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Allexander M. McDaniel for the degree of Master of Science in Biological and Ecological Engineering presented on August 17, 2015

Title: Evaluating the Sustainability of an Advanced Biofuel using Attributional and Consequential Life Cycle Assessments

Abstract approved:

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Attributional and consequential life cycle assessments are useful in evaluating the environmental impacts of a process, product, or decision. Both types of life cycle assessments differ however in their scope and their ability to answer specific questions. In order to fully understand and compare the environmental impacts of a sugarcane versus napier grass derived advanced biofuel production system on Maui, HI both consequential and attributional approaches were undertaken. Results from the attributional approach identified three hotspots existing within the production process; advanced biofuel production, harvesting, and hydrogen production. Using the attributional approach napier grass was shown to have lower environmental impacts than sugarcane in all categories analyzed using the TRACI 2.1 impact assessment methods. Results from the consequential approach highlight the major differences between the two types of life cycle assessments. Under a consequential approach sugarcane showed a lower environmental impact in a majority of impact categories using the same TRACI 2.1 methods. This was mainly due to the displacement of sugar produced form sugar beets and sugarcane in other parts of the United States. The results of this study emphasize the importance of the different choices when implementing a life cycle assessment. Where possible both approaches should be undertaken in order to obtain a more complete picture of the environmental impacts of a product, process, or decision.

Evaluating the Sustainability of an Advanced Biofuel Using Attributional and Consequential Life Cycle Assessments

by
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Allexander M. McDaniel, Author

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Without the support of my parents this would not have been possible. The knowledge that I can always count on you gives me the courage to face problems head on when life throws curveballs. To my mom, through your struggles you taught me to never give up and you continue to inspire me. Dad, you are always the first person to ask how you can help when I am in a difficult situation, I know you would give me the shirt off your back without hesitation if I asked. Despite the rough exterior you are easily one of the most generous people I know. This is a trait I hope to emulate and pass down in the McDaniel family. Donovan, I remember on one of our road trips watching you save a man trapped in a burning vehicle. While everyone else stood around frozen and panic stricken as the situation unfolded, you didn’t think twice to risk your life to save a total stranger. You always taught me to do the right thing even if it isn’t easy, to be brave and bold in the face of uncertainty, because of you I am a better person.

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CONTRIBUTION OF AUTHORS

Allex McDaniel completed the project under the guidance provided Dr. Ganti Murthy. Dr. Andrew Hashimoto was project lead for the Hawaii biofuel directive. Dr. Susan Crow and her students provided data regarding changing soil conditions of field plots. Dr. Richard Ogoshi provided data regarding field inputs from sugarcane and napier grass plots.

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LIST OF ABBREVIATIONS

ALCA – Attributional Life Cycle Assessment

BAU- Business as Usual

CLCA – Consequential Life Cycle Assessment

ET – Ecotoxicity

FAME – Free Acid Methyl Ester

GBEP – Global Bioenergy Partnership

GW - Global Warming

GWP – Global Warming Potential

LB – Liquid Biofuels

LCA - Life Cycle Assessment

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

NREL – National Renewable Energy Lab

PCOF – Photochemical Ozone Formation

PM – Particulate Matter

RE – Respiratory Effects

Introduction

The global population has been predicted to continuing growing from the current 7.2 billion people to between 9.6 and 12.3 billion by the year 2100.[1] The very real possibility of the global population increasing by an astonishing 50% in the next 90 years leads to the question how do we provide food, water, shelter, and energy for all of these people? In our modern society the most heavily used and obvious finite resource is petroleum. Organic matter buried for long periods of time under heat and pressure comprises what we now know as petroleum.[2] The process happens over such a long time period that it is essentially non-renewable. This poses a problem because a staggering number of products we use on a day to day basis are either made from petroleum or have been transported by the use of petroleum. It is safe to say that if we were to run out of petroleum in the near future many aspects of society would be difficult to maintain.

In order to continue evolving and growing it is necessary to either learn to live without petroleum and other limited resources, or to create a substitutable product which is abundant and not finite. Biofuels and bioproducts fit the criteria to replace petroleum because they are renewable and generally derived from agricultural residues or crops bred for that specific purpose, called feedstocks. The methods by which these renewable materials are converted into usable products vary as widely as the feedstocks themselves.

Some examples of common sustainable biofuels are starch ethanol, vegetable biodiesel, cellulosic ethanol, and algal biodiesel. The biofuel of interest in this paper is a novel advanced biofuel produced from lignocellulosic material whose production process is similar to cellulosic ethanol. The sustainability of the advanced biofuel will be evaluated using a technique called life cycle assessment which is discussed in greater detail in the following sections.

Biofuels

Biofuels - liquid, gaseous, or solid - are a form of energy that are derived from organic feedstocks. The focus of this research will be liquid biofuels (LB). There is a highly diverse set of LBs that are produced, each with different advantages and drawbacks. Probably the most well-known and commonly used LBs are ethanol and biodiesel. Both of these fuels can be produced in a multitude of ways with numerous feedstocks. There are also a variety of co-products that are generated, depending on the chosen route of production.

Starch Ethanol

The ethanol industry can be traced back to the oil embargo in the 1970s and began to grow from rising concerns over stable and reliable energy sources.[3] The first generation ethanol biofuel was produced from starch, mainly derived from corn, because of its economic viability.[4] Starch ethanol is relatively easy to produce due to the simplicity of hydrolysis of the α-1,4 glycolytic bond via amylase and α-1,6 bonds being cleaved by glucoamylase enzymes. This hydrolysis yields glucose monomers which are readily fermented to ethanol and CO_2.[4] This process results in relatively high yields of ethanol at a marketable price due to the co-production of other saleable items such as distillers dried grains(DDG) or distillers dried grains and solubles (DDGS) from dry milling or gluten meal and gluten feed from wet milling.[5]

Lignocellulosic Ethanol

Proponents against the development of biofuels have taken issue with the use of food products to produce fuels, as this could create conflicts. This dispute arises from a growing demand for food having to compete with a growing demand for energy. An example of such a conflict is the use of corn starch, which is a food product, and using that starch instead to produce ethanol. This argument has led to the development of the lignocellulosic biofuels, or fuels derived from the inedible portion of crops, called stover for corn residues.[6] While stover is common a feedstock used for producing lignocellulosic fuels other feedstocks such as poplar trees, sugarcane bagasse, switchgrass and ryegrass are also used.[6]

Stover is composed of mainly cellulose, hemicellulose, and lignin, all of which play key structural roles in plants. Cellulose is chemically very similar to amylose, as they are comprised of the same monomer, glucose, with one of the major differences being the type of bond between the glucose monomers. Amylose contains α-1,4 bonds while the cellulose contains β-1,4 bonds. Increased hydrogen bonding between cellulose strands causes cellulose fibers to be extremely tight knit, making the β-1,4 bonds much more difficult to break. The increased protection of the β-1,4 bonds makes cellulose a strong and robust structural fiber. A typical plant composition consists of anywhere between 30% and 60% cellulose by mass.[7,8,9]

Hemicellulose is another carbohydrate polymer common in plants and typically comprises 5% to 40% by mass.[7,8,10] Hemicellulose, in contrast to cellulose, is a heteropolymer commonly consisting of glucose, galactose, mannose, xylose, arabinose, and fructose.[11] The relative abundance of each monomer is highly dependent on plant species and cell type.[11] The most common sugars present in hemicellulose is xylose as it forms the bulk of the backbone.[12] Due to the highly heterogeneous nature and high diversity of sugars, hemicellulose is not able to be fermented to ethanol with the same efficiency as cellulose. Due to the high abundance of xylose in many feedstocks, efficient fermentation of this sugar is crucial for the economic viability of lignocellulosic fuels.[13]

Lignin is highly complex and heterogeneous phenolic polymer that is by far the most recalcitrant piece of the biomass.[14] Lignin cannot fermented by yeast and so after removal of the cellulose and hemicellulose from the biomass the residual lignin is generally burned to produce heat and electricity for the biofuel production process.

Reducing biomass recalcitrance by opening up the structure to facilitate subsequent enzymatic hydrolysis is called pretreatment .[14] Improved enzyme access to the substrates if cellulose and hemicellulose can be achieved using several different methods. Some common methods of pretreatment include liquid hot water, dilute acid, dilute alkali, over liming, and steam explosion.[15,16]

Vegetable Oil Biodiesel

Starch and lignocellulose ethanol are common biofuels; however they are by no means the only biofuels to be found on the market. Biodiesel is also a very common biofuel that can be produced through transesterification of used oils and fats from restaurants or cafeterias.[4] The oil is first strained to remove particulate matter (PM). After obtaining a PM free oil the triglycerides are treated with methanol and sulfuric acid to create fatty acid methyl esters (FAME). Following this step methanol and a strong base, normally NaOH or KOH, is added with more methanol to transesterify the FAME's and produce biodiesel and glycerin.[4,17] This mixture is then easily separated by allowing it to settle for ample time as the density of glycerin and biodiesel are different.

Algal Biodiesel

While repurposing used cooking oil for fuel is feasible for a small group of users, it could not provide enough fuel to be useful on a national scale. This fact has sparked research aimed towards producing lipids, FFAs, in other manners in order to increase the production capacity for biodiesel. A majority of this new research for alternative biodiesel feedstocks has been aimed at high lipid content algae. Many algae contain a high portion of lipids and FFAs for storing energy.[18] These lipids can be transesterified in the same manner as in the vegetable oil biodiesel process.

A highly diverse set of biofuels coupled with the numerous methods to arrive at the final product requires a thorough evaluation of each scenario in order to assess the strengths and weaknesses. This tool must allow consistent comparison and evaluation of environmental impacts and also be able to identify areas in need of improvement, called hotspots, in order to provide researchers an area to focus continued process development. One such utensil is life cycle assessment, which will be the focus of this paper.

Life Cycle Assessment

While closely examining the highly diverse pathways and feedstocks used for producing biofuels and bioproducts one question naturally arises, which pathway and feedstock is best? The answer to this question is complex and highly dependent on the criteria that are considered "best". In order to answer this question, a tool called life cycle assessment (LCA) has been developed, sometimes described as a cradle to grave analysis. LCAs can be used to aid in making decisions between alternative scenarios or hot spot identification within a single process. The type of LCA performed depends on the question that needs to be answered.

Attributional Vs. Consequential LCA

There are two distinct approaches to LCA, each with its own strength and weakness. Attributional LCA (ALCA) aims at quantifying the direct effect of a product on the environment.[19] ALCAs are essentially relationships between average inputs and outputs of a product that can be likened to stoichiometry. These are useful for hot spot identification of within a process, or for carbon counting in order to ensure a product meets certain specific environmental compliance standards. However ALCAs leave out indirect effects that are commonly seen when using LCA in a comparative or decision making context.[19]

Consequential LCAs (CLCA) take into account the direct and indirect consequences of a decision. CLCAs are best used in the context of decision making where the results will be used to impart some change in policy, or product development.[20] However one drawback of the CLCA is the high degree of uncertainty associated with the indirect effects of a decision, leading to a high level of uncertainty in the results of the LCA. In an effort to reduce the uncertainty within CLCA, it is common to use economic models such as partial equilibrium or general equilibrium models.[21] These models inform the changes in supply or demand of a product due to a decision which determines the indirect effects of the decision. A careful choice of the appropriate LCA method to implement is based on the type of question being asked.

Implementing LCA

In an effort to reduce the variability between LCA practitioners the International Standard Organization (ISO) has implemented a set of standards the clearly layout the preferred methodology that should be followed. These standards, ISO 14044 and 14040, clearly lay out how system boundaries should be drawn, and how allocation should be performed, both of these areas introduce high levels of variability.[22,23]

When performing a LCA it is important to have a well-defined goal and scope definition for the study. The goal of the LCA is related to the type of question the study is attempting to answer. The scope is the choice of what must be included in the study to give results that help achieve the goal. This is the first step in the iterative process of performing a LCA.[24] This step is crucial because it will help determine how accurate the results need to be and the type of information needed to contribute meaningfully to the scenario being studied. Therefore the scope and goal definitions have implications for the time and cost required to perform the LCA.[25]

The second step in performing an LCA is to apply the life cycle inventory (LCI). The LCI has many stipulations and requirements that must be carefully executed in order to be considered an accurate representation. When executing an LCI one of the first things that must be done is to define a functional unit. The functional unit is a defined quantity of the product on which the study is focused around. This user defined unit is used as the reference for the LCI and all emissions and waste calculated within the

LCI will be in accordance with the defined amount of product. A careful choice of functional unit definition is needed especially in the case of comparative LCA. In order for a comparison to be valid the functional units must be comparable. An example of such is comparing the results of a LCA for electricity and one for diesel. It would be difficult to compare results for a LCA based around 1000 MJ of electricity to a LCA based around the production of 100 gallons of diesel since the functional units do not agree. However by changing the 100 gallons of diesel functional unit to a volume of diesel that is equivalent to 1000MJ then the systems can be easily compared.

Following the definition of a functional unit a product system is constructed following ISO standards regarding system boundary selection and allocation. The product system is a representation of the entire production process for a product and generally includes acquisition of raw materials, transportation, and refinement but may also include use and disposal, depending on the predefined scope of the study.[25]

Several LCI databases exist with differing quality, regional, and market focuses. There are a few free databases that exist such as the USDA and U.S. LCI databases, the latter of which was developed by the National Renewable Energy Lab (NREL). However the quality of these databases have come under scrutiny because not all processes undergone peer review. Other privately developed databases have undergone critical review such as GaBi and Ecoinvent and provide reliable data.

The LCI is then analyzed by the use of life cycle impact assessment methods (LCIA) where types of emissions and waste are each assigned to a specific category of concern, giving a cumulative score for each category. Some examples of common impact categories seen in LCIA methods are: global warming, ecotoxicity, respiratory effects, ozone depletion, acidification, and eutrophication. While there is overlap between some LCIA methods there are several methods with totally unique categories. The choice of the LCIA method used goes back to the goal definition. When studies are concerned with items such as carbon credits it is advisable to choose a LCIA method with a global warming category. When performing an agricultural LCAs many times categories such as eutrophication and ecotoxicity are the most useful.

The final LCA result is the cumulative effect from each category within the LCIA method. This brings us back to the question of which pathway and feedstock is best. In many cases when comparing different production pathways or materials one method is not better in all categories but only a select few.

The entire process of executing a LCA is iterative and involves interpreting and evaluating results at each step and deciding whether to move forward or backward in the process to achieve the desired outcome (Figure 1).

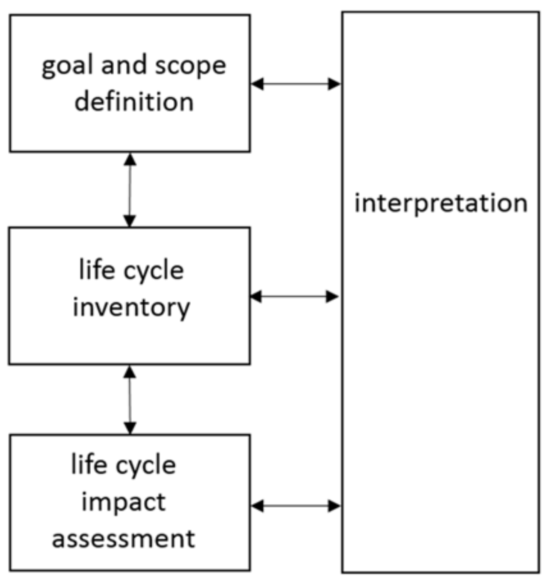

Figure 1: Process of Performing a LCA - A flow chart indicating the iterative process by which a LCA is performed.

Contentious Issues in LCA

The definition of a product system boundary, or system boundary, has been a controversial issue in LCA for many years. The system boundary is the cut-off point for unit processes, which are smaller sub-processes within the larger product system (Figure 2). It can be argued that every product in the world is related to each other through a long chain of relationships. Including all products in the world and their emissions is not feasible to perform accurately, nor is it necessary. Therefore defining a system boundary in a systematic manner is important for LCAs because if a system boundary is chosen arbitrarily, results for the same product system could differ dramatically between practitioners. This would make results from LCAs unreliable and not useful because products cannot be equated "apples-to-apples" which is needed for a fair comparison.

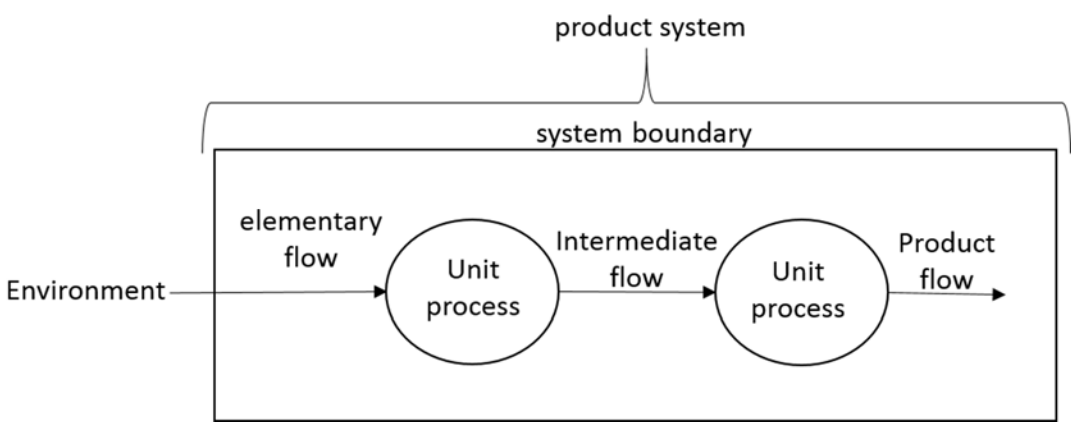

Figure 2: Components of a LCA - A general layout of components names and locations within a LCA

Another provocative issue and important aspect to consider when interpreting and performing LCAs is how co-products are handled.[20] A co-product is a non-waste or emission flow that is produced by a process. One such example is the refinement of gasoline where crude oil is input but the result of refinement consists of kerosene, light gas oil, heavy gas oil, gasoline, naphtha, and residual fuel oil. All of these products are produced during a single process. If performing a LCA of gasoline, it would be inaccurate to attribute all emissions and energy use during the production process solely to gasoline. In order to solve this problem, different allocation methods have been developed to split up the total emissions of a multi-output system in a systematic manner. It is permissible to allocate values based on the relative mass, energy, or economic values of all products that are produced.[26]

Life cycle assessment is a powerful tool that can be used to improve a single process, compare two or more products or services, or evaluate outcomes of a policy change. In order for the LCA to be valid it is essential to systematically follow the procedures set forth to ensure the most accurate results. Interpreting and evaluating the results at every step is necessary in order to continue progressing towards the desired outcome in an efficient manner.

Advanced Biofuel Production on Maui, Hawaii

The Hawaiian Islands lie in the middle of the Pacific Ocean, far from any continent. Their extreme remoteness and limited natural resources necessitate the importation of many items essential to modern life. Crude oil was the most heavily imported commodity, in terms of monetary spending between 2010 and 2013.[27] Nearly six times more money was spent importing crude oil than the second largest import, aircraft. Hawaii's heavy dependence on imported oil is very clear, making it vulnerable to supply shortages if imports were to be interrupted.

The strategic importance of Hawaii to the United States interests in the Pacific gives rise to a need for a steady supply of aviation fuel for use in civilian and military aircraft. The most secure manner to supply a steady stream of fuel is to produce it directly on the islands. Hawaii does not have any known oil reserves and so the only option that enable production of fuel on the islands is by creating a biofuel industry.[28] In this manner Hawaii would be able to establish some level of energy independence.

The largest portion of the Hawaiian economy is attributed to tourism, with people being drawn from all over the world to experience the pristine beaches and coral reefs.[29] Therefore, if a biofuel industry is to be successful here it must not have negative impacts on the environment and possibly indirectly harm the state's largest industry. Maintaining this high quality and valuable environment is of critical importance for the development of a biofuel industry.

One feedstock that can be used to produce biofuel is sugarcane. This is due to high yields per acre and relatively high cellulose content.[30] Maui, Hawaii is home to the last remaining cane plantation on the Hawaiian Islands, totaling 36,000 acres.[31] Currently this plantation not only produces raw sugar at their refining facilities but also generates electricity by burning the agricultural residues, called bagasse, that are left after squeezing the carbohydrate rich solution from the raw cane. This bagasse is then burned and produces sufficient energy to meet all energy and heat needs for the process in addition to producing excess electricity that is sold to the grid.[32]

Napier grass is another promising feedstock that produces high yields and has robust growth. While it is not currently grown on Hawaii, switching to napier grass may prove to be less environmentally detrimental than cane due to different agricultural requirements.

A LCA would help to determine which feedstock will have the least effect on different categories of environmental impacts, and also identify hotspots to assist in sustainable development. The results from such a study have important implications for not only Hawaii's economy, but also for U.S. interests in the pacific.

A Comparative Well-to-Gate Attributional Lifecycle Assessment of Sugarcane and Napier grass for Advanced Biofuel Production on Maui

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In review

Introduction

Due to the limited natural resources on the Hawaiian Island chain and also their extreme remoteness, nearly all of the energy on the islands must be imported. Other than military use, in 2013 Hawaii consumed 875 million liters of aviation fuel, 601 million liters of highway and non-highway diesel fuel.[27] The Islands high demand and the heavy reliance on imported fuel makes them vulnerable to supply shortages. A supply of liquid fuels produced within the state would help increase Hawaii's energy security.

Cellulosic ethanol is a promising technology and has attracted much attention in recent years.[33,34] However it has several drawbacks.[35] A comparatively low energy content of ethanol, 27MJ/Kg, makes ethanol unusable as an aviation fuel.[36,37] To address the energy deficit it is necessary to oligomerize the ethanol, to produce long chain molecules such as those in diesel and aviation fuel with similar energy densities to that of diesel fuel.[38,39] The oligomers then undergo hydrogenation to reach the final high energy product. Here-in this process of producing long chain aviation fuel analogs from cellulosic feedstocks will be referred to as the advanced biofuel process. Another limitation of ethanol is the maximum theoretical yield. In the yeast ethanol fermentation pathway only 51% (w/w) of the initial mass of glucose is captured in ethanol, with the other 49% being lost as CO_2. In contrast an acetogenic fermentation pathway has a maximum theoretical yield of 100% that is captured in the product, which provides a large incentive to explore this avenue of fermentation. The acetic acid can then be used to produce ethanol or other industrially relevant compounds such as ethylacetate.

Proper feedstock selection is crucial for biofuel production in order for the process to be economically and environmentally sustainable. Traits that are characteristic of an ideal feedstock are high yielding, quick growing, low resource inputs, high cellulose content, robust, and is non-competitive with food. The use of cellulosic material as a biofuel feedstock is promising because in this manner the inedible components of the crops become a co-product that also generates revenue. Feedstocks that are of particular interest to this study are sugarcane and napier grass.

Sugarcane plantations, whose main objective is raw sugar production, have a long history on the Hawaiian Islands. During this time its cultivation has been streamlined. Sugarcane plantations in Hawaii operate year round, and harvest only once every two years in contrast to the rest of the world, and is ratooned 2-3 times.[40] The primary objective of the sugarcane industry is the production of raw sugar, with other coproducts such as molasses also being produced as byproducts from the processing of cane into raw sugar. The manufacture of raw sugar produces a fibrous organic material known as sugarcane bagasse, or simply bagasse. The bagasse is generally burned at the refining facilities to provide the necessary process steam and electricity for the sugar extraction process. Roughly 80% of the bagasse is used to meet the energy needs for the refinery and the remaining 20%, corresponding to ~6% of the original harvested cane mass on a wet basis, is used to produce electricity that is exported to the grid for consumption.

Sugarcane bagasse, variety 65-7052, generally consists of 31-43% cellulose, 12-25% hemicellulose, and 23-27% lignin, although it can vary across different cultivars.[30] High cellulose and hemicellulose content make bagasse a potential feedstock for second generation cellulosic fuels. Sugarcane bagasse has undergone extensive research aimed at evaluating its suitability as a feedstock, yielding results that show a promising future [35,41–43]

Napier grass is a C4 perennial grass in the same family as sugarcane, *poaceae*, which is commonly grown in developing countries as fodder for cattle. It is considered an invasive weed in many areas of the United States and therefore is not cultivated for cattle fodder as is common elsewhere. Although not historically grown on the Hawaiian Islands napier grass is a promising alternative to sugarcane derived biofuels due to its proven robust nature, high yields, and ability to grow on marginal lands.

In contrast to the relatively long growth period for Hawaiian sugarcane, napier grass can be harvested every six months. Reported values for the composition of napier grass are; 45.66% cellulose, 33.67% hemicellulose, 20.60% Lignin (Figure 3).[44]

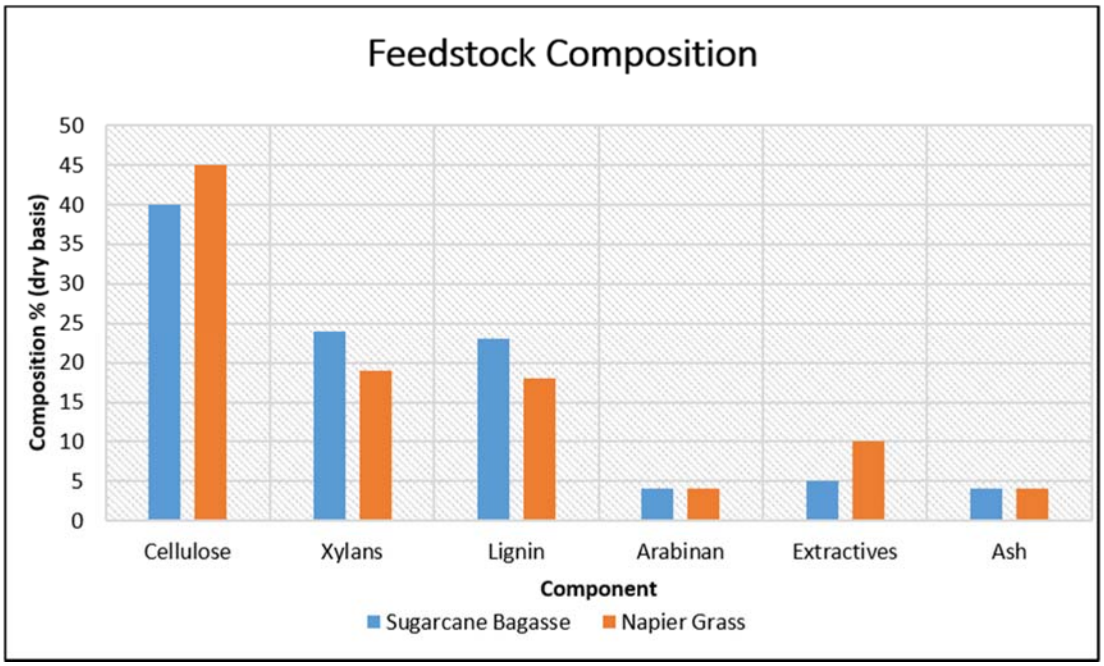


Figure 3: Feedstock Composition [30,44]

Burning of sugarcane during harvest operations releases large amount of particulate matter, and VOC's such as formaldehyde and acetaldehyde.[45,46] Incidents of respiratory diseases and asthma have been shown to be higher in the areas in close proximity to cane burns in brazil.[47,48] Due to this the impact category of Respiratory Effects (RE) is of considerable importance in assessing biofuels produced from sugarcane which requires burning prior to harvesting operations. In addition to the RE category it is also of interest to examine the photochemical ozone formation (PCOF) because ground level ozone is known to have human health effects, particularly respiratory problems, in addition to damaging crops after prolonged exposure.[49]

Methods

Goal and Scope

It is critical to assess the impacts of large scale production of advanced biofuels on the environment and their use of resources including water and arable land. Such an analysis is also essential to identify the most appropriate option among various alternate feedstocks and technology pathways. Quantifying the effects from changes in resource use between feedstocks such as; land requirements, fertilizer and pesticide input, and water use is crucial in order to aid in choosing between potential feedstocks. Therefore this study aims to provide useful information to aid in the sustainable development of a Hawaiian advanced biofuel industry. Specifically this study aims to:

- Assess environmental impacts of biofuel production using sugarcane and napier grass as feedstocks
- Identify unit processes with significant environmental impact

The scope of this study is a cradle-to-gate attributional lifecycle assessment of a sugarcane bagasse and napier grass derived advanced biofuel produced through an advanced biofuel process. The functional unit for both product systems is 1000MJ of energy as Dodecane, which is assumed to be an average of the fuel produced by the advanced biofuel process, and is used as a proxy for aviation fuel. The boundary selection was performed using the RMEE (Relative Mass-Energy-Economic) method with a cutoff value of 5%(Figure 4).[26] This implies that any unit processes whose output stream contributed more than 1.17 Kg, 50MJ, or $1.73 per functional unit is included within the system boundary. The one exception to the system boundary is the acetogenic yeast production which fell within the boundary but was not included due to lack of data regarding their culturing and production.

Co-product allocation was performed using allocation by mass where possible. One exception to this is the advanced biofuel process, which produces a small amount of electricity through waste heat recovery, along with the main fuel product, making allocation by mass impossible. Instead the system displacement method was used for allocation. System boundary is shown in Fig. 4. Furthermore a table displaying all values and sources used to define the system boundary can be found in the supplemental materials section B.

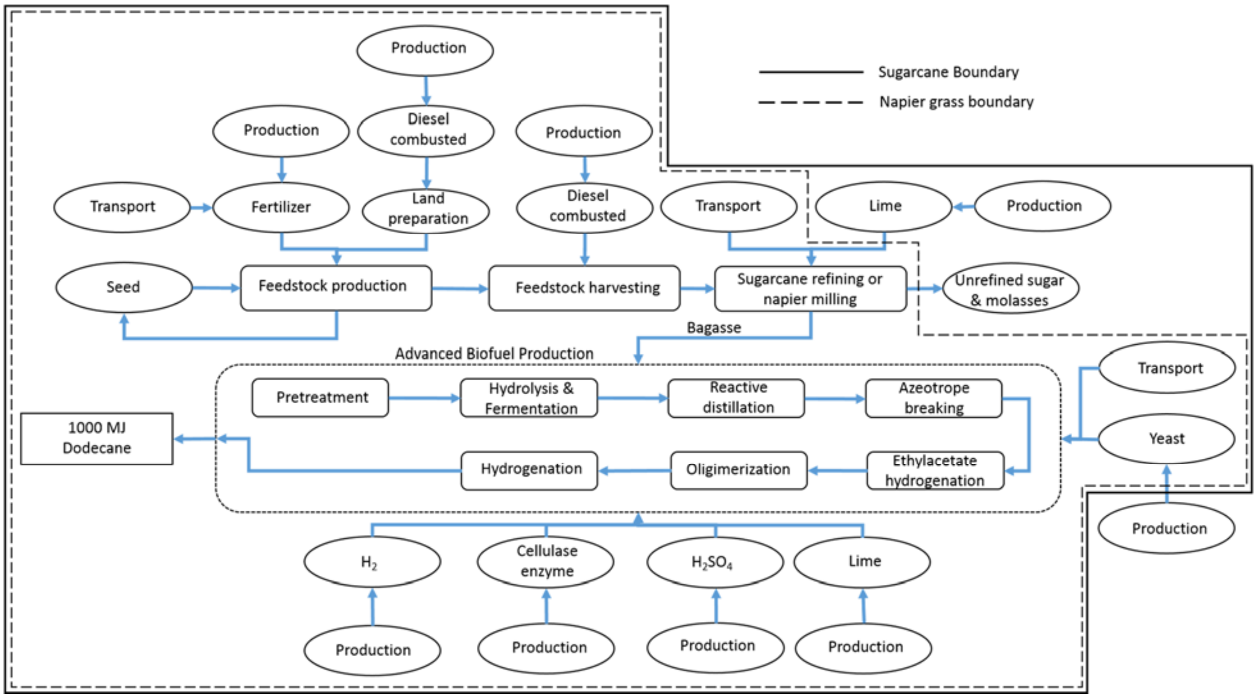


Figure 4: System Boundaries - Block flow diagram of the advanced biofuel product systems depicting the system boundaries of each analysis.

Life Cycle Inventory

Primary Data

Data for sugarcane production, and harvesting operations were provided by Dr. Richard Ogoshi of the University of Hawaii at Manoa (Table I).

Table I: Primary Data - Data collected from field study plots

Biomass Production		
Species	Cultivar	Yield (Tons/Ac*2yrs)
Sugarcane	3792	42.2
Napier Grass	Green	29.3
Chemical Application		
Chemical type	Application Rate (Kg/Ac)	
Urea	344.47	
Lime	1000	
Fuel Use		
Total Diesel 2013 (Gallons)	1409126	
Total Gasoline 2013 (Gallons)	174225	
Total Acres	35556	

Soil emissions during feedstock production and soil carbon data were collected by Dr. Susan Crow and coworkers, from the University of Hawaii, on sugarcane and napier grass plots. The plots contained a majority of Oxisol Molokai soils, at an elevation of approximately 100 meters above sea level.[51] Due to a highly inhomogeneous soil landscape, and high variability in climate on Maui coupled with the heavy dependence of field emissions on soil types and climate these values are not representative of the entire sugarcane plantation on Maui.[52–54] Advanced biofuel production data was obtained from a processes model constructed in Aspen plus software, based on the NREL cellulosic ethanol model that has been modified to have additional processing steps leading to an advanced biofuel represented as dodecane.[55,56]

Feedstock production

Agricultural production includes land preparations, cultural habits, and harvesting. This primary data was all provided by University of Hawaii and Hawaii Commercial & Sugarcane (HC&S) company, and included; fertilizers, diesel and gasoline usage, irrigation volumes, and yields. Sugarcane is assumed to be ratooned three times at two year intervals. Napier grass is assumed to be ratooned six times in six month intervals for a stand life of 3 years. All samples for soil emissions data were collected and analyzed by the University of Hawaii Department of Natural Resources and Environmental Management.[51]

Advanced biofuel production

The process model was adapted from an earlier NREL model for cellulosic ethanol production using dilute acid pretreatment that was modified for a poplar feedstock.[56,55] The input feedstock composition was modified to represent the composition of napier grass and sugarcane (Figure 3).[30,44]The model was constructed in Aspen plus software and was constructed for the production of hydrocarbon fuels through an acetic acid intermediary. The main components of the model include; pretreatment, Hydrolysis, Fermentation, Reactive distillation, Azeotrope breaking, Ethyl acetate hydrogenation, Ethylene production, Oligimerization, and a second Hydrogenation step, in addition to process utilities for heat generation, and waste water treatment.(Figure 5)

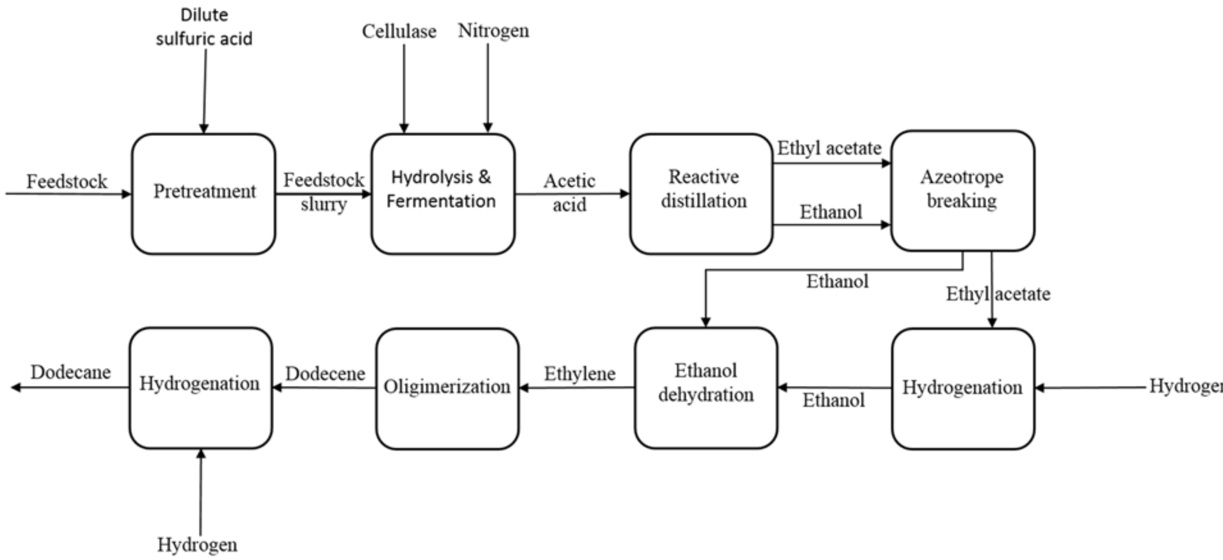


Figure 5: Advanced Biofuel Production Scheme - A block flow diagram depicting the material flows and processing steps to convert the feedstocks to advanced biofuel (dodecane)

Created Unit Processes

Unit processes created for the model can be seen in table's II-VI. Furthermore a table displaying all values and sources used to define the system boundary can be found in the supplemental materials.

Table II: Land Preparation Unit Process

Inputs	Sugarcane	Napier Grass	Units	**Outputs**	Sugarcane	Napier Grass	Units
Diesel	219	219	l	Land Prep	1	1	ac
Planting	1	1	ac				
Labor	3	3	hrs				
Ploughing	3	3	ac				
Rolling	1	1	ac				
100 Hp Tractor	2	2	items				
Rotary Cultivator	1	1	ac				
Gasoline	26	26	l				

Table III: Feedstock Production Unit Process

Inputs	Sugarcane	Napier Grass	Units	**Outputs**	Sugarcane	Napier Grass	Units
Rain	1400	1400	m^3	Feedstock	56	31	tonnes(wb)
Water, Well	74	74	tonnes	Methane	-0.48	-0.70	Kg
Water Fresh	660	660	m^3	Carbon Dioxide	-52	-55	Kg
Land Prep	.125	.125	ac	Dinitrogen Monoxide	0.06	0.08	Kg
Seed	660	460	Kg				
Nitrogen Fertilizer	340	340	Kg				

Table IV: Harvesting Unit Process - values adapted from* [45]

Inputs	Sugarcane	Napier Grass	Units	**Outputs**	Sugarcane	Napier Grass	Units
Feedstock	56	31	tonnes(wb)	Harvested Feedstock	41	28	tonnes(wb)
100 Hp Tractor	2.2E-04	2.2E-04	items	Seed Cane	1.5	1	tonnes(wb)
Diesel	150	150	l	Particulates*	26	0	Kg
Gasoline	19	19	l	Formaldehyde*	1.6	0	Kg
				PAH*	0.10	0	Kg
				Acetaldehyde*	0.50	0	Kg

Table V: Feedstock Processing Unit Process - Values for sugarcane processing adapted from.[57] *Napier grass values have been assumed to be the same as those for the corn milling process from USDA crop data v 1.1 database.*

Inputs	Sugarcane	Napier Grass	Units	**Outputs**	Sugarcane	Napier Grass	Units
Ground Calcium Carbonate	4	0	Kg	Bagasse	420	1900	Kg(wb)
Transport, Diesel Powered	1.1	0.45	t*km	Sugar And Molasses	1.2	0	tonnes
Feedstock	7	2	tonnes(wb)	Nitrogen Oxides	1.5	0	Kg
Phosphoric Acid	0.3	0	Kg	Dinitrogen Monoxide	0.1	0	Kg
Steel for Agricultural Machinery	0	0.82	Kg	Particulates<10µm	0.8	0.3	Kg
				Methane	0.2	0	Kg
				Biological Oxygen Demand	0.0010	0	Kg
				Suspended Solids	0.002	0	Kg
				Sulfur Oxides	0.60	0	Kg

Table VI: Advance biofuel production unit process

Inputs	Sugarcane	Napier Grass	Units	**Outputs**	Sugarcane	Napier Grass	Units
Acetogenic yeast	1200	1200	Kg	Fuel (Dodecane)	1400000	1600000	MJ
Cellulase	1200	1200	Kg	Acetic Acid	10	11	Kg
Transport, Truck, Diesel Powered	81	81	t*Km	Nitrates	6800	6900	Kg
Sulfuric Acid	2400	2500	Kg	Ethanol	2900	2900	Kg
Bagasse	325	340	tonnes(wb)	Hydrogen Sulfide	230	220	Kg
Hydrogen	5800	6300	Kg	Ethyl Acetate	310	320	Kg
Water	1500	1500	m^3	Carbon Dioxide	18	23	Kg
Calcium Carbonate	50	50	Kg	Oxygen	24000	27000	Kg
Ammonia	1700	1700	Kg	Nitrogen	430000	430000	Kg
				Nitrogen dioxide	1300	1500	Kg
				Ammonia	24	24	Kg
				Sulfuric Acid	0.1	0.1	Kg
				Calcium Carbonate	48	48	Kg
				Process Water	1800	1800	m^3
				Hydrogen	0.3	0.3	Kg
				Butene	670	730	Kg
				Ethene	64	68	Kg
				Methane	0.0040	0.0040	Kg
				Sulfur Dioxide	27	33	Kg
				Nitric Acid	0.00040	0.000090	Kg
				Electricity	2300	2400	MJ

Allocation

The proper allocation of co-products is crucial within life cycle assessments. Adhering to ISO 14044 and 14040 guidelines co-product allocation was avoided where possible, however where allocation could not be avoided it was done by mass and system displacement.[22,23] The most critical allocation within a process was within the sugarcane processing to raw sugar. Sugarcane bagasse and raw sugars, with molasses being included with the raw sugar, were attributed 0.26 and 0.74 of the emissions respectively based on the masses of the two co-products (Table V). Allocation was not necessary for napier grass grinding because it produces no co-product. Allocation by system displacement was done for the advanced biofuel production process which produces a net 2313MJ and 2447MJ as electricity per functional unit for sugarcane and napier grass respectively (Table VI).

Life Cycle Impact Assessment

The Life cycle Impact Assessment (LCIA) was performed using the EPA developed TRACI 2.1 methods and was implanted in and OpenLCA version 1.4 framework.[50] TRACI 2.1 includes ten different impact categories (Table VII). [49]

Table VII: TRACI 2.1 Categories -Life Cycle Impact Assessment (LCIA) method categories within the EPA TRACI 2.1 method

Impact Category	Units
Acidification	Kg SO_2 eq
Ecotoxicity (Et)	Comparative Toxic Units (CTUe)
Eutrophication	Kg N eq
Global Warming (GW)	Kg CO_2 eq
Human Health- Carcinogenics	CTUh
Human Health-Non-Carcinogenics	CTUh
Ozone Depletion	Kg O_3 eq
Photochemical Ozone Formation (PCOF)	Kg CFC-11 eq
Resource Depletion-Fossil Fuels	MJ surplus
Respiratory Effects (Re)	(Particulate Matter 2.5µm) Kg PM 2.5 eq

Key Assumptions

All raw sugar produced from sugarcane is sold as a commodity and none was used in the biofuel production process (Figure 4). The moisture content of harvested sugarcane is 70wt%. The bagasse is burned until the heat and electricity needs for the raw sugar production unit process were met, 80% of the bagasse of the leaving 6%wb of the original harvested sugarcane to be converted into biofuels. The filter cake produced during raw sugar processing is assumed to capture 100% of the phosphorus, which is then re-applied to the fields during planting operations.

Sugarcane is assumed to be harvested once every two years while napier grass was assumed to be harvested every six months. Total fuel use for sugarcane and napier production were assumed to be equal due to lack of data in the literature regarding mechanical harvesting fuel consumption for napier grass.

The energy consumed during the advanced biofuel production process is assumed to be derived from the feedstock, 23% of the energy is met by burning residual solids from the process, mostly lignin, and the remaining 77% is produced by burning bagasse. Fuel use was not counted towards emissions and accordingly CO_2 sequestered during plant growth was not incorporated into the study (Figure 6).

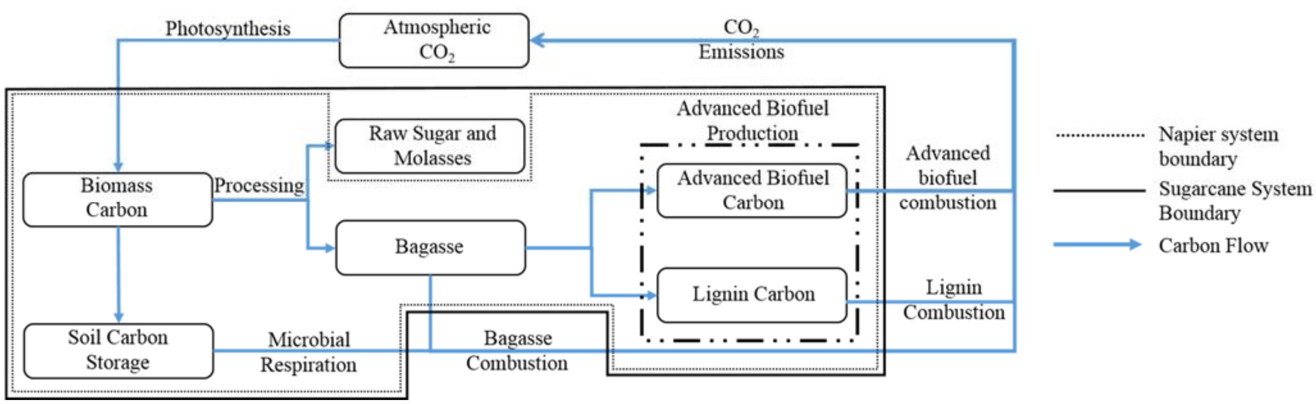


Figure 6: Carbon Balance – Showing carbon flows that were and were not considered in the analysis

Results

A comprehensive list of life cycle impact assessment results can be seen in table VIII. Impact categories considered here are global warming (GW), Respiratory Effects (RE), and photochemical ozone formation (PCOF) due to local concern over cane burning and the global concern over global climate change.

Table VIII: TRACI 2.1 LCIA Results – A complete list results for all categories of the TRACI 2.1 LCIA method

Impact Category	Sugarcane	Napier Grass	Units
Ecotoxicity	9.2	7.3	CTU e
Global Warming	78.0	52.0	Kg CO2 eq
Human Health-Carcinogenic	6.2E-08	6.7E-09	CTUh
Photochemical Ozone Formation	22.0	19.0	Kg O3
Ozone Depletion	1.6E-08	2.1E-09	Kg CFC-11 eq
Respiratory Effects	0.65	0.02	Kg PM2.5 eq
Human Health- Non-Carcinogenic	1.9E-07	7.6E-08	CTUh
Acidification	1.4	1.2	Kg SO2 eq
Eutrophication	1.2	1.1	Kg N eq
Resource Depletion-Fossil Fuels	0.36	0.32	MJ surplus

The total GW emissions for sugarcane and napier grass were 77.4 Kg CO_2 eq/1000MJ dodecane and 52.3 Kg CO_2 eq/1000MJ dodecane respectively (Table VIII). The largest single contributor to the GW impact category is the hydrogen production produced from steam reformation of natural gas (Figure 7). Hydrogen is used within the advanced biofuel production process to reduce ethyl acetate to ethanol and to saturate unsaturated fuel molecules (Figure 5). There was no sizable difference between the two feedstocks for emissions from hydrogen production, sugarcane emitting 32.1 Kg CO_2 and napier emitting 31.5 Kg. Fertilizer use and diesel used for feedstock production and harvesting operations round out the top three GW contributing activities from the two processes, both of these categories are much larger for sugarcane than for napier grass. Nearly 80% of the GW emissions is attributed to CO_2, and 15% due to N_2O produced during the production of fertilizers and sugarcane processing, the remaining 5% is attributed to methane.

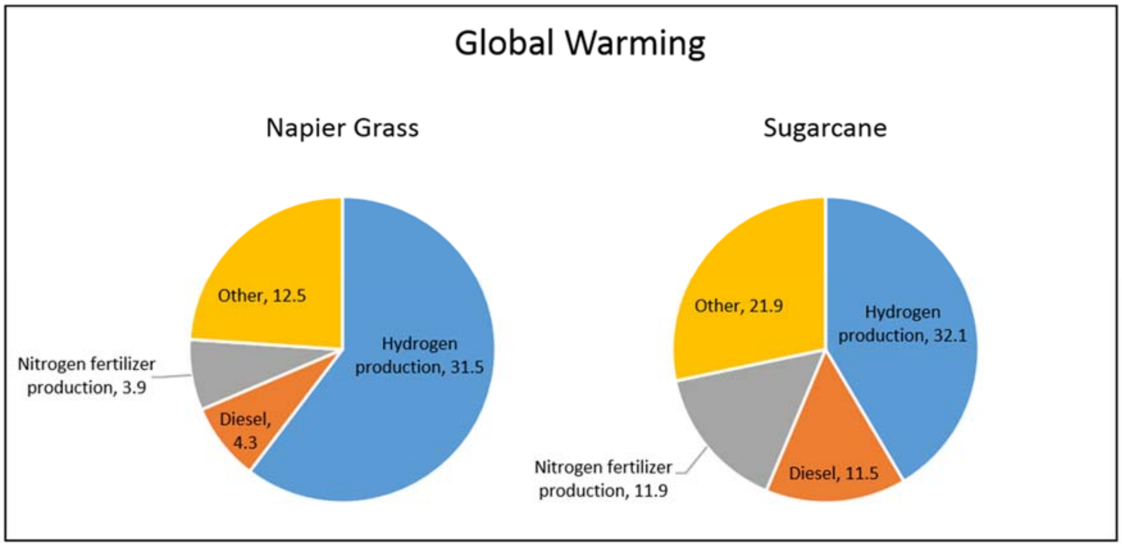


Figure 7: ALCA Global Warming Components - The total global warming emissions (Kg CO_2eq) contributed by each crop used for advanced biofuel production.

Results for RE of sugarcane are over 30 times higher than that of napier, 0.645 Kg PM 2.5 eq and 0.015 Kg PM 2.5 eq respectively. This is overwhelmingly due to the particulate matter released during the burning of the sugarcane fields which accounts for nearly 97% of the total RE from sugarcane. This is a common practice for sugarcane harvesting while napier grass is readily harvested without burning the fields allowing for a much lower RE impact.

A majority of the PCOF category, 69% and 87% for sugarcane and napier respectively, is attributed to NO_2 emissions from the advanced biofuel production process. Other minor contributions to PCOF are from the diesel combusted during harvesting, land preparation, and transportation activities in the form of NO_x (Figure 8).

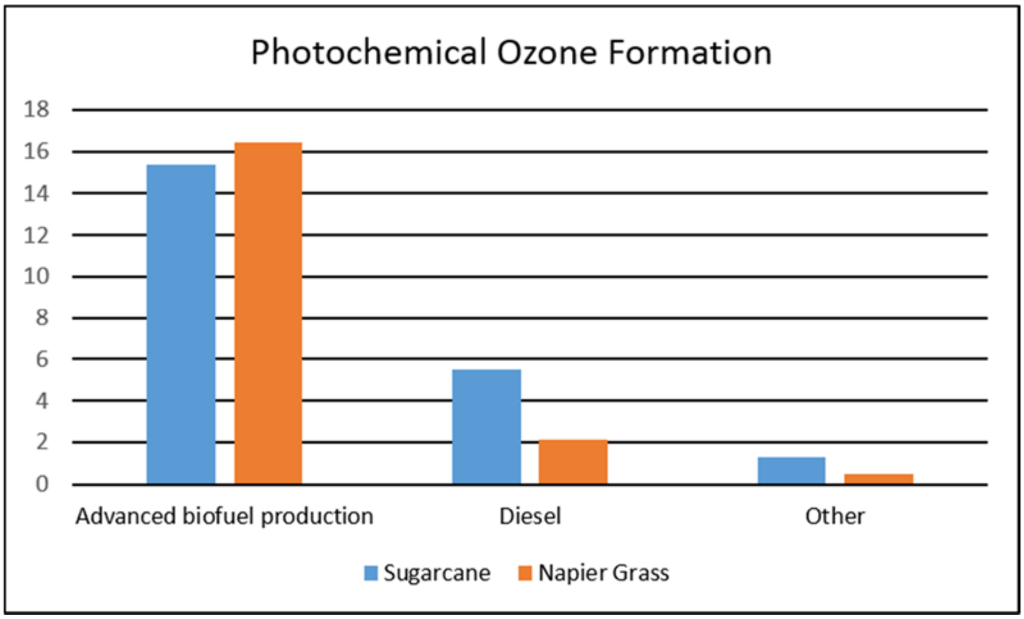


Figure 8: Photochemical Ozone Formation Components - Major process contributions to the overall photochemical ozone formation impact category (Kg O_3 eq)

A scenario in which sugarcane did not undergo pre-harvest burning was also investigated in order to evaluate the potential gains from avoiding this cultural practice (Table IX). The most significant gains are acquired in the GW category although it is still well above napier grass. With the pre-harvest field burning avoided the respiratory effects are on par with napier grass as would be expected.

Table IX: Sugarcane Without Pre-Harvest Burning - Sugarcane and napier impact assessment results under a scenario with no pre-harvest cane burning compared to the baseline scenario

Impact Category	**Sugarcane (base scenario)**	**Sugarcane (No Pre-Harvest Burning)**	**Napier Grass (base scenario)**	**Units**
Ecotoxicity	9.2	8.1	7.3	CTU e
Global Warming	78.0	70.0	52.0	Kg CO2 eq
Human Health-Carcinogenic	6.2E-8	8.6E-9	6.7E-9	CTUh
Photochemical Ozone Formation	22.0	20.0	19.0	Kg O3
Ozone Depletion	1.6E-8	1.4E-8	2.1E-9	Kg CFC-11 eq
Respiratory Effects	.65	0.02	.02	Kg PM2.5 eq
Human Health- Non-Carcinogenic	1.9E-7	1.5E-7	7.6E-8	CTUh
Acidification	1.4	1.3	1.2	Kg SO2 eq
Eutrophication	1.2	1.2	1.1	Kg N eq
Resource Depletion-Fossil Fuels	0.36	0.36	0.32	MJ surplus

There is a relatively high degree of uncertainty within the advanced biofuel process data. This is because the model has undergone only minimal validation of the methods used for conversion of lignocellulosic material into advanced biofuel. This process is only theoretical currently and so direct measurement of emissions and input data is not possible. Therefore in order to account for some of this uncertainty a montecarlo analysis, 1000 simulations, was performed using normal distributions for all flows within the advanced biofuel production process. The standard deviation was chosen so that 95% of the data results in less than a 10% deviation from the mean. Results regarding all three impact categories investigated show they are statistically different (Table X).

Table X: Uncertainty results - Minimum and maximum values, 95% confidence, due to uncertainties within the advanced biofuel production process

Sugarcane			
Category	Mean	Min	Max
GW	77	73	83
PCOF	22	21	24
RE	0.65	0.60	0.69
Napier Grass			
Category	Mean	Min	Max
GW	52	49	56
PCOF	19	18	20
RE	0.015	0.014	0.016

Discussion

GW is also highly impacted by the production of hydrogen used for hydrogenation of the ethyl acetate to ethanol and saturation of oligimers within the biofuel production process. The amount of hydrogen used is sensitive to the feedstock composition, +10% increase in cellulose content led to a ~5% decrease of H_2 consumption. Investigating the hydrogen requirements for different cultivars of sugarcane and napier grass, based on cellulose content, can confirm this result. This could also help to reduce the GW impact category if biofuel production yields can be held relatively constant throughout the different cultivars.

All other major contributors for GW are larger for sugarcane than for napier grass. This is likely due to low bagasse yields after meeting process heat and energy needs. A sensitivity analysis showed that a 10% increase in the bagasse yielded after the processing step leads to a 5% reduction in GW emissions and a 9% reduction in RE emissions. In order to match the emissions from napier the sugarcane processing would have to allow for 260Kg of bagasse per ton feedstock be used for advanced biofuel production, leaving only 40kg's to meet process needs. If another renewable energy source such as wind, solar, or wave energy could be used to meet process energy requirements then sugarcane outperforms napier in several impact categories (Table XI).

Table XI: Sugarcane Processing Alternate Energy Source - Results for a scenario using other renewable resources to meet sugarcane processing energy requirements

Impact Category	Sugarcane (All Bagasse to Biofuel)	Napier Grass (Base Scenario)	Units
Ecotoxicity	8.2	7.3	CTU e
Global Warming	51.0	52.0	Kg CO2 eq
Human Health-Carcinogenic	1.9E-8	6.7E-9	CTUh
Photochemical Ozone Formation	17.2	19.0	Kg O3
Ozone Depletion	3.6E-9	2.1E-9	Kg CFC-11 eq
Respiratory Effects	0.16	.02	Kg PM2.5 eq
Human Health- Non-Carcinogenic	6.2E-8	7.6E-8	CTUh
Acidification	1.1	1.2	Kg SO2 eq
Eutrophication	1.2	1.1	Kg N eq
Resource Depletion-Fossil Fuels	0.35	0.32	MJ surplus

The advanced biofuel production process had the highest contribution to the PCOF impact category. The sizable contribution of the advanced biofuel production process to the overall emissions suggests that this process is an area where efforts to reduce emissions should be focused, particularly PCOF, for either feedstock option. The advanced biofuel process is a newly developed method by which drop-in biofuels are produced, and process optimizations could lead to lower environmental impacts.

As was expected RE is significantly larger for sugarcane with nearly 97%, of the total 0.65 Kg PM2.5eq attributed to pre-harvest cane burning. Avoiding field burning through improvements in mechanical harvesters and pest management strategies is one of the strategies that could be used to reduce this impact. Marked improvements in ecotoxicity and PCOF are seen along with the expected reduction in RE, making the RE category comparable to the napier grass. Furthermore RE can be reduced markedly by using more bagasse for advanced biofuel production and meeting sugarcane processing energy needs with other renewable resources (Table XI).

Conclusions

Sugarcane has more exaggerated environmental effects in all categories, RE, PCOF, and GW, examined in this study. RE is over thirty times higher for sugarcane, 0.65 Kg PM2.5 eq, compared to 0.02 Kg PM2.5 eq for napier grass and is mainly attributable to pre-harvest field burning. If pre-harvest burning is avoided then sugarcane RE is on par with napier grass. Alternatively RE can be reduced a discernable amount by allocating more bagasse to the production of advance biofuel which also improves the GW category. This is because by increasing the amount of bagasse allocated to biofuel production a smaller area of sugarcane must be harvested to produce the same amount of bagasse that is converted to an equivalent amount of advanced biofuel. Using 87% of the produced bagasse for advanced biofuel production puts the GW of sugarcane on par with napier and reduces the RE for cane to just over ten times greater than napier, a significant improvement. The PCOF category is marginally larger for sugarcane than for napier grass. Overall Napier grass appears to have an overall smaller environmental impact when considering the categories relevant to the goal and scope of this study.

Consequential LCA

Introduction

The uses and implementation of a CLCA are very different when compared to the frequently implemented ALCA. During the goal and scope definition phase of LCA it is necessary to make a thoughtful and deliberate choice between ALCA and CLCA. ALCA is most useful for hotspot identification within a process while CLCA is most useful when evaluating a decision that will affect the changes in supply or demand of the product of interest or a similar substitutable product.[19] These two scenarios frequently overlap, and both an ALCA and CLCA are relevant to the study. However, often times only a single type of LCA is implemented. This has important consequences on policy and environmental compliance standards because it allows a relatively large degree of variation in the results. Both methods of LCA have merits and drawbacks but in order to get the most complete picture both types should be performed and weighed against each other.

Some Major differences between ALCA and CLCA are data types, co-product allocation, and their intended use. ALCA's use average data and give an absolute amount of emissions while CLCA gives marginal emissions which are concerned with deviations from the standard situation. In CLCA c-product allocation is avoided and instead system expansion is the preferred method of handling co-products. The intended use of CLCA is also different from ALCA. CLCA's are intended to inform policy makers on the consequences of a decision. ALCA on the other hand is used more frequently for determining hotspots to aid in the sustainable development of a product.

Methods

Goal and scope

The goal of this study is to answer the following two questions: what are the environmental consequences of diverting sugarcane bagasse from electricity generation towards aviation biofuel production? and what are the environmental consequences of replacing sugarcane bagasse with napier grass as a biofuel feedstock for aviation biofuel production?

The scope of this study is a cradle-to-gate CLCA for the production of 1000 MJ of energy. There is no allocation within the product system due to system expansion. The system boundary was drawn using the RMEE method at 5% (Figure 9).[26]

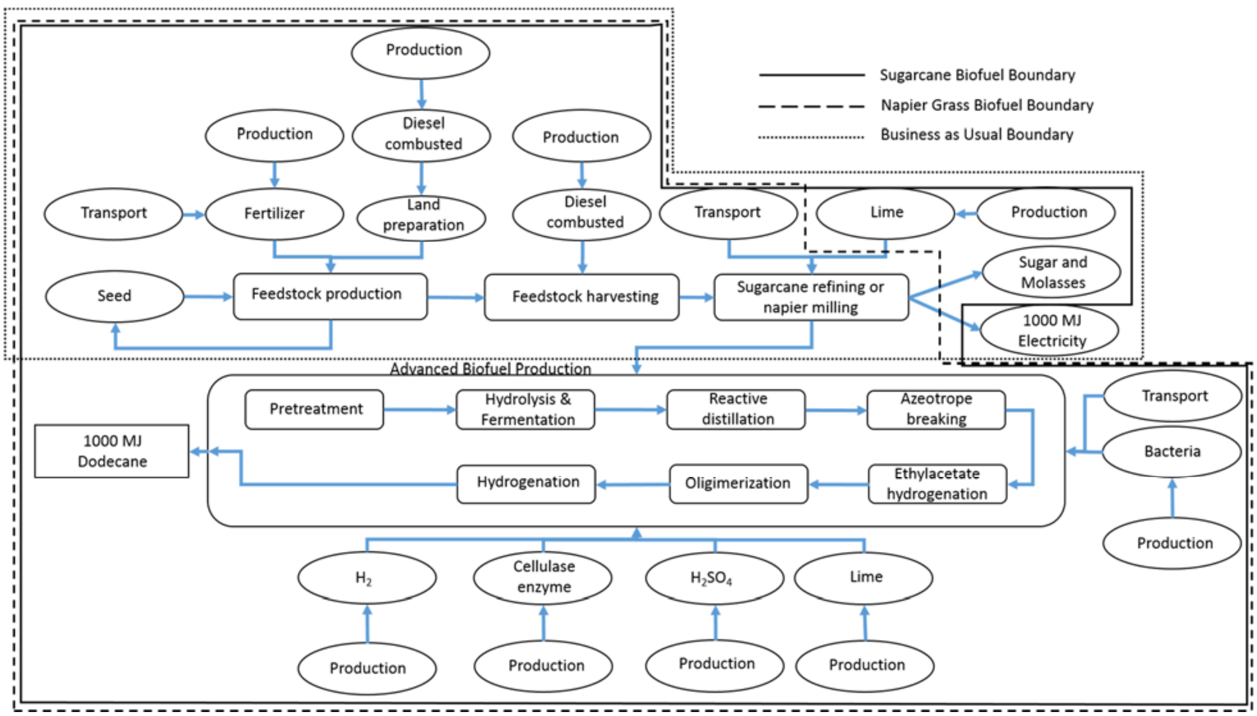


Figure 9: 5% RMEE boundary – Showing the included processes for each scenario investigated

Life Cycle Inventory

The marginal technologies identified were sugar refinement and electricity generation from biomass and the marginal technology used varies between scenarios (Figure 10). System expansion was used to avoid allocation as is suggested for CLCA.[58] The expanded system used substitutable products consisting of electricity and sugar produced from 50.6% sugar beet and 49.4% sugarcane which is representative of the US sugar market.[59] The sugar beet sugar and sugarcane sugar processes data are average data for the rest of the world, from the Ecoinvent 3.1. The increased electricity production was assumed to be the HI electricity mix that is represented in the NREL USLCI database, but was adapted by removing the portion of electricity produced from biomass which is all assumed to be produced by burning of bagasse (Table XII).

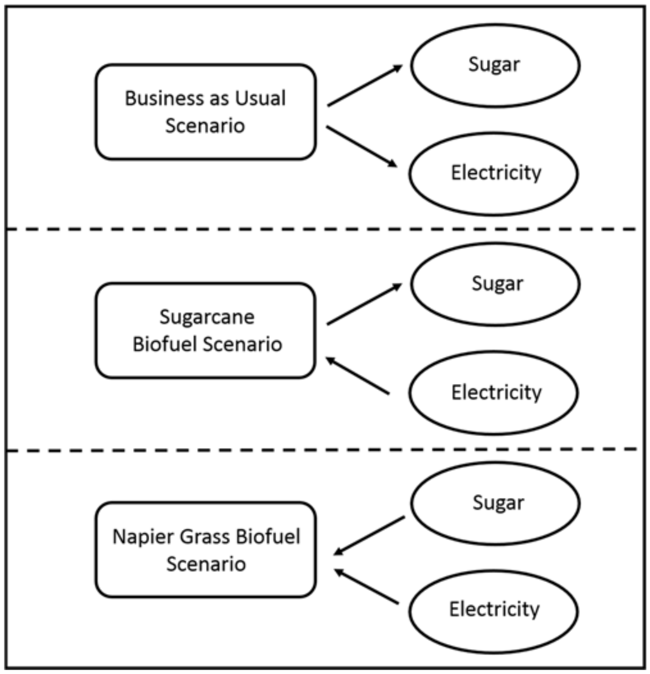


Figure 10: Marginal technologies - Each scenario has different marginal tehcnologies. An arrow pointing to one of the marginal technologies indicates maintianing current capacity, while an arrow away from the marginal technology indicates the increased production of a substitutable good.

Table XII: Modifications to NREL USLCI "electricity, high voltage - HICC" - Showing only the modifications made to the standard NREL USLCI unit process. All other flows present in the process were kept constant.

Inputs	Value	Unit	Outputs	Value	Unit
Biowaste	0	km	CO_2 - biogenic	0	kg
Sugarcane Bagasse	0.511	kg			
Electricity - HICC	-1	kWh			

First a "Business as Usual" (BAU) scenario was developed to act as a baseline of comparison. In this scenario the excess bagasse produced during the sugarcane refinement process was used for generating electricity at a cogeneration facility, giving the maximum capacity of 16 MW.[27]

The second scenario investigated is the "sugarcane biofuel" in which the bagasse is diverted away from electricity production and is instead used for advanced biofuel production. The consequence of this is an increase in the production of electricity derived from other sources, mainly petroleum and coal, in order to make up for the deficit caused by the decrease in biomass derived electricity.

The final scenario investigated, "napier grass biofuel", uses all 36,000 acres of the sole remaining sugarcane plantation in HI. This land is repurposed to grow napier grass in order to produce advanced biofuel. Substitutable products for system expansion were sugar and electricity in this case.

All of the product systems were built and implemented in OpenLCA 1.4 and using a functional unit of 1000MJ of dodecane, the same functional unit used in the ALCA, in order to allow comparison between the results of both LCA studies. A multitude of databases were used to complete data gaps, although Ecoinvent 3.1 was used where possible. Data regarding enzyme and HI electricity production was adapted from the NREL USLCI database. For a complete list of values used for created unit processes regarding sugarcane production practices, sugar refining, and electricity please refer to Tables III-VII and Table XII.

Life Cycle Impact Assessment

The LCI was analyzed using TRACI 2.1 impact assessment methods. The main categories examined here are the GW, PCOF, and RE categories. This allows comparison of results obtained for the CLCA to be compared to results for ALCA.

Key Assumptions

It was assumed that the demand for crude oil, electricity, and sugar are totally inelastic and supply will adjust to meet demand. These assumptions were made based on the size of the Maui, HI market in comparison to the global markets for these goods. It is also assumed that crude oil imports will not be affected and that the crude oil will be used for producing electricity rather than be refined into aviation fuel.

Results

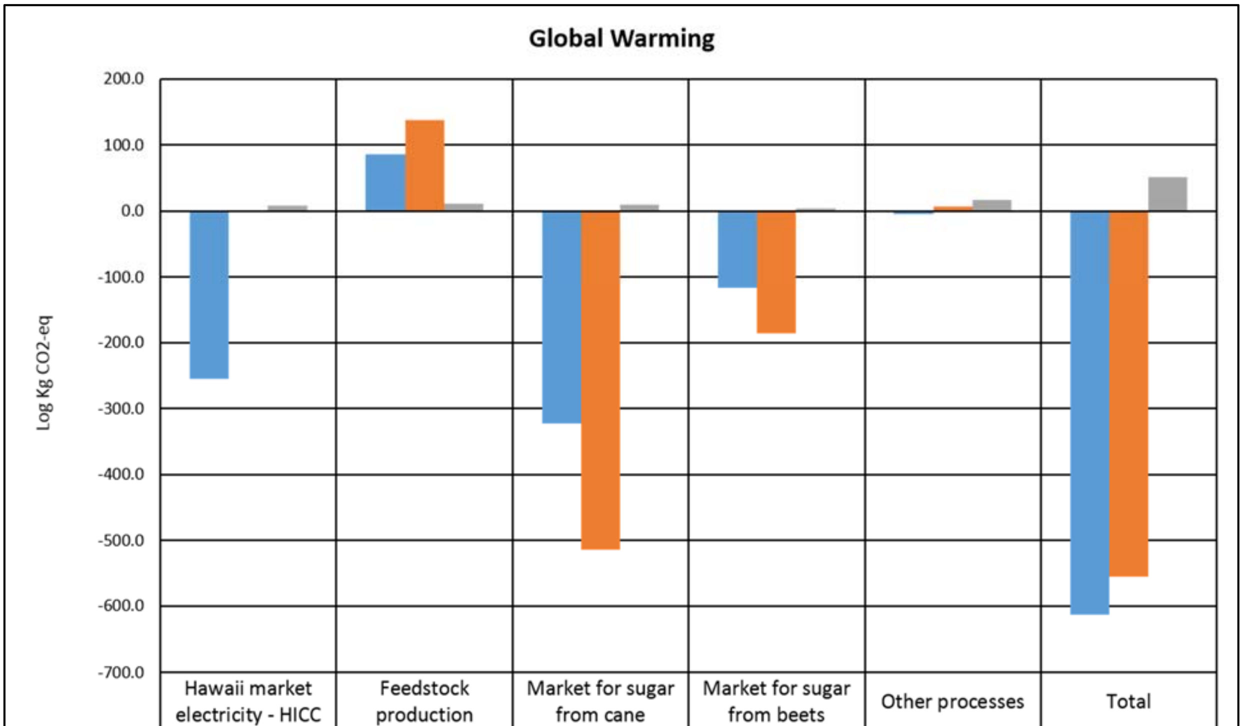
The BAU scenario had the least environmental impact towards global warming and ecotoxicity when compared to the other scenarios. It had a higher score than napier grass, but lower than the sugarcane scenario, for respiratory effects. (Table XIII)

Table XIII: CLCA TRACI 2.1 Results – A full list of results for all TRACI 2.1 categories

Impact category	BAU	Sugarcane	Napier	unit
Ecotoxicity	-1469.6	-885.7	132.20	CTUe
Acidification	-1.8	0.1	1.20	Kg SO2 eq
Eutrophication	-2.1	44.2	41.80	Kg N eq
Global warming	-613.4	-555.7	51.70	Kg CO2 eq
HH - non-carcinogens	-4.1E-05	-8.3E-06	4.8E-06	CTUh
Respiratory effects	1.4	2.3	3.1E-02	Kg PM2.5 eq
Resource depletion - fossil fuels	-13.9	106.9	82.40	MJ Surplus
Photochemical ozone formation	52.4	17.6	19.10	Kg O3 eq
HH - carcinogenics	1.3E-05	-1.5E-06	1.1E-06	CTUh
Ozone depletion	-1.0E-05	-2.8E-06	3.6E-06	Kg CFC - 11 eq

Significantly, the napier grass biofuel scenario was the only one investigated here which yielded a positive result for GW and ET, indicating net emissions into the environment. Napier grass had a non-negative score on the results in each GW component, meaning there was a net output of CO_2 (Figure 11). Another notable result is the two orders of magnitude difference of results regarding respiratory effects when comparing napier grass biofuel to both of the sugarcane scenarios due to the lack of pre-harvest burning of napier grass.

A large majority of the GW impact category in all cases was due to either the displaced production or increased production of sugar from alternative sources (Figure 11). There was also a significant CO_2 savings in the BAU scenario from the displacement of electricity produced from petroleum and coal by electricity produced from biomass.



	Hawaii market electricity - HICC	Feedstock production	Market for sugar from cane	Market for sugar from beets	Other processes	Total
BAU	-254.8	86.5	-323.3	-117.2	-4.6	-613.4
Sugarcane	0.4	137.7	-514.3	-186.5	7.0	-555.7
Napier	8.3	11.4	10.5	3.8	17.6	51.7

Figure 11: CLCA Global Warming Components - Showing the major contributions to the GW category for all scenarios

Discussion

The scenario with the smallest environmental impact is the BAU if we regard GW and ET as the most important categories. The BAU scenario provides an additional 58 Kg of CO_2 eq savings per 1000 MJ when compared to the next best option, the sugarcane biofuel scenario. The napier grass biofuel scenario yields the highest GW score. The main cause of this is a need to increase in sugar production, from sugar beets and sugarcane, nationally and internationally. The data used in this examination shows that the sugar production process in Hawaii is much more efficient than elsewhere, giving large GW savings under both scenarios in which sugar is a co-product. Another interesting point to note is the relative magnitude of the napier grass biofuel scenario when compared to both sugarcane scenarios. All major GW contributors for napier grass are significantly smaller in magnitude than either sugarcane scenario. This is attributed to the large amount of bagasse burned to meet sugar refining energy needs, leaving relatively little bagasse for fuel production while all of the napier grass is used to produce advanced biofuel.

The ET results provide nearly two times the savings under the BAU scenario as compared to the sugarcane biofuel scenario. Similar to GW the major savings in ET were due to improved practices in HI for sugarcane processing and with large savings from biomass electricity production when compared to the HI electricity mix consisting mainly of petroleum and coal.

Interestingly, the BAU scenario has a lower RE score than the sugarcane biofuel scenario. This is due to a decreased biomass to energy conversion efficiency under the sugarcane biofuel scenario when compared to the more efficient BAU scenario. Decreased efficiency translates to more biomass required to produce an equivalent amount of energy. However despite the fact that the RE score is higher for the sugarcane biofuel scenario than the BAU scenario, the total actual RE effects due to cane burning would be the same. Due to geographically constrained production of sugarcane on the islands there is little room to expand cane fields, meaning that the total available land area for production must remain constant. This fact necessitates that the total RE score for each process are the same, because both cases have the same amount of sugarcane land available for cultivation, and only the emissions per 1000 MJ differ because of different energy conversion efficiencies.

Conclusion

The most environmentally friendly scenario, in terms of GW and ET, is the BAU in which biomass is burned for electricity, displacing grid electricity consisting mainly of petroleum and coal. This scenario also displaces sugar production elsewhere which provides a savings in emissions for many categories. However, if it is desired to reduce dependence on imported liquid fuels then the sugarcane biofuel scenario is the most environmentally friendly choice when considering GW and ET although it is the most harmful in terms of RE. Based on concerns over cane burning this may not be the more desirable of the biofuel scenarios. Napier grass produced the largest score for GW and ET categories but had the lowest RE score. The results of this study illustrate that one scenario does not necessarily outperform the others in all categories and often is only better in some categories. Therefore the best scenario depends on the priorities of those implementing the decision and stakeholders.

The Global Bioenergy Partnership Sustainability Indicators for Bioenergy

Introduction

The issue of sustainability has been a common topic of debate in recent years.[60] One of the largest issues is the debate over what the definition of sustainability should encompass. Does it mean only sustainable development, sustainable economics, or environmental sustainability? To resolve this issue the Global Bioenergy Partnership (GBEP) defines sustainability as consisting of three pillars of sustainability that encompass environmental, social, and economic sustainability. Using the GBEP framework a more whole and comprehensive examination of the sustainability can be achieved.

Methods

A life cycle impact assessment method was developed to implement the GBEP environmental pillar of sustainability. This method is aimed at providing information regarding the specific objectives within the environmental pillar of sustainability (table XIV).[61]

Table XIV: GBEP Environmental Pillar Categories

GBEP Environmental Pillar Categories
Lifecycle Greenhouse Gas (GHG) Emissions
Soil Quality
Harvest Levels Of Wood Resources
Emissions Of Non-GHG Air Pollutants, Including Air Toxics
Water Use And Efficiency
Water Quality
Biological Diversity In The Landscape
Land Use And Land Use Change Related To Bioenergy Feedstock Production

Established and relevant categories from different LCIA methods were compiled to produce the GBEP pillar of Environmental sustainability (Table XV). Implementing this framework in a LCIA method allows for fast evaluation for the environmental portion of the GBEP definition of sustainability.

Table XV: GBEP Category References - GBEP categories listed here were compiled from the corresponding reference LCIA method and impact categories listed below. All other categories within the GBEP environmental pillar were developed by the author.

GBEP Impact Category	Reference LCIA Method	Reference Method Impact Category
Biological Diversity	Ecosystem Damage Potential	Total-Linear, Land Transformation
Grey Water Pollutants	CML 2001	Freshwater Aquatic Ecotoxicity-FAETP 500a
Global Warming Potential	IPCC 2007	Climate Change – GWP 100a
Non-Greenhouse Gas Air Pollutants	CML 2001	Photochemical Oxidation(Summer Smog) – High NO_X, POCP
Occupational Hazards	Eco-Indicator 99(E,E)	Human Health - Carcinogenics

The social and economic pillars of GBEP defined sustainability are beyond the scope and capabilities of most current LCA software and databases and therefore could not be incorporated into a single unified tool at this time. To fully evaluate sustainability as defined by GBEP a separate social LCA and economic model should be used to complete the remaining pillars.

For a complete list of flows and impact factors included in each GBEP category please refer see Appendix C (Tables XXVIII-XXXVII).

Results

The environmental sustainability of sugarcane and napier grass biofuels were are also examined using the GBEP LCIA methods (Table XVI). The GBEP categories that most closely resemble those present in the TRACI 2.1 methods are: GWP, Biological Diversity, and Occupational Hazards.

Table XVI: GBEP CLCA Results - GBEP categories that most closely resemble the impact categories represented within the TRACI impacts categories analyzed under the CLCA scenario

GBEP Impact Category	BAU	Sugarcane	Napier	Units
Global Warming Potential	-330	-110	38	Kg CO2 eq
Biological Diversity	-20	-31	1	ha
Occupational Hazards	-3.0E+04	-5.0E+04	990	points

The global warming potential (GWP) category is comparable to the global warming category of TRACI 2.1. The GBEP trends seen here for the CLCA scenario are similar to those observed using the TRACI 2.1 methods (Tables XIII and XVI). BAU is the least impactful, followed by sugarcane biofuel, and finally napier grass biofuel. Furthermore the napier grass biofuel scenario is the only one which elicits a net output of GWP and GW emissions. While the magnitudes differ greatly when compared to the TRACI results this can be explained by different weights, or emission factors, being applied to the individual chemicals released. Table XVII illustrates that the same unit processes that were highlighted when using the TRACI method continue to be major hotspots when using the GBEP methods. This shows that the GBEP methods are consistent with other more established methods and the method is able to identify hotspots with accuracy.

Table XVII: GBEP GWP Major Contributors - The unit processes that contributed most to the GWP of each product system

Unit Process	BAU	Sugarcane	Napier
Harvesting	83	130	26
Market For Sugar From Sugarcane	-120	-190	4
Market For Sugar From Sugar Beet	-41	-65	1
Market For Electricity	-250	0	8
Other	-2	15	-1
Total	-330	-110	38

The GBEP biological diversity category attempts to capture similar effects as TRACI's ecotoxicity, however there are some major differences between them. The biggest difference is the discrepancy in units, biological diversity impacts are described in terms of hectares while ecotoxicity has units CTUe, Comparative Toxic Units. Due to the differences in units the two categories are not directly comparable but no other category within the GBEP methods attempts to capture impacts of this nature. For this reason a legitimate comparison between the two cannot be made.

A similar argument can be made for the occupational hazards and RE categories. The difference in reference units between categories makes an equal comparison of the methods impossible. Nonetheless, it may be useful to use both TRACI and GBEP methods specifically because of these differences. By using both methods one can achieve a more wholesome view of the impacts of the item being studied.

Discussion

When the CLCA scenario was analyzed using both TRACI 2.1 and GBEP methods compared similar trends in the results were observed. This gives credit to the validity of the GBEP methods developed here. However there are differences in the magnitudes of the scores in each category for all scenarios. This is due to differences in the impact factors assigned to different flows. The impact factors may vary greatly among different methods. Additionally, not all elementary flow categories listed for each emission are included in all the methods. This means that some flows may be neglected during the LCIA depending on which method is chosen. Therefore these differences also play a role in the different magnitudes that are seen when comparing the TRACI 2.1 and GBEP methods.

Conclusion

The GBEP LCIA methods are able to give similar trends to other more established methods, showing their validity. These methods allow one to evaluate the environmental sustainability pillar under the three pillar GBEP sustainability strategy. Other methods may be used in conjunction with the GBEP LCIA method in order to complete the other two pillars of sustainability. Some other suggested methods to use alongside the GBEP environmental LCIA methods are social LCA for evaluating the social pillar and general equilibrium models for evaluating the economic pillar. Using the GBEP methods developed here sustainability can be examined in compliance with the GBEP definition of sustainability and used with other methods to successfully evaluate all aspects of sustainability.

Conclusion

Using ALCA napier grass biofuel was demonstrated to have fewer environmental impacts in all three LCIA categories examined: GW, ET, and RE. Three hot spots were identified; advanced biofuel production, hydrogen production, and harvesting operations. Harvesting operations were the root cause of the RE observed in the sugarcane biofuel system. The RE category is also where the napier grass biofuel offered the biggest gains, being an entire order of magnitude smaller than that of sugarcane. Examining only ALCA results, napier grass appears to be the most environmentally friendly choice for producing advanced biofuel on Maui, HI.

CLCA results suggest that a sugarcane biofuel is the most environmentally benign way, in terms of GW and ET, to produce the advanced biofuel. The BAU and sugarcane biofuel scenario both provided a large savings of CO_2. This result is mainly due to sugar produced on the island displacing sugar produced elsewhere. Napier grass biofuel was the only scenario which obtained positive results, a net emission of CO_2. The net production of CO_2 for napier grass biofuel is attributed to sugar production being shifted elsewhere -because napier grass produces no sugar- in order for supply to meet the demand. Napier grass did have a lower RE score than both sugarcane scenarios which was consistent with the ALCA result, again due to pre-harvest burning activities. From a purely environmental standpoint the results of the CLCA recommend that the BAU scenario be continued. However with the objective to produce advanced biofuel on the islands, the sugarcane biofuel is the best scenario to reduce GW and ET.

The ALCA and CLCA results deliver opposing results, however they both provide useful insight regarding process development. The increased range of CLCA takes into account the indirect as well as direct effects of implementing a decision. The narrowed view of ALCA is good for quantifying the direct impacts of a process. The usefulness of both types of LCA has been demonstrated and it is recommended that both CLCA and ALCA should be performed when possible in order to achieve greater insight into the environmental impacts of a system.

GBEP's broader definition of sustainability is vital to ensure that every aspect -environmental, economic, and social- is taken into account when developing a new policy or product. A LCIA method in alignment with the GBEP pillar of environmental sustainability was developed and implemented. The GBEP results were compared to the TRACI 2.1 results for the CLCA of BAU, sugarcane biofuel, and napier grass biofuel. The only categories that allow direct comparison were GWP and GW because they both have a reference unit of Kg CO_2 eq. The GW and GWP results showed the same trend for the three scenarios investigated. The GBEP categories of biological diversity and occupational hazards were not able to be directly compared to TRACI 2.1 categories of ET and RE, respectively, due to differences in reference units between the categories. While the GBEP categories are not easily compared to the accepted TRACI methods, they are able to provide information deemed pertinent by an international coalition of scientists. The GBEP methods are an ideal tool because the results can be easily integrated with other tools such as social LCA and economic models in order to provide an exhaustive view of sustainability.

Future research needs should address the uncertainty associated with the emissions factors within the LCIA methods to give more consistent results between studies. Databases such as USDA, NREL, and Ecoinvent should develop unit processes that encompass labor and cost in order to integrate other aspects of GBEP sustainability more easily within the framework of LCA. Database development also needs to begin including degrees of uncertainty within the unit processes in order to provide a distribution of results which is more realistic than a single value. Continued the development of LCA will help establish it as a reputable and reliable source of information, securing the future of the field, and providing guidance to build a more sustainable world.

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Appendix

A) Primary Data

Table XVIII: Primary data provided by University of Hawaii collaborators

Biomass Production		
Species	Cultivar	Yield (Tons/Ac*2yrs)
Sugarcane	3792	42.2
Napier Grass	Green	29.3
Chemical Application		
Chemical type	Application Rate (Kg/Ac)	
Urea	344.47	
Lime	1000	
Fuel Use		
Total Diesel 2013 (Gallons)	1409126	
Total Gasoline 2013 (Gallons)	174225	
Total Acres	35556	

B) Calculated System Boundary Values

Table XIX: Napier Grass Advanced Biofuel Production Unit Process Boundary Values

Napier Grass Advanced Biofuel Production					
Flow	**Unit**	**Amount**	**Mass (Kg)**	**Energy (MJ)**	**Economic (USD)**
Acetogenic Bacteria	kg	1.0	1.0	NA	NA
Ammonia	kg	1.5	1.5	NA	NA
Calcium Carbonate, In Ground	kg	0.0	0.0	NA	NA
Enzyme, Cellulase, Novozyme Celluclast	kg	1.0	1.0	NA	NA
Hydrogen, Liquid, Synthesis Gas, At Plant	kg	5.4	5.4	NA	NA
Napier Grass Milling	Kg	295.3	295.3	NA	NA
Sulfuric Acid, At Plant	kg	2.2	2.2	NA	NA
Transport, Combination Truck, Short-Haul, Diesel Powered, Hawaii	t*km	0.1	NA	NA	NA
Water	m3	1.3	NA	NA	NA

Table XX: Napier Grass Processing Unit Process Boundary Values

Napier Grass Processing					
Flow	**Unit**	**Amount**	**Mass (Kg)**	**Energy (MJ)**	**Economic (USD)**
Agricultural Machinery	kg	0.1	0.1	NA	NA
Napier Grass Harvested	kg	306.1	306.1	NA	NA
Transport, Refuse Truck, Diesel Powered, Hawaii	t*km	0.1	NA	NA	NA

Table XXI: Napier Harvesting Unit Process Boundary Values

Napier Harvesting					
Flow	**Unit**	**Amount**	**Mass (Kg)**	**Energy (MJ)**	**Economic (USD)**
100 Hp Tractor	Item(s)	9.9E-06	NA	NA	NA
Diesel, Combusted In Industrial Equipment	gal (US liq)	1.80377	5.712544	NA	NA
Gasoline, Combusted In Equipment	gal (US liq)	0.22399	0.631416	NA	NA
Napier Grass Production V2	ton	0.33484	334.8359	NA	NA

Table XXII: Napier Production Unit Process Boundary Values

Napier Production					
Flow	**Unit**	**amount**	**Mass (Kg)**	**Energy (MJ)**	**Economic (USD)**
Land Prep Sugarcane	ac	0.00286	NA	NA	NA
Nitrogen Fertilizer, Production Mix, At Plant	kg	3.939	3.938998	NA	NA
Seed Napier Grass	kg	5.23173	5.231732	NA	NA
Water, Fresh	m3	7.59504	NA	NA	NA
Water, Rain	m3	16.0038	NA	NA	NA
Water, Well, In Ground	ton	0.84389	NA	NA	NA

Table XXIII: Sugarcane Advanced Biofuel Production Unit Process Boundary Values

Sugarcane Advanced Biofuel Production					
Flow	**Unit**	**Amount**	**Mass (Kg)**	**Energy (MJ)**	**Economic (USD)**
Acetogenic Bacteria	kg	0.77	0.77	0.00	0.00
Ammonia	kg	1.12	1.12	0.00	0.00
Ground Calcium Carbonate	kg	0.03	0.03	0.00	0.00
Enzyme, Cellulase, Novozyme Celluclast	kg	0.77	0.77	0.00	0.00
Ethanol, Denatured, Forest Residues, Thermochem	kg	1.97	1.97	0.00	0.00
Hydrogen, Liquid, Synthesis Gas, At Plant	kg	3.80	3.80	0.00	0.00
Sugarcane Milling, Bagasse	ton	0.21	213.66	0.00	0.00
Sulfuric Acid, At Plant	kg	1.59	1.59	0.00	0.00
Transport, Combination Truck, Short-Haul, Diesel Powered, Hawaii	t*km	0.05	0.00	0.22	0.00
Water	m3	0.98	0.00	0.00	0.00

Table XXIV: Sugarcane Processing Unit Process Boundary Values

Sugarcane Processing					
Flow	**Unit**	**Amount**	**Mass (Kg)**	**Energy (MJ)**	**Economic (USD)**
Quicklime, At Plant	kg	2.04	2.04	NA	NA
Phosphoric Acid, At Plant	kg	0.15	0.15	NA	NA
Sugarcane Harvested	ton	3.57	3566.50	NA	NA
Transport, Refuse Truck, Diesel Powered, Hawaii	t*km	0.56	0.02	2.50	NA

Table XXV: Sugarcane Harvested Unit Process Boundary Values

Sugarcane Harvested					
Flow	**Unit**	**Amount**	**Mass (Kg)**	**Energy (MJ)**	**Economic (USD)**
100 Hp Tractor	Item(s)	1.8306E-05	NA	NA	NA
Diesel, Combusted In Industrial Equipment	gal (US liq)	3.33493104	10.5617	451.94684	15.60747728
Gasoline, Combusted In Equipment	gal (US liq)	0.41411967	1.1674	50.721341	1.813844147
Sugarcane Production V3	ton	3.5665	3566.5	69190.1	NA

Table XXVI: Sugarcane Production Unit Process Boundary Values

Sugarcane Production					
Flow	**Unit**	**Amount**	**Mass (Kg)**	**Energy (MJ)**	**Economic (USD)**
Land Prep Sugarcane	ac	0.00457459	NA	NA	NA
Nitrogen Fertilizer, Production Mix, At Plant	kg	12.6148825	12.6149	NA	NA
Seed Cane	kg	24.2453138	24.2453	NA	NA
Water, Fresh	m3	24.3221668	NA	NA	NA
Water, Rain	m3	51.2500187	NA	NA	NA
Water, Well, In Ground	ton	2.70083646	NA	NA	NA

Table XXVII: Land Prep Unit Process Boundary Values

Land Prep					
Flow	**Unit**	**Amount**	**Mass (Kg)**	**Energy (MJ)**	**Economic (USD)**
100 Hp Tractor	Item(s)	0.064	NA	NA	NA
Diesel, Combusted In Industrial Equipment	gal (US liq)	1.8576	5.88302	247.08681	NA
Planting	ac	0.032	NA	NA	NA
Tillage, Ploughing	ac	0.096	NA	NA	NA
Tillage, Rolling	ac	0.032	NA	NA	NA
Tillage, Rotary Cultivator	ac	0.032	NA	NA	NA
Gasoline, Combusted In Equipment	l	0.229664	0.17092	7.3495438	0.265565076
Labor	hr	0.096	NA	NA	NA

C) GBEP LCIA Methods

Table XXVIII: GBEP Occupational Hazards Impact Factors

Flow	Impact Factor (Points)	Flow	Impact Factor (Points)
Acenaphthene	3.2903	Ethene, Chloro-	0.0054968
Acetaldehyde	0.0041806	Ethene, Tetrachloro-	0.009329
Acetaldehyde	0.017865	Ethene, Trichloro-	0.0015387
Acrylonitrile	0.80516	Ethylene Oxide	3.5419
Aldehydes, Unspecified	0.027097	Ethylene Oxide	2.6903
Aldrin	621290	Formaldehyde	0.019181
Arsenic	476.13	Formaldehyde	0.096194
Arsenic	255.48	Lindane	167.23
Arsenic, Ion	1271.6	Methane, Dichloro-, Hcc-30	0.0084387
Arsine	476.13	Methane, Dichloro-, Hcc-30	0.009271
Benzene	0.079742	Methane, Dichlorofluoro-, Hcfc-21	0.0067742
Benzene	0.048387	Methane, Tetrachloro-, R-10	16.219
Benzene, Hexachloro-	1596.8	Nickel	0.000081484
Benzo(A)Pyrene	77.032	Nickel	0.83032
Butadiene	0.30581	Nickel, Ion	1.3374E-06
Cadmium	2612.9	PAH, Polycyclic Aromatic Hydrocarbons	50.323
Cadmium	77.032	Pah, Polycyclic Aromatic Hydrocarbons	3.2903
Cadmium, Ion	1378.1	Particulates, < 2.5 Um	0.18929
Chloroform	0.50323	Particulates, > 2.5 µm, And < 10µm	1
Chloroform	0.50903	Phenol, Pentachloro-	139.55
Chromium Vi	0.000015987	Phthalate, Dibutyl-	1033.5
Chromium Vi	113.03	Phthalate, Dioctyl-	12.852
Chromium Vi	0.0071226	Polychlorinated Biphenyls	38.129
Dioxins, Measured As 2,3,7,8-Tetrachlorodibenzo-P-Dioxin	3464500	Propylene Oxide	0.33677
Epichlorohydrin	0.0058452	Propylene Oxide	0.22645
Ethane, 1,1,2-Trichloro-	0.2129	Sodium Dichromate	0.22895
Ethane, 1,2-Dichloro-	0.57677	Styrene	0.00047226
Ethane, Hexachloro-	0.41032	Styrene	0.023613
Ethene, Chloro-	0.0040452		

Table XXIX: GBEP Biological Diversity Impact Factors

Flow	Impact Factor (ha)	Flow	Impact Factor (ha)
Transformation, From Arable	0.095	Transformation, to arable	-0.095
Transformation, From Arable, Non-Irrigated	0.095	Transformation, to arable, non-irrigated	-0.095
Transformation, From Arable, Non-Irrigated, Diverse-Intensive	0.095	Transformation, to arable, non-irrigated, diverse-intensive	-0.095
Transformation, From Arable, Non-Irrigated, Fallow	0.455	Transformation, to arable, non-irrigated, fallow	-0.455
Transformation, From Arable, Non-Irrigated, Monotone-Intensive	0.03	Transformation, to arable, non-irrigated, monotone-intensive	-0.03
Transformation, From Dump Site	0.025	Transformation, to dump site	-0.025
Transformation, From Dump Site, Benthos	0.025	Transformation, to dump site, benthos	-0.025
Transformation, From Dump Site, Inert Material Landfill	0.025	Transformation, to dump site, inert material landfill	-0.025
Transformation, From Dump Site, Residual Material Landfill	0.025	Transformation, to dump site, residual material landfill	-0.025
Transformation, From Dump Site, Sanitary Landfill	0.025	Transformation, to dump site, sanitary landfill	-0.025
Transformation, From Dump Site, Slag Compartment	0.025	Transformation, to dump site, slag compartment	-0.025
Transformation, From Forest	7.75	Transformation, to forest	-7.75
Transformation, From Forest, Extensive	12.75	Transformation, to forest, extensive	-12.75
Transformation, From Forest, Intensive	4.25	Transformation, to forest, intensive	-4.25
Transformation, From Forest, Intensive, Clear-Cutting	1.75	Transformation, to forest, intensive, clear-cutting	-1.75
Transformation, From Forest, Intensive, Normal	1.75	Transformation, to forest, intensive, normal	-1.75
Transformation, From Forest, Intensive, Short-Cycle	1.75	Transformation, to forest, intensive, short-cycle	-1.75
Transformation, From Heterogeneous, Agricultural	0.095	Transformation, to heterogeneous, agricultural	-0.095

Transformation, From Industrial Area, Vegetation	0.1025	Transformation, to industrial area, vegetation	-0.1025
Transformation, From Mineral Extraction Site	0.025	Transformation, to mineral extraction site	-0.025
Transformation, From Pasture And Meadow	0.14	Transformation, to pasture and meadow	-0.14
Transformation, From Pasture And Meadow, Extensive	0.14	Transformation, to pasture and meadow, extensive	-0.14
Transformation, From Pasture And Meadow, Intensive	0.14	Transformation, to pasture and meadow, intensive	-0.14
Transformation, From Permanent Crop	1.15	Transformation, to permanent crop	-1.15
Transformation, From Permanent Crop, Fruit	1.15	Transformation, to permanent crop, fruit	-1.15
Transformation, From Permanent Crop, Fruit, Extensive	1.9	Transformation, to permanent crop, fruit, extensive	-1.9
Transformation, From Permanent Crop, Fruit, Intensive	1.15	Transformation, to permanent crop, fruit, intensive	-1.15
Transformation, From Permanent Crop, Vine	1.15	Transformation, to permanent crop, vine	-1.15
Transformation, From Permanent Crop, Vine, Extensive	1.9	Transformation, to permanent crop, vine, extensive	-1.9
Transformation, From Permanent Crop, Vine, Intensive	1.15	Transformation, to permanent crop, vine, intensive	-1.15
Transformation, From Sea And Ocean	0.2	Transformation, to sea and ocean	-0.2
Transformation, From Shrub Land, Sclerophyllous	5.3	Transformation, to shrub land, sclerophyllous	-5.3
Transformation, From Traffic Area, Rail Embankment	0.175	Transformation, to traffic area, rail embankment	-0.175
Transformation, From Traffic Area, Rail Network	0.0525	Transformation, to traffic area, rail network	-0.0525
Transformation, From Traffic Area, Road Embankment	0.0525	Transformation, to traffic area, road embankment	-0.0525
Transformation, From Traffic Area, Road Network	0.0525	Transformation, to traffic area, road network	-0.0525

Transformation, From Tropical Rain Forest	780	Transformation, to tropical rain forest	-780
Transformation, From Unknown	0.0425	Transformation, to unknown	-0.0425
Transformation, From Urban, Continuously Built	0.025	Transformation, to urban, continuously built	-0.025
Transformation, From Urban, Discontinuously Built	0.125	Transformation, to urban, discontinuously built	-0.125
Transformation, From Water Bodies, Artificial	0.0475	Transformation, to water bodies, artificial	-0.0475
Transformation, From Water Courses, Artificial	0.0475	Transformation, to water courses, artificial	-0.0475

Table XXX: GBEP Allocation of New Land Impact Category

Flow	Impact Factor (ha)	Flow	Impact Factor (ha)
Transformation, From Permanent Crop, Fruit	1	Transformation, to industrial area, vegetation	1
Transformation, To Arable	1	Transformation, from unknown	1
Transformation, To Dump Site, Slag Compartment	1	Transformation, to industrial area, benthos	1
Transformation, To Water Courses, Artificial	1	Transformation, from traffic area, road network	1
Transformation, From Permanent Crop, Vine	1	Transformation, to industrial area, built up	1
Transformation, From Traffic Area, Road Embankment	1	Transformation, from industrial area, vegetation	1
Transformation, To Water Bodies, Artificial	1	Transformation, from urban, continuously built	1
Transformation, From Forest, Extensive	1	Transformation, from permanent crop, vine, intensive	1
Transformation, From Urban, Discontinuously Built	1	Transformation, to arable, non-irrigated	1
Transformation, From Mineral Extraction Site	1	Transformation, from forest, intensive, clear-cutting	1
Transformation, From Permanent Crop, Vine, Extensive	1	Transformation, from forest	1
Transformation, From Pasture And Meadow, Intensive	1	Transformation, from forest, intensive, normal	1
Transformation, To Traffic Area, Road Embankment	1	Transformation, from shrub land, sclerophyllous	1
Transformation, From Tropical Rain Forest	1	Transformation, from forest, intensive	1
Transformation, From Water Courses, Artificial	1	Transformation, from permanent crop, fruit, extensive	1
Transformation, To Dump Site, Sanitary Landfill	1	Transformation, to dump site, inert material landfill	1

Transformation, From Traffic Area, Rail Network	1	Transformation, from permanent crop, fruit, intensive	1
Transformation, From Industrial Area	1	Transformation, from forest, intensive, short-cycle	1
Transformation, From Permanent Crop	1	Transformation, to industrial area	1
Transformation, To Traffic Area, Road Network	1	Transformation, to heterogeneous, agricultural	1
Transformation, From Water Bodies, Artificial	1	Transformation, to arable, non-irrigated, monotone-intensive	1
Transformation, To Traffic Area, Rail Embankment	1	Transformation, to traffic area, rail network	1
Transformation, To Dump Site, Residual Material Landfill	1	Transformation, from pasture and meadow	1
Transformation, From Pasture And Meadow, Extensive	1	Transformation, from sea and ocean	1
Transformation, To Dump Site	1	Transformation, to arable, non-irrigated, diverse-intensive	1
Transformation, From Traffic Area, Rail Embankment	1		

Table XXXI: GBEP Land use Change Impact Category

Flow	Impact Factor (ha)	Flow	Impact Factor (ha)
Transformation, From Permanent Crop	1	Transformation, from industrial area	-1
Transformation, To Heterogeneous, Agricultural	1	Transformation, from forest, intensive	1
Transformation, From Forest, Intensive, Short-Cycle	1	Transformation, from permanent crop, vine, intensive	1
Transformation, To Forest, Extensive	-1	Transformation, from arable, non-irrigated	1
Transformation, To Forest, Intensive, Clear-Cutting	1	Transformation, from pasture and meadow, intensive	1
Transformation, From Unknown	1	Transformation, from traffic area, road embankment	-1
Transformation, To Dump Site, Residual Material Landfill	1	Transformation, from tropical rain forest	1
Transformation, From Dump Site, Slag Compartment	-1	Transformation, from arable, non-irrigated, monotone-intensive	1
Transformation, From Traffic Area, Road Network	-1	Transformation, to mineral extraction site	1
Transformation, From Dump Site, Inert Material Landfill	-1	Transformation, from dump site, benthos	-1
Transformation, To Sea And Ocean	-1	Transformation, to permanent crop, vine, intensive	1
Transformation, From Mineral Extraction Site	-1	Transformation, to urban, continuously built	1
Transformation, To Traffic Area, Road Network	1	Transformation, from water bodies, artificial	-1
Transformation, To Dump Site, Inert Material Landfill	1	Transformation, to dump site, slag compartment	1
Transformation, To Permanent Crop, Fruit, Intensive	1	Transformation, from permanent crop, fruit	1
Transformation, To Industrial Area, Built Up	1	Transformation, to dump site, benthos	1
Transformation, To Water Courses, Artificial	1	Transformation, to tropical rain forest	-1

Transformation, To Urban, Discontinuously Built	1	Transformation, to traffic area, rail/road embankment	1
Transformation, To Industrial Area, Vegetation	1	Transformation, from urban, continuously built	-1
Transformation, From Dump Site, Residual Material Landfill	-1	Transformation, to industrial area	1
Transformation, From Dump Site	1	Transformation, from traffic area, rail network	-1
Transformation, To Forest, Intensive, Normal	1	Transformation, to arable, non-irrigated, fallow	1
Transformation, To Permanent Crop	1	Transformation, to permanent crop, vine, extensive	1
Transformation, To Shrub Land, Sclerophyllous	-1	Transformation, to forest, intensive	1
Transformation, To Permanent Crop, Fruit, Extensive	1	Transformation, to arable, non-irrigated, diverse-intensive	1
Transformation, To Dump Site, Sanitary Landfill	1	Transformation, to traffic area, rail embankment	1
Transformation, From Sea And Ocean	1	Transformation, from forest, extensive	1
Transformation, To Arable	1	Transformation, from permanent crop, fruit, intensive	1
Transformation, To Permanent Crop, Vine	1	Transformation, from forest	1
Transformation, To Unknown	1	Transformation, to pasture and meadow, intensive	-1
Transformation, From Dump Site, Sanitary Landfill	-1	Transformation, from water courses, artificial	-1
Transformation, From Traffic Area, Rail Embankment	-1	Transformation, from permanent crop, fruit, extensive	1
Transformation, From Arable	1	Transformation, to traffic area, rail network	1
Transformation, From Permanent Crop, Vine	1	Transformation, to forest, intensive, short-cycle	1

Transformation, From Arable, Non-Irrigated, Diverse-Intensive	1	Transformation, from industrial area, vegetation	-1
Transformation, From Forest, Intensive, Normal	1	Transformation, from forest, intensive, clear-cutting	1
Transformation, From Urban, Discontinuously Built	-1	Transformation, from arable, non-irrigated, fallow	1
Transformation, From Pasture And Meadow, Extensive	1	Transformation, from shrub land, sclerophyllous	1
Transformation, From Industrial Area, Built Up	-1	Transformation, to forest	-1
Transformation, To Industrial Area, Benthos	1	Transformation, from pasture and meadow	1
Transformation, From Heterogeneous, Agricultural	1	Transformation, to arable, non-irrigated, monotone-intensive	1
Transformation, To Permanent Crop, Fruit	1	Transformation, to dump site	1
Transformation, To Pasture And Meadow	-1	Transformation, to pasture and meadow, extensive	-1
Transformation, From Industrial Area, Benthos	-1	Transformation, to arable, non-irrigated	1
Transformation, To Traffic Area, Road Embankment	1	Transformation, from permanent crop, vine, extensive	1
Transformation, To Water Bodies, Artificial	1		

Table XXXII: GBEP Non- GHG Air Pollutants

Flow	Impact Factor (Kg Ethene eq)	Flow	Impact Factor (Kg Ethene eq)
Ethanol	0.399	1-Pentene	0.977
Acetaldehyde	0.641	Ethene	1
Methane, Dichloro-, Hcc-30	0.068	Propane	0.176
Butanol	0.62	2-Methyl-2-butene	0.842
Methyl Acetate	0.059	Ethyne	0.085
Formaldehyde	0.519	Cumene	0.5
Benzene, Ethyl-	0.73	3-Methyl-1-butanol	0.433
Heptane	0.494	Toluene	0.637
Ethene, Trichloro-	0.325	Methyl formate	0.027
Methane, Monochloro-, R-40	0.005	Butane	0.352
Ethene, Tetrachloro-	0.029	o-Xylene	1.053
Methyl Ethyl Ketone	0.373	Isoprene	1.092
Methane, Biogenic	0.006	Ethane, 1,1,1-trichloro-, HCFC-140	0.009
Propanol	0.561	Propene	1.123
Benzaldehyde	-0.092	Methane, fossil	0.006
Benzene	0.218	Hexane	0.482
Diethyl Ether	0.445	Chloroform	0.023
Carbon Monoxide, Fossil	0.027	Formic acid	0.032
Ethane	0.123	Styrene	0.142
4-Methyl-2-Pentanone	0.49	2-Methyl-1-propanol	0.36
2-Methyl Pentane	0.479	Sulfur dioxide	0.048
Butadiene	0.851	Ethylene glycol monoethyl ether	0.386
Propionic Acid	0.15	2-Propanol	0.188
T-Butyl Methyl Ether	0.175	Acetone	0.094
Cyclohexane	0.29	Ethyl acetate	0.209
Propanal	0.798	Acetic acid	0.097
Methanol	0.14	m-Xylene	1.108
Pentane	0.395		

Table XXXIII: GBEP GWP Impact Category

Flow	Impact Factor (Kg Co_2 eq)	Flow	Impact Factor (Kg Co_2 eq)
Carbon Monoxide, Biogenic	1.57	Methane, trichlorofluoro-, CFC-11	4750
Ethane, 1,1,1,2-Tetrafluoro-, Hfc-134a	1300	Ethane, pentafluoro-, HFC-125	3500
Methane, Dichlorodifluoro-, Cfc-12	10900	Methane, chlorotrifluoro-, CFC-13	14000
Methane, Chlorodifluoro-, Hcfc-22	1810	Ethane, 1,1-dichloro-1-fluoro-, HCFC-141b	725
Carbon Monoxide	1.57	Ethane, 1,1-difluoro-, HFC-152a	124
Dinitrogen Monoxide	298	Ethane, 1-chloro-1,1-difluoro-, HCFC-142b	2310
Chloroform	30	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	10000
Carbon Monoxide	1.57	Methane	25
Ethane, Hexafluoro-, Hfc-116	12200	Methane, tetrachloro-, R-10	1400
Carbon Dioxide, Fossil	1	Methane, fossil	25
Carbon Dioxide, Land Transformation	1	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	6130
Hydrocarbons, Chlorinated	10.6	Methane, bromotrifluoro-, Halon 1301	7140
Ethane, 2,2-Dichloro-1,1,1-Trifluoro-	77	Ethane, 1,1,1-trifluoro-, HFC-143a	4470
Nitrogen Fluoride	17200	Sulfur hexafluoride	22800
Methane, Trifluoro-, Hfc-23	14800	Ethane, chloropentafluoro-, CFC-115	7370
Methane, Tetrafluoro-, R-14	7390	Methane, biogenic	25
Methane, Monochloro-, R-40	13	Methane, dichlorofluoro-, HCFC-21	210
Methane, Dichloro-, Hcc-30	8.7	Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	609
Methane, Difluoro-, Hfc-32	675	Methane, bromo-, Halon 1001	5
Methane, Bromochlorodifluoro-, Halon 1211	1890		

Table XXXIV: GBEP Soil Quality Impact Category

Flow	Impact Factor (Kg C)	Flow	Impact Factor (Kg C)
Soil Loss By Erosion Into Water	1	carbon; injected/knifed in manure at an unknown time	1
Carbon; Using Unspec. Method In Manure At An Unknown Time	1	Carbon; using unspec. method in manure in fall before planting; biogenic	1
Carbon; Injected/Knifed In Manure In Spring Before Planting; Biogenic	1	carbon; applied in limestone	1
Carbon; Using Unspec. Method In Manure In Spring Before Planting; Biogenic	1	Carbon; broadcast w/o incorp. in manure in fall before planting; biogenic	1
Carbon; Broadcast W/ Incorp. In Manure At An Unknown Time	1	Carbon; broadcast w/ incorp. in manure in fall before planting; biogenic	1
Carbon; Broadcast W/O Incorp. In Manure At An Unknown Time	1	carbon; injected/knifed in manure in fall before planting; biogenic	1
Carbon, In Organic Matter, In Soil	1	Carbon	1
Carbon; Broadcast W/ Incorp. In Manure In Spring Before Planting; Biogenic	1	carbon; applied in dolomite	1
Carbon; In Below-Ground Residue; Biogenic	1	carbon; in above-ground residue left on field; biogenic	1
Carbon; Applied In Sewage Sludge	1	Carbon; broadcast w/o incorp. in manure in spring before planting; biogenic	1

Table XXXV: GBEP Change in Food Availability Impact Category

Flow	Impact Factor (ha)	Flow	Impact Factor (ha)
Transformation, From Arable, Non-Irrigated, Diverse-Intensive	-1	transformation; from arable, from fallow to rice	1
Transformation, To Permanent Crop, Fruit	1	transformation; from arable, from unspec. use to rice	1
Transformation, To Arable, Non-Irrigated	1	Transformation, to pasture and meadow, organic	1
Transformation, From Arable, Non-Irrigated, Monotone-Intensive	-1	Transformation, to arable, non-irrigated, monotone-intensive	1
Transformation, To Permanent Crop, Fruit, Intensive	1	transformation; from arable, from unspec. use to corn	1
Transformation, To Arable, Non-Irrigated, Monotone-Intensive	1	Transformation, from arable, non-irrigated, monotone-intensive	-1
Transformation; From Arable, From Fallow To Corn	1	Transformation, to permanent crop	1
Transformation; From Arable, From Unspec. Use To Oats	1	transformation; from arable, from unspec. use to wheat	1
Transformation, To Arable, Non-Irrigated, Diverse-Intensive	1	Transformation, to permanent crop, fruit, intensive	1
Transformation, To Pasture And Meadow, Extensive	1	Transformation, to pasture and meadow, intensive	1
Transformation, From Arable, Non-Irrigated, Diverse-Intensive	-1	Transformation, from forest	-1
Transformation, To Permanent Crop, Vine	1	Transformation, to permanent crop, fruit, extensive	1
Transformation, To Permanent Crop, Vine, Extensive	1	Transformation, from permanent crop, vine, extensive	-1
Transformation, To Permanent Crop, Vine, Intensive	1	Transformation, to pasture and meadow, extensive	1
Transformation; From Arable, From Unspec. Use To Peanuts	1	transformation; from arable, from fallow to soybeans	1

Transformation, To Permanent Crop, Vine	1	Transformation, to heterogeneous, agricultural	1
Transformation, From Pasture And Meadow, Extensive	-1	Transformation, from permanent crop, fruit	-1
Transformation, To Arable	1	Transformation, from arable, non-irrigated	-1
Transformation, To Arable, Non-Irrigated, Diverse-Intensive	1	Transformation, to arable	1
Transformation; From Arable, From Fallow To Wheat	1	Transformation, from permanent crop, fruit, extensive	-1
Transformation, To Pasture And Meadow	1	Transformation, to permanent crop, fruit, extensive	1
Transformation, From Permanent Crop, Vine, Intensive	-1	Transformation, to pasture and meadow, intensive	1
Transformation, From Permanent Crop, Vine	-1	Transformation, to pasture and meadow	1
Transformation, From Permanent Crop, Vine, Extensive	-1	Transformation, from arable	-1
Transformation, From Permanent Crop, Fruit, Extensive	-1	Transformation, from permanent crop	-1
Transformation, From Arable	-1	Transformation, from permanent crop, fruit, intensive	-1
Transformation; From Arable, From Unspec. Use To Soybeans	1	Transformation, to permanent crop	1
Transformation, To Permanent Crop, Vine, Intensive	1	Transformation, from permanent crop, vine, intensive	-1
Transformation; From Arable, From Unspec. Use To Cotton	1	Transformation, from arable, non-irrigated	-1
Transformation, To Heterogeneous, Agricultural	1	Transformation, from forest	-1
Transformation, To Arable, Non-Irrigated	1	transformation; from arable, from fallow to cotton	1

Transformation, From Pasture And Meadow, Intensive	-1	Transformation, to arable, organic	1
Transformation, From Permanent Crop	-1	Transformation, to permanent crop, fruit	1
Transformation, From Permanent Crop, Fruit	-1	Transformation, from permanent crop, fruit, intensive	-1
Transformation, To Permanent Crop, Vine, Extensive	1	Transformation, from permanent crop, vine	-1

Table XXXVI: GBEP Grey Water Pollutants Impact Category

Flow	Impact Factor (Kg 1,4-DCB eq)	Flow	Impact Factor (Kg 1,4-DCB eq)
Vanadium, Ion	8904.3	Barium	226.17
Propylene Oxide	0.036846	Acenaphthene	170.63
Phthalate, Dioctyl-	2.7709	Chromium VI	27.656
Chromium, Ion	6.8646	Phenol, pentachloro-	10.523
Beryllium	20601	Styrene	0.000010125
Methane, Dichloro-, Hcc-30	0.000033287	Lead	0.048931
Toluene	0.000070434	Permethrin	916.78
Molybdenum	472.93	Benzene	0.000083682
Benomyl	4.5856	Acrylonitrile	79.24
Arsenic, Ion	205.33	Azinphos-methyl	194.39
O-Xylene	0.000093068	Cadmium	51.55
Formaldehyde	8.2559	Ethane, 1,1,1-trichloro-, HCFC-140	0.00012179
Chromium Vi	0.10861	Lead	0.11644
Arsenic	1.2331	m-Xylene	0.000043747
Benzene, Chloro-	0.36032	Ethane, 1,2-dichloro-	0.022783
Mercury	103.61	Cobalt	1.2154E-18
Tin	0.12312	Fentin hydroxide	378.55
Dichromate	13.302	Dichromate	13.302
Pirimicarb	1670.2	Molybdenum	472.93
Chromium Vi	0.32362	Thallium	7955
Beryllium	8201.5	Antimony	19.61
Antimony	19.61	Tin	0.051762
Trichlorfon	3307.7	Vanadium	328.94
Vanadium, Ion	8904.3	Benzene, ethyl-	0.54552
Thallium	7955	Antimony	1.0111
Mercury	58.689	Cyanazine	805.78
Thallium	182.16	Phthalate, dibutyl-	76.409
Tributyltin Compounds	452510	Mercury	58.689
Molybdenum	7.4443	Selenium	2899.1
Benzene	0.000083682	Phenol	1.5159
Methane, Dichloro-, Hcc-30	0.000033287	Phthalate, dimethyl-	3.0847
Molybdenum	472.93	Mercury	0.402
Cobalt	3384.5	Beryllium	8201.5
Beryllium	90724	Molybdenum	472.93
Phenol, 2,4-Dichloro	1.4036	Cadmium	101.72
Copper	55.48	Carbon disulfide	105.17
Vanadium	208.53	Ethene, chloro-	0.027867

Ethene, Tetrachloro-	0.69635	Selenium	2899.1
Vanadium	208.53	Phthalate, dibutyl-	0.000029224
Chloroform	0.000095153	Ethane, 1,2-dichloro-	0.00011849
Phenol, Pentachloro-	10.523	Ethane, 1,2-dichloro-	0.00011849
Ethoprop	11056	Phenol	1.5159
Antimony	2.29	Molybdenum	7.4443
Zinc	3.0275	Copper, ion	1149.3
M-Xylene	0.59829	Dichromate	13.302
Tin, Ion	10.096	Sodium dichromate	0.12848
Chlorothalonil	1.0381	Benzene, ethyl-	0.00013123
Vanadium	328.94	Chloroform	0.042349
Ethane, 1,1,1-Trichloro-, Hcfc-140	0.10959	Antimony	7.5698E-21
Chloroform	0.000095153	Chloroform	0.042349
Thallium	182.16	Ethene, tetrachloro-	0.00041293
Sodium Dichromate	0.12848	Ethene, tetrachloro-	0.00020211
Carbon Disulfide	105.17	Selenium	2899.1
Cobalt	726.05	Phthalate, dimethyl-	3.0847
Arsenic, Ion	205.33	Benzene	0.000083682
Chloroform	0.00004483	m-Xylene	0.59829
Arsenic	1.2331	Phenol	237.01
Barium	14.992	Selenium	379.23
Bifenthrin	103.19	Acenaphthene	170.63
Ethene, Chloro-	0.027867	Carbon disulfide	0.032959
Ethene, Trichloro-	0.096977	Copper, ion	1149.3
Beryllium	20601	Ethylene oxide	9.7955
Vanadium, Ion	8904.3	Methane, dichloro-, HCC-30	0.000033287
Ethane, 1,1,1-Trichloro-, Hcfc-140	0.00012179	Phenol	237.01
Acrylonitrile	79.24	Chromium	0.027152
Ethane, 1,2-Dichloro-	0.022783	Ethene, tetrachloro-	0.00041293
Barite	1.4063E-19	Antimony	1.0111
Thallium	7955	Chromium VI	3.5347E-22
Ethene, Tetrachloro-	0.00041293	Beryllium	8201.5
Ethene, Tetrachloro-	0.00041293	Benzene, ethyl-	0.00013123
Vanadium	328.94	Phenol, 2,4-dichloro	1.4036
Thallium	282.22	Toluene	0.000070434
Arsenic, Ion	205.33	Ethene, trichloro-	0.000038106
Styrene	0.000050907	Benzene, pentachloro-	0.36814
Benzene, Ethyl-	0.54552	m-Xylene	0.000043747
Lead	0.11644	Ethylene oxide	9.7955
Nickel, Ion	3215.5	Ethene, tetrachloro-	0.69635

Carbon Disulfide	105.17	Cadmium, ion	1512.5
Ethene, Trichloro-	0.000038106	Ethene, trichloro-	0.000038106
Ethene, Chloro-	2.8615E-06	Phenol	1.5159
O-Xylene	0.000015123	Benzene	0.091442
Thiram	685.84	Ethene, chloro-	2.8615E-06
Dioxins, Measured As 2,3,7,8-Tetrachlorodibenzo-P-Dioxin	2112300	Cadmium	101.72
Phthalate, Dimethyl-	3.0847	Mercury	103.61
Chromium Vi	0.32362	Selenium	2899.1
Molybdenum	7.4443	Oxydemeton-methyl	970.45
Cobalt	3384.5	Lead	9.6157
Acrolein	519.44	Lindane	97.422
Chromium Vi	27.656	Chloroform	0.000095153
Carbon Disulfide	0.032959	Chromium VI	0.10861
Copper	31.494	Acenaphthene	27544
Butadiene	3.2531E-07	Carbofuran	584.53
Tin	0.12312	Tin, ion	10.096
Ethane, 1,1,1-Trichloro-, Hcfc-140	0.000071035	Acenaphthene	170.63
Antimony	2.29	Xylene	0.57983
Mercury	1704.1	Phthalate, butyl-benzyl-	76.409
Nickel	103.13	Phenol	237.01
Ethene	0.022491	Propylene oxide	0.036846
Acenaphthylene	27544	Cadmium	51.55
Aldrin	283.11	Thallium	282.22
Dichromate	13.302	Benzo(a)pyrene	87.77
Trifluralin	39.769	Arsenic, ion	3.8204E-20
Metamitron	0.41287	Antimony	19.61
Thallium	7955	Xylene	0.57983
Cobalt	726.05	Tributyltin compounds	452510
Nickel, Ion	3215.5	Acrylonitrile	0.0060361
Ethene, Chloro-	2.8615E-06	Benzene, pentachloro-	0.36814
Butadiene	3.2531E-07	Beryllium	20601
Copper	55.48	Copper	31.494
Phthalate, Dimethyl-	3.8217E-07	Benzene, pentachloro-	0.36814
Chromium	0.027152	Hydrogen fluoride	4.611
Barium	35.879	Ethane, 1,2-dichloro-	0.00011849
Chromium, Ion	6.8646	o-Dichlorobenzene	1.0114
Antimony	2.29	Phthalate, dioctyl-	2.7709
Ethene	0.022491	Barium	2.3916E-19
Cobalt	3384.5	Mercury	103.61

Ethane, 1,1,1-Trichloro-, Hcfc-140	0.10959	o-Dichlorobenzene	1.0114
Acenaphthylene	27544	Tin, ion	10.096
Cadmium, Ion	1512.5	Molybdenum	7.5385
Formaldehyde	0.00021261	PAH, polycyclic aromatic hydrocarbons	27544
Carbon Disulfide	105.17	Beryllium	8201.5
Ethene	1.0497E-12	Tin	0.12312
Ethane, 1,1,1-Trichloro-, Hcfc-140	0.00012179	Phthalate, dioctyl-	2.7709
Barium	226.17	Nickel, ion	6.0943E-19
Zinc, Ion	91.085	Vanadium	208.53
Barite	132.99	Chromium VI	27.656
Chlorpyrifos	355.77	Barium	226.17
Nickel	69.769	Xylene	8.7267E-06
Dnoc	1.1889	Nickel	103.13
Metazachlor	3.9264	Cobalt	3384.5
Cobalt	726.05	Lead	9.6157
Phthalate, Dibutyl-	76.409	o-Dichlorobenzene	1.0114
Benzo(A)Pyrene	87.77	Formaldehyde	280.73
Phenol, 2,4-Dichloro	1.4036	Chloroform	0.042349
Cadmium, Ion	2.5261E-20	o-Dichlorobenzene	0.0012882
Nickel	69.769	Tributyltin compounds	3.0115
Copper, Ion	4.1094E-20	o-Xylene	0.000093068
Tin	0.051762	Ethene	0.022491
Butadiene	3.2531E-07	Hydrogen fluoride	4.611
Zinc	3.0275	o-Dichlorobenzene	1.0114
Toluene	0.29451	Benzo(a)pyrene	87.77
Lead	9.6157	o-Xylene	0.000093068
Copper, Ion	1149.3	Chromium	0.027152
Dioxins, Measured As 2,3,7,8-Tetrachlorodibenzo-P-Dioxin	2112300	PAH, polycyclic aromatic hydrocarbons	170.63
Acephate	50.947	Barium	35.879
Benzene, Dichloro	0.0028764	Molybdenum	472.93
Cobalt	291	m-Xylene	0.59829
Acenaphthene	27544	Methane, tetrachloro-, R-10	0.20696
Phthalate, Butyl-Benzyl-	0.000031872	Selenium	990.55
O-Xylene	0.56462	Ethene, trichloro-	0.096977

Pah, Polycyclic Aromatic Hydrocarbons	27544	Styrene	0.43967
Arsenic	2.5675	Acenaphthylene	27544
Tributyltin Compounds	4.0182	Zinc	2.0136
Zinc, Ion	91.085	Beryllium	90724
Acenaphthylene	0.11633	Xylene	0.57983
Copper	31.494	Lead	0.048931
Ethene, Trichloro-	0.000038106	Methane, bromo-, Halon 1001	0.032679
Formaldehyde	8.2559	Styrene	0.000050907
Phenol, Pentachloro-	10.523	Benzene, hexachloro-	1.3255
Methane, Tetrachloro-, R-10	0.0002502	Ethylene oxide	0.098657
Zinc	2.0136	Benzene, hexachloro-	1.3255
Toluene	0.000070434	Barium	226.17
Carbendazim	2006.6	Methane, tetrachloro-, R-10	0.0002502
Vanadium, Ion	8904.3	Ethylene oxide	0.098657
2,4-D	29.495	Barite	132.99
Copper, Ion	1149.3	Benzene, hexachloro-	1.3255
O-Dichlorobenzene	1.0114	Chromium VI	0.10861
Ethene	1.4259E-11	Methane, dichloro-, HCC-30	0.000033287
M-Xylene	0.59829	Ethylene oxide	0.0037782
Phthalate, Dibutyl-	76.409	Barium	226.17
Nickel	103.13	Ethane, 1,1,1-trichloro-, HCFC-140	0.00012179
Chromium, Ion	6.8646	Lead	0.11644
Cypermethrin	199340	Acrolein	519.44
Phenol, 2,4-Dichloro	1.4036	Selenium	2899.1
Chloroform	0.000095153	Nickel, ion	3215.5
Molybdenum	7.5385	PAH, polycyclic aromatic hydrocarbons	170.63
Tin, Ion	9.4573E-23	Nickel, ion	3215.5
Methane, Tetrachloro-, R-10	0.20696	Acrolein	519.44
Ethene, Trichloro-	0.000038106	Benzo(a)pyrene	87.77
Phthalate, Butyl-Benzyl-	76.409	Formaldehyde	280.73
Tin, Ion	10.096	o-Dichlorobenzene	1.0114
Ethylene Oxide	9.7955	Phenol	1.5159
Benzene	0.091442	Mercury	1704.1
Acenaphthene	170.63	Cadmium, ion	1512.5
Cobalt	3384.5	Benzene, ethyl-	9.4381E-06

Benzo(A)Pyrene	87.77	Glyphosate	3.6719
Antimony	2.29	Chromium VI	0.32362
Isoproturon	167.93	Methane, bromo-, Halon 1001	0.032679
Tributyltin Compounds	452510	Zinc, ion	1.7611E-21
Acenaphthylene	27544	Tin	0.051762
O-Xylene	0.56462	Dichromate	13.302
Thallium	7.8988E-18	Tin, ion	10.096
Methane, Dichloro-, Hcc-30	0.012289	Sodium dichromate	0.12848
Endosulfan	2.207	Mercury	58.689
Mercury	58.689	Chloroform	0.000095153
Propylene Oxide	3.9649	Copper, ion	1149.3
O-Xylene	0.000093068	Diuron	345.48
Mercury	1704.1	Toluene	0.29451
Lead	0.11644	Nickel	103.13
Copper	55.48	Mecoprop	30
Molybdenum	7.5385	Zinc	2.0136
Zinc	3.0275	Tin	0.12312
Zinc, Ion	91.085	PAH, polycyclic aromatic hydrocarbons	170.63
Ethene	1.4259E-11	Benzene, ethyl-	0.00013123
Selenium	7.3785E-18	Ethane, 1,2-dichloro-	0.00011849
Ethylene Oxide	9.7955	Barium	226.17
Nickel, Ion	3215.5	Barite	132.99
Barite	132.99	Benzene	0.091442
Ethene, Tetrachloro-	0.69635	Toluene	0.000008269
Glyphosate	0.92165	Aldicarb	95850
Methane, Bromo-, Halon 1001	0.032679	Hydrogen fluoride	4.611
Pah, Polycyclic Aromatic Hydrocarbons	170.63	Cadmium, ion	1512.5
Barite	132.99	Beryllium	90724
Butadiene	3.2531E-07	Lead	9.6157
Methane, Bromo-, Halon 1001	0.032679	Butadiene	3.2531E-07
Ethane, 1,1,1-Trichloro-, Hcfc-140	0.00012179	Benzene, ethyl-	0.54552
Methane, Dichloro-, Hcc-30	0.012289	Methane, tetrachloro-, R-10	0.20696
Phenol, Pentachloro-	10.523	Lead	9.6157
Copper	31.494	Tributyltin compounds	4.0182
Ethane, 1,2-Dichloro-	0.00011849	Cobalt	291

Ethene	0.022491	Benzene, pentachloro-	0.36814
Deltamethrin	24.099	Antimony	19.61
Arsenic, Ion	205.33	Cobalt	291
Phenol, Pentachloro-	10.523	Methane, dichloro-, HCC-30	0.000033287
Ethene, Tetrachloro-	0.69635	Carbon disulfide	0.032959
Arsenic	2.5675	Mercury	1704.1
Lead	5.5714E-23	Carbon disulfide	0.032959
Selenium	990.55	Captan	0.4015
Selenium	379.23	Ethene, chloro-	0.027867
Phthalate, Dioctyl-	2.7709	Barium	226.17
Phenol, 2,4-Dichloro	1.4036	Ethane, 1,2-dichloro-	0.000087666
Pah, Polycyclic Aromatic Hydrocarbons	0.11633	Molybdenum	6.5877E-19
Barium	14.992	Phenol	0.000017284
Arsenic	1.2331	Cadmium, ion	1512.5
Methane, Tetrachloro-, R-10	0.00018925	Ethene, trichloro-	0.096977
Benzene, Hexachloro-	1.3255	Benzene, dichloro	0.0028764
Zinc	2.0136	Styrene	0.000050907
Benzene, Ethyl-	0.54552	Selenium	379.23
Acenaphthene	27544	Acenaphthene	170.63
Propylene Oxide	3.9649	Lead	0.048931
Selenium	379.23	Antimony	1.0111
Propylene Oxide	3.9649	Phthalate, butyl-benzyl-	76.409
Zinc	3.0275	Iprodion	0.2333
Ethylene Oxide	0.098657	Ethene, chloro-	0.027867
Benzene, Chloro-	0.36032	Ethene	1.4259E-11
Methane, Tetrachloro-, R-10	0.0002502	Selenium	990.55
Acrylonitrile	79.24	Dinoseb	20140
O-Xylene	0.56462	Thallium	282.22
Beryllium	90724	Cobalt	291
Molybdenum	7.5385	Cadmium	51.55
Ethene, Chloro-	2.8615E-06	Benzene, ethyl-	0.00013123
Tin	0.051762	m-Xylene	0.000043747
Molybdenum	7.4443	Cobalt	3384.5
Metolachlor	1893.7	Tributyltin compounds	452510
Zinc	2.0136	Benzene, hexachloro-	1.3255
Formaldehyde	8.2559	Phthalate, dimethyl-	3.0847
Antimony	1.0111	Styrene	0.000050907
Mercury	103.61	Toluene	0.000070434

Molybdenum	7.5385	Atrazine	344.6
Chromium	0.027152	Thallium	182.16
Ethane, 1,2-Dichloro-	0.022783	Fentin acetate	380.99
Benzene, Dichloro	0.0028764	Ethylene oxide	0.098657
Ethylene Oxide	0.098657	Selenium	379.23
Cadmium, Ion	1512.5	Toluene	0.000070434
Lead	9.6157	Carbaryl	23.153
Zinc, Ion	91.085	Acrylonitrile	79.24
Dioxins, Measured As 2,3,7,8-Tetrachlorodibenzo-P-Dioxin	2112300	Barium	35.879
Toluene	0.29451	Benzene, chloro-	0.00025859
Phthalate, Dioctyl-	0.00014339	Thallium	182.16
Methane, Dichloro-, Hcc-30	0.012289	Ethene, trichloro-	0.096977
Chromium Vi	27.656	Copper	31.494
Vanadium, Ion	8904.3	Arsenic	1.2331
Vanadium	328.94	Carbon disulfide	0.0065293
Phenol	237.01	Propylene oxide	0.036846
Carbon Disulfide	105.17	PAH, polycyclic aromatic hydrocarbons	170.63
Acenaphthene	27544	Dichromate	13.302
Propylene Oxide	0.036846	Beryllium	8201.5
Benzene	9.1944E-06	Benzene, dichloro	0.0028764
Parathion	497.63	Chromium VI	27.656
Benzene, Chloro-	0.36032	Chromium VI	27.656
Formaldehyde	280.73	Benzene	0.000083682
Selenium	379.23	Cobalt	726.05
Selenium	990.55	Nickel	69.769
Mcpa	0.46289	Methane, tetrachloro-, R-10	0.20696
Vanadium	208.53	Chloridazon	1.7968
Disulfoton	72.479	Benzene	0.000083682
Tin, Ion	10.096	Acenaphthene	27544
M-Xylene	0.000043747	Carbon disulfide	105.17
Cadmium	51.55	Chromium VI	0.32362
Simazine	2332.5	Dimethoate	8.9438
Antimony	19.61	Hydrogen fluoride	4.611
Chromium, Ion	6.8646	Chromium VI	0.10861
Arsenic	2.5675	Vanadium, ion	2.3929E-18
Ethene, Chloro-	2.8615E-06	Nickel	69.769
Benzene, Chloro-	0.36032	Nickel, ion	3215.5
Acrolein	519.44	Thallium	282.22

O-Xylene	0.56462	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	2112300
Oxamyl	29.532	Beryllium	90724
Vanadium	208.53	Methane, tetrachloro-, R-10	0.0002502
O-Xylene	0.000093068	Antimony	19.61
Ethane, 1,1,1-Trichloro-, Hcfc-140	0.10959	Styrene	0.43967
Dioxins, Measured As 2,3,7,8-Tetrachlorodibenzo-P-Dioxin	2112300	Benzene, ethyl-	0.00013123
Copper	55.48	Cadmium	101.72
Nickel	69.769	Barite	132.99
Chromium Vi	0.32362	Acenaphthylene	27544
Beryllium	90724	Arsenic	2.5675
Styrene	0.000050907	Sodium dichromate	0.12848
Formaldehyde	280.73	Acenaphthylene	27544
Arsenic	2.5675	Sodium dichromate	0.12848
Pah, Polycyclic Aromatic Hydrocarbons	27544	Lead	0.048931
Chromium, Ion	6.8646	Thallium	7955
Chloroform	0.042349	Ethane, 1,1,1-trichloro-, HCFC-140	0.10959
Toluene	0.29451	Phthalate, dibutyl-	76.409
Barium	14.992	Xylene	0.57983
Propylene Oxide	3.9649	Propylene oxide	0.00044122
Molybdenum	472.93	Thallium	7955
Mecoprop-P	30	Mercury	58.689
Copper	31.494	Chromium, ion	6.8646
M-Xylene	7.2348E-06	Phthalate, butyl-benzyl-	76.409
Methane, Bromo-, Halon 1001	0.032679	Vanadium, ion	8904.3
Cadmium	51.55	Benzene, pentachloro-	0.36814
Ethene, Chloro-	1.4091E-06	Ethene, trichloro-	0.000015545
Styrene	0.43967	Carbon disulfide	0.032959
Ethane, 1,2-Dichloro-	0.022783	Ethene, tetrachloro-	0.00041293
Cadmium	101.72	Cobalt	291
Acrolein	519.44	Formaldehyde	8.2559
Methane, Tetrachloro-, R-10	0.0002502	Barium	14.992

Beryllium	1.5677E-16	Mercury	1704.1
Thallium	182.16	Barium	35.879
Tin	0.12312	Lead	0.11644
Styrene	0.43967	Zinc, ion	91.085
Pah, Polycyclic Aromatic Hydrocarbons	27544	Formaldehyde	8.2559
Copper, Ion	1149.3	Methane, dichloro-, HCC-30	5.0188E-06
Mercury	1704.1	Benzene, dichloro	0.0028764
Hydrogen Fluoride	4.611	Acenaphthene	27544
Beryllium	20601	Phenol	1.5159
Chromium, Ion	8.8367E-23	Propylene oxide	0.036846
Zinc, Ion	91.085	Bentazone	8.2847
Methane, Dichloro-, Hcc-30	0.012289	Antimony	1.0111
Ethene	1.4259E-11	Barium	14.992
Benzene	0.091442	m-Xylene	0.000043747
Dichromate	1.7002E-22	Acenaphthene	0.11633
Tri-Allate	49.603		

Table XXXVII: GBEP Energy Consumption Impact Category

Flow	Impact Factor (MJ)	Flow	Impact Factor (MJ)
Electricity, Lignite Coal, At Power Plant	15.084	Energy, kinetic (in wind), converted	1
Energy, Primary, From Water Power	1	Energy, solar	1
Electricity, Nuclear, At Power Plant	11.25	Electricity, biomass, at power plant	15.52
Electricity, Diesel, At Power Plant	11.91	Electricity, cogenerated, at plant	1
Energy, From Biomass	1	Electricity, anthracite coal, at power plant	11.57
Electricity, Nuclear, At Power Plant	11.25	Energy, unspecified	1
Energy, Geothermal	1	Electricity, diesel, at power plant	11.91
Electricity, Natural Gas, At Power Plant	11.63	Electricity, biomass, at power plant	15.52
Electricity, Bituminous Coal, At Power Plant	15.39	Energy, from hydro power	1
Electricity, Residual Fuel Oil, At Power Plant	10.98	Electricity, natural gas, at power plant	11.63
Electricity, Residual Fuel Oil, At Power Plant	10.98		