} \cdot \begin{pmatrix} RF_{GHG_i}(t_1) \\ RF_{GHG_i}(t_2) \\ \dots \end{pmatrix}$$

Summing up the CRFs of different GHGs for each GHG emission/removal source, the total CRF_j was calculated for the three contributions: carbon sequestration, burning emissions and residues decomposition:

$$CRF_j(t) = \sum_{i=1}^{n} CRF_{j,GHG_i}(t)$$

Calculation of the net cumulative RF

The Net Cumulative Radiative Forcing (NCRF) was calculated by summing the CRFs of each emission/removal source:

$$NCRF = \sum_{i=1}^{TH} CRF_j(t)$$

The NCRF thus calculated is a measure of the impact of the woody biomass system biogenic carbon emissions and sequestration contributes.

Results

Figure LCA-FD.5 shows the cumulative Radiative Forcing for a 50-year rotation period (A), and for a 75-year rotation period (B), normalized by 1 kg of residues. Three different components - carbon sequestration, burning emissions and residues decomposition - and the total - are represented. Carbon sequestration is represented by the black curve and shows a negative Radiative Forcing decreasing over time. The orange line represents the cumulative Radiative Forcing of burning emissions, including different GHGs (CO_2, CH_4 and N_2O). The green line represents the cumulative Radiative Forcing of residues decomposition, including CO_2 and CH_4. The blue line represents the net cumulative Radiative Forcing as sum of all the contributions.

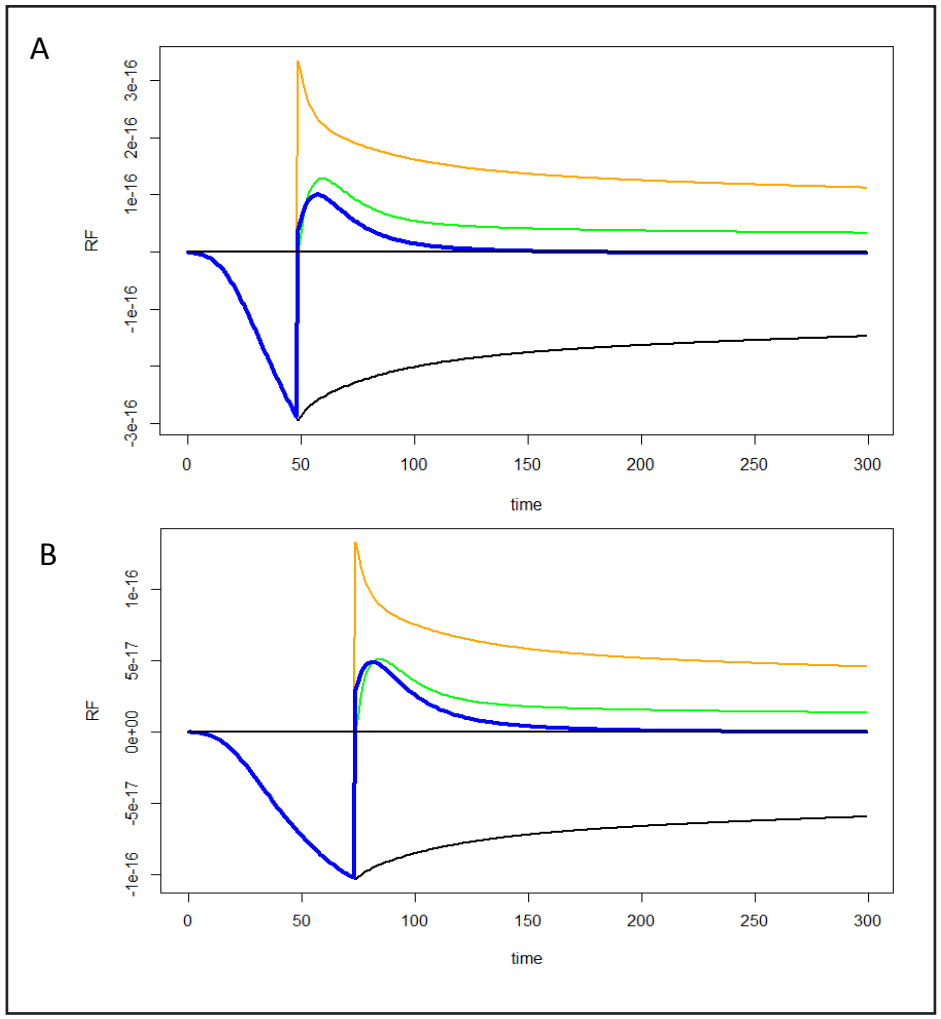


Figure LCA-FD.5. Cumulative Radiative Forcing for a 50-year (A) and 75-year (B) rotation period for a single cycle.

The curves are the result of the sum of the products of the emission/sequestration profiles of each GHG by its decay functions. A pulse of GHG will stay in the atmosphere for a number of years depending on its decay function, e.g. while CH_4 and N_2O completely decay within 500 years, although with different slopes, a pulse of CO_2 emitted at time 0 stays in the atmosphere for over 500 years. Therefore the quantity of GHG that is still in the atmosphere from previous emissions will be summed to the new emissions creating an increasing cumulative effect in terms of Radiative Forcing. It should be noted that the decay function does not describe a physical phenomenon but it is a function that says how long a pulse of emission will stay in the atmosphere given its previous concentration in the atmosphere and the capacity of the ecosystem to remove it, e.g. in case of CO_2 by absorption in the oceans or by trees through photosynthesis or by transfer to the soil. This cumulative effect is responsible for global warming, expressed in terms of Radiative Forcing, which is, therefore, dependent on the concentration of greenhouse gases already existing in the atmosphere and on the overall capacity of the ecosystem to remove them from the atmosphere. Same consideration is valid for carbon sequestration, where the benefit in terms of cooling effect is cumulative, as the reduction of greenhouse gas concentration in the atmosphere positively reflects on the warming effect caused by the emission of an additional pulse of GHG. Summing up the cumulative Radiative Forcing over the horizon time, which is equal to approximate the area under the curve of the net cumulative Radiative Forcing (blue line), we can determine the overall effect on global warming. For one 50-year rotation period, the sum of cumulative Radiative Forcing over 300 years is -2.379003e-15. For one 75-year rotation period, the sum is -1.727329e-15. The ratio between the two cumulative Radiative Forcing for one rotation period is therefore 1.38.

If we consider the repetition of cycles of carbon sequestration, residues decomposition and biomass burning for the 300-year period, which includes five cycles for the 50-year rotation period and three for the 75-year rotation period, the results are shown in Figure LCA-FD.6.

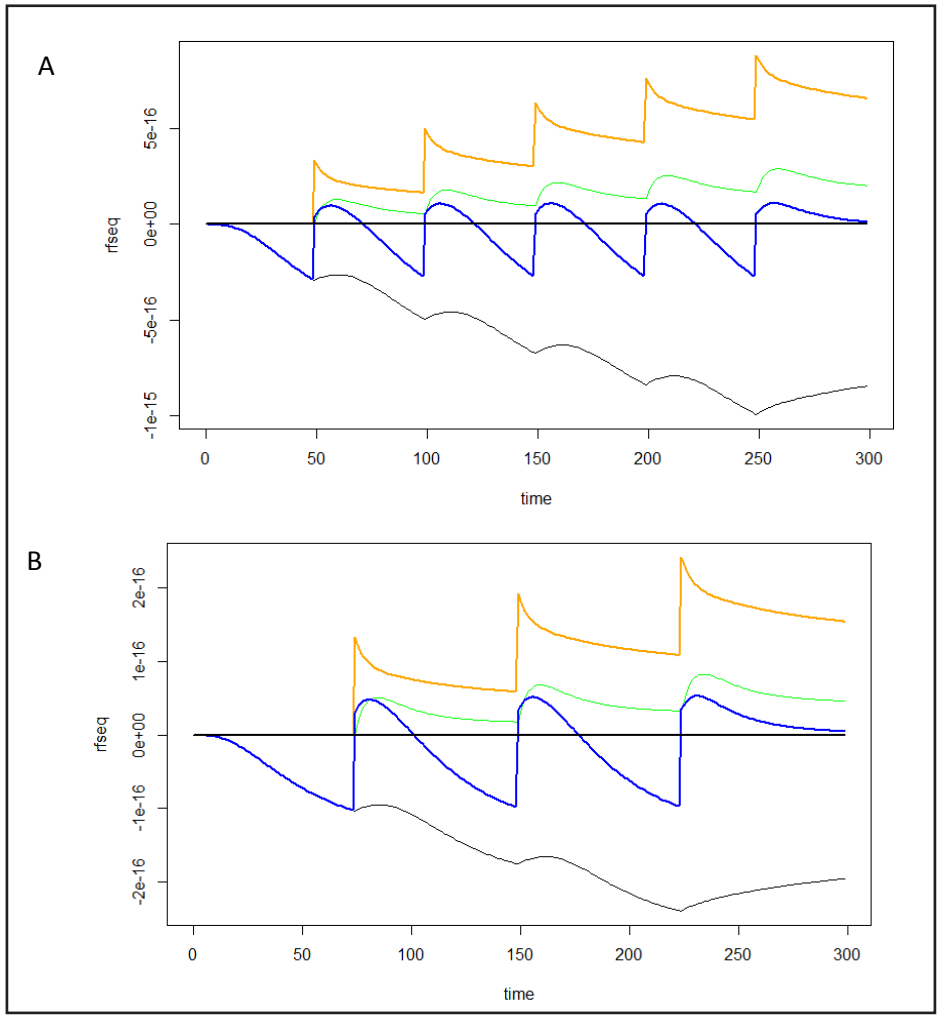


Figure LCA-FD.6. Cumulative Radiative Forcing for 50-year (A) and 75-year (B) rotation cycles for 3 cycles

For the 50-year rotation period (Figure LCA-FD.6A) the net cumulative Radiative Forcing fluctuates between negative and positive values. For the first 50 years the cumulative RF is net negative because only carbon sequestration occurs. At year 50, all burning emissions are released (orange line) and decomposition emissions start (green line). The same trend repeats itself over the horizon time until the last rotation period when only emissions occur. It is possible to notice that the cumulative Radiative Forcing of burning emissions (orange line) increases over time throughout the horizon time. With the assumptions made, the integral of the net Radiative Forcing over time (represented by the area under the blue curve) results net negative in the first rotation period (0-50 years), since no emissions are accounted for, and fluctuates between positive and negative in the following rotation periods (51-250 years) and is positive in the last rotation period (251-300 years) since no forest growth was accounted for to close the mass balance. The values of cumulative net Radiative Forcing were calculated. Turning points (TP), which are the times when the cumulative net Radiative Forcing switches from negative to positive, were also calculated. The total negative cumulative Radiative Forcing, calculated by summing up the negative contributions over the 300-year horizon time, is $-24.93*10^{-15}$ W m^{-2} while the total positive cumulative Radiative Forcing, calculated by summing up the positive contributions over the 300-year horizon time, is $8.15*10^{-15}$ W m^{-2} given a net Radiative Forcing of $-18.78*10^{-15}$ W m^{-2} over the 300 years.

The rotation period is an important factor in this analysis since it determines the year of harvesting and consequently the ratios of merchantable and residues to the total biomass. In general, as the year of harvesting is postponed, the percentage of merchantable increases and the percentage of residues decreases. Figure LCA-FD.6B shows the results of the analysis for a rotation period of 75 years, keeping constant all the other parameters. Compared to the 50-year rotation period, the cumulative Radiative Forcing is overall higher, meaning that the benefit in terms of global warming is lower, with a net Radiative Forcing of $-5.34*10^{-15}$ W m^{-2} over the 300 years. The longer the rotation period, the lower the benefit on global warming, due to the cumulative effect of carbon sequestration as compared to the pulse burning emissions. The ratio between the two cumulative Radiative Forcing of the 50-year rotation period system divided by 75-year rotation period system over 300 years is therefore 3.51. This means that the net benefit in terms of global warming of the 50-year rotation period system is 3.5 times higher than the 75-year rotation period system.

Burning ratio is the ratio between the biomass that is burned to produce bioenergy and the biomass that stays in forest to decompose. In the base case scenario the burning ratio was assumed to be 0.75. Increasing the burning ratio, the percentage of biomass that gets burned increases and the percentage of biomass that decomposes in forest decreases over time. Increasing the burning ratio, the orange line corresponding to burning emissions is shifted up and the green line corresponding to decomposition emissions is shifted down. Overall the net cumulative Radiative Forcing decreases if the burning ratio increases. Therefore we can assert that one time burning of biomass has a lower impact on global warming in the long term than its decomposition on the forest floor. Leaving residual woody biomass on the forest floor to decompose, not only represents a waste of a precious renewable resource, but is also responsible for higher impact on global warming in the long term.

Conclusions/Discussion

In this study a methodology was developed to calculate the impact on global warming of biogenic carbon emissions - including biomass burning and decomposition of residues left in forest - and sequestration, through the Radiative Forcing analysis. As opposed to the carbon neutrality assumption, which is used in the large majority of the studies about the environmental impacts of biomass based bioenergy, and which asserts that biogenic emissions are balanced by carbon sequestration and that their impact on global warming can be neglected, this study shows that the impact on global warming of biogenic contributions largely depends on site-specific conditions, such as type of forest growth rate, type of species, biomass decomposition rates, and on forest management conditions, such as rotation period length and burning ratio. Multiple forest management and burn scenarios were simulated, however, the total cumulative Radiative Forcing was net negative in all the cases analysed. Therefore, for the selected area of study, we can conclude that assuming carbon neutrality represents a conservative assumption. The results show that, reducing the rotation period from 75 to 50 years, the net benefit in terms of global warming over 300 years is 1.4 times higher and, considering the repetition of cycles of carbon sequestration, residues decomposition and biomass burning over the same time frame, the benefit is 3.5 times higher. Moreover, the net cumulative Radiative Forcing decreases if the burning ratio increases. Therefore we can conclude that one time burning of biomass has a lower impact on global warming in the long term than its decomposition on the forest floor and that leaving residual woody biomass on the forest floor to decompose, not only represents a waste of a precious renewable resource, but is also responsible for higher impact on global warming in the long term.

Sensitivity of various co-products allocation methodologies in the overall LCA of IPK

Objectives

In the process of producing bio-jet fuel, the bio-conversion process produces two economically viable co-products, activated carbon and lignosulphonate. Accordingly, allocation of the upstream environmental burdens among the co-products is critical for this research. Allocation in general is defined as partitioning the input and/or output flows of a process or a product system between the product system under study and one or more other product systems (ISO, 2006b). In case of co-products, ISO 14044 proposes a hierarchy of dealing with the allocation issue by (i) trying to avoid any allocation by using system expansion or product subdivision, (ii) if allocation cannot be avoided, ISO protocol suggests using some physical relationships for allocation, like mass, volume or energy, and (iii) using non-physical relationships, like economic allocation, as the least favored alternative. However, this hierarchy is highly controversial and is not universally accepted for a number of obvious issues. This paper presents the significant variations that occur in environmental impact assessment of woody biomass based bio-jet fuel as a result of adoption of different allocation alternatives.

System Boundary

Utilizing a 'Woods-to-Wake' (WTWa) Life Cycle Assessment (LCA) methodology, which is comparable to a well-to-wake LCA for fossil based aviation fuel, this paper assesses the environmental implications residual woody biomass based bio-jet fuel. The bioconversion process presented in this paper uses mild bisulfite (MBS) pre-treatment of the feedstock liberating the C6 sugars which then go through enzymatic hydrolysis, saccharification and fermentation to produce isobutanol (iBuOH). The isobutanol is converted to bio-jet fuel (iso-paraffinic kerosene, IPK) using a proprietary biocatalytic fermentation and oligomerization process. The WTWa environmental impacts of producing woody biomass jet-fuel are then compared to WTWa impacts of producing fossil based jet-fuel (Figure LCA-FD.7).

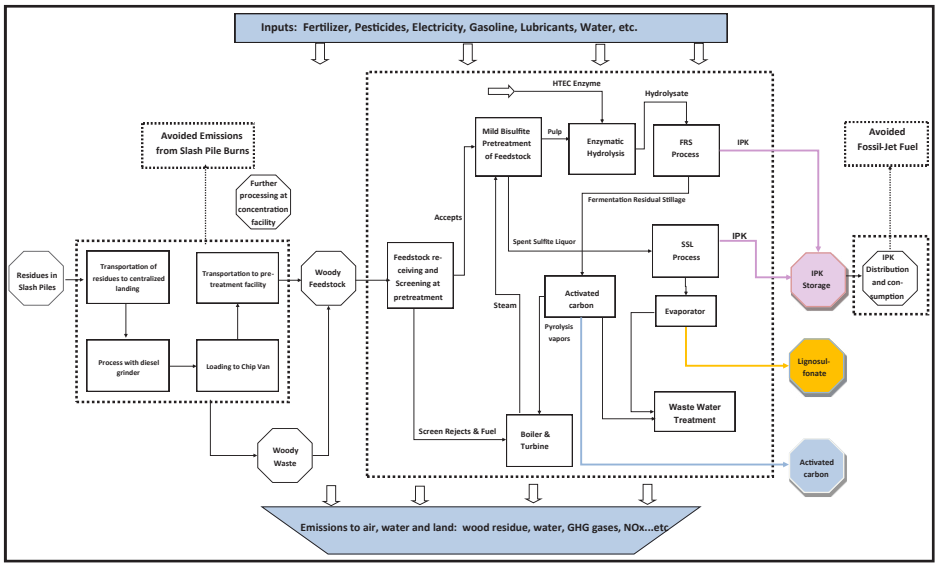


Figure LCA-FD.7: System Boundary of IPK with two co-products

Allocation Methods

LCA definition for co-products:

- Some processes generate multiple output streams in addition to waste streams. In attributional LCAs, only some of these output streams are of interest with respect to the primary product being evaluated.
- The term co-product is used to define all output streams, other than the primary product, that are not waste streams and that are not used as raw materials elsewhere in the system.

LCA burden allocation:

- partitioning the input and output flows of a process or a product system between the product system under study and one or more of the other product systems
- ISO methods suggest the following hierarchy (highly controversial and fluid)
    1. System expansion and avoided credit
    2. Based of physical relationships (mass/volume/energy)
    3. Other non-physical relationships (economic)

Results and Discussion

The results obtained from different levels of avoided biomass burn credit reveal that the primary environmental benefit as a result of avoided biomass burns is than of the local air quality impacts. The significant beneficial respiratory impact associated with avoided biomass burns can be observed from Figure LCA-FD.8. The reduced emissions of various carcinogens in the air also lead to a significant improvement of the carcinogenic health impact. It may be noted that for global warming, carcinogenic and non-carcinogenic impact assessments, bio-jet is clearly the environmentally preferred alternative. However, for respiratory effect, the inclusion of the avoided burn credit tips the balance in favor of bio-jet.

To be able to consider the various levels of carbon storage and displacement credits, the following values are used:

	GHG Avoidance (Credits)
• Activated Carbon (displacement)	1.9 kgCO2e/kg
• Activate Carbon (C Storage)	2.9 kgCO2e/kg
• Lignosulfonate (displacement)	0.28 kgCO2e/kg
• Lignosulfonate (C Storage)	net zero benefit

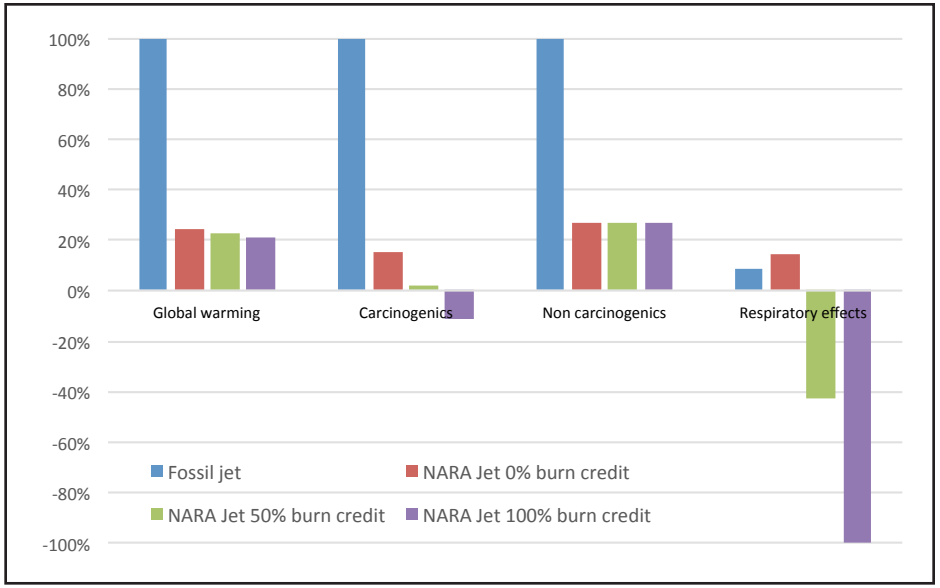


Figure LCA-FD.8. LCA impact assessments for IPK with different levels of avoided burn credit

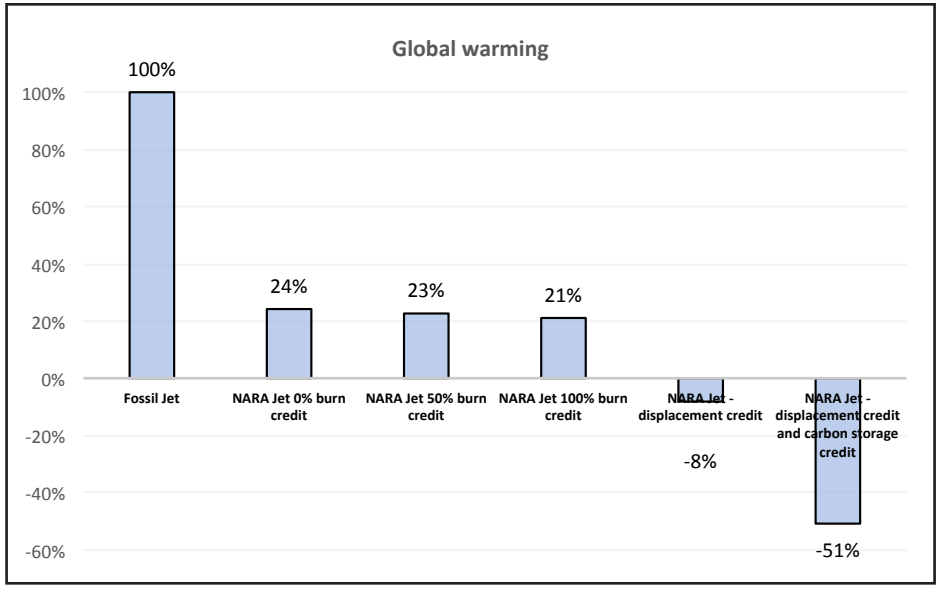


Figure LCA-FD.9. Global warming impact assessments for IPK with different allocation alternatives

As can be observed from Figure LCA-FD.9, GWP impact reduces significantly as we consider the displacement credit and the carbon storage credit associated with the co-products. The reduction is to the level that IPK can be considered a net carbon sink. This indicates that using bio-jet fuel along with its co-products is not only slows down the global warming, but may lead to reversing the negative impacts of global warming.

Conclusions

Meeting EISA targets:

With reduction in GHG number ranging between 76% to 151%, it is evident that NARA BioJet has significantly lower impact than the mandated 60% threshold.

The cleaner NARA IPK is a result of:

- Lower impact and efficient bio-refining process with high recovery rate
- However, the most important is the production of co-products that
    - Share the mass allocated system impacts
    - And/or displaces higher impact or fossil based products

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