Title

Life Cycle Environmental Impacts of Biofuels: The Role of Co-products

Author

Zhang, Yizhen

Publication Date

2018

Life Cycle Environmental Impacts of Biofuels: The Role of Co-products

By

YIZHEN ZHANG
DISSERTATION

Submitted in partial satisfaction of the requirement for the degree of

DOCTOR OF PHILOSOPHY

in

Transportation Technology and Policy

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

Alissa Kendall, PhD (Chair)

Jean VanderGheynst, PhD

Bryan M. Jenkins, PhD

Committee in Charge

2018

TO MY DEAR MOM.

Yizhen Zhang
December 2017
Transportation Technology and Policy

Life Cycle Environmental Impacts of Biofuels: The Role of Co-products

ABSTRACT

Biofuels are often forecast to provide significant reductions in the greenhouse gas (GHG) emissions from the transportation sector globally. Many countries have regarded bioenergy development as a solution to both climate change mitigation and foreign energy dependence. It is projected that biofuel production may contribute up to a quarter of transportation fuel supply by 2050. But uncertainties and concerns still remain with respect to the environmental performance of biofuels, including their contribution to GHGs. Life cycle assessment (LCA) is a powerful tool for evaluating the environmental impacts of emerging technologies. However, existing LCAs are inconsistent in their selection of system boundaries, modeling assumptions, and treatment of co-products, which lead to wide variations in results, and make the comparisons of biofuel pathways challenging. Co-products usually play an essential role in biofuel production system, both economically and environmentally. Thus the treatment strategies of co-product are considered critical to LCA results.

Studies presented in this dissertation assess several types of biofuels, including first generation, second generation and advanced biofuels, which are produced from terrestrial feedstocks (e.g., corn grain and corn stover) and algae. A variety of researchers have identified the importance of treating co-products in LCAs. This study focuses on the improvement of LCA methodology for assessing biofuel co-products. This dissertation contributes to current knowledge and methodology in following ways: 1) it develops a comprehensive life cycle energy, carbon and water model for microalgae biofuel production 2) it improves co-product allocation strategies in LCA; and 3) it explores the indirect impacts on ocean resources induced by algal oil production at large scale, which has not been examined previously.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

First and foremost, a special thank needs to be given to my mentor and advisor, Dr. Alissa Kendall, for encouraging me and supporting me throughout the last five years. You have been so instrumental in my growth during my PhD studies. You taught me how to be a better researcher and a reviewer. And you always believed in me. I would like to acknowledge my committee members Dr. VanderGheynst and Dr. Jenkins for their support and guidance. I truly appreciate all that you have done for me.

I would like to thank Kiara and ALL of my fellow graduate students. Thanks for always being supportive to each other, making our research group productive and full of fun. I want to thank my best friends, Derek and Eli, for sharing my passion for renewable energy, and staying by my side through the raining and snowing days.

Finally, I would like to thank my family, my dearest parents for loving me all the time. Thanks for bringing me up into a happy and strong person. You are always my biggest inspiration. Thank you for everything, Dad and Mom.

Chapter 1 Introduction

1.1 Background

In order to achieve the goal of reducing greenhouse gas (GHG) emissions, dependency on fossil fuels, and dependency on imported fuels, a large supply of low carbon renewable transportation fuels is required in the near future. Biofuels are expected to play a substantial role in achieving these goals globally. For example, in the European Union (EU), a 33% increase of biomass based energy by 2020 from 2013 has been set forth in the National Renewable Action Plans (NREAPs) [1]. By the year 2022, 36 billion gallons of renewable fuel will be blended into transportation fuels based on mandates from the U.S.' expanded Renewable Fuel Standard (RFS2). RFS2 categorizes biofuels into four groups, including conventional biofuel, cellulosic biofuel, biomass-based diesel and advanced biofuels, where the latter two are required to have at least 50% lower life cycle GHG emissions, or carbon intensity (CI), than conventional petroleum diesel [2]. In California, renewable fuels including biofuels are promoted by the Low Carbon Fuel Standard (LCFS), which seeks to reduce the CI of transportation fuels by 10% in 2020 based on a sales-weighted average [3].

Many policies, including RFS2 and LCFS, require a known CI of each fuel included in the program to assure the reduction of carbon emissions using a life cycle assessment (LCA) approach. LCA attempts to measure the full, or system-wide, environmental impacts of products and systems. In the U.S. and EU, the increasing use of LCA-based analysis to evaluate the performance of biofuels and mitigate climate change in policies has indicated the usefulness of LCA as a tool for decision-making, and revealed the challenges of developing environmentally preferable and sustainable biofuel pathways.

Most biofuel production processes are complex, multi-functional systems. They produce biofuel products along with economically valuable co-products, such as animal feed and fertilizers. Those co-products are usually important for determining both the economic viability and environmental performance of biofuels. The challenge and implication of handling co-products in LCAs for biofuel production systems have been widely discussed by researchers [4-7]. In this dissertation, a closer examination and modeling of co-product utilization and the methods of handling them in LCA is conducted.

1.2 LCA Methodology for Handling Co-products

1.2.1 Closed-loop and Open-loop Systems

Different treatment strategies for co-products can reflect different system design concepts. A *closed-loop system* is defined when reusing and recycling of co-products occur within the production system, so that the system boundary of analysis can contain just the production system. An *open-loop system* is defined when co-products are utilized outside the systems boundary. It is often necessary to expand the system boundary to include relevant markets for the co-products. A comparison diagram for open- and closed-loop system is shown in Figure 1-1.

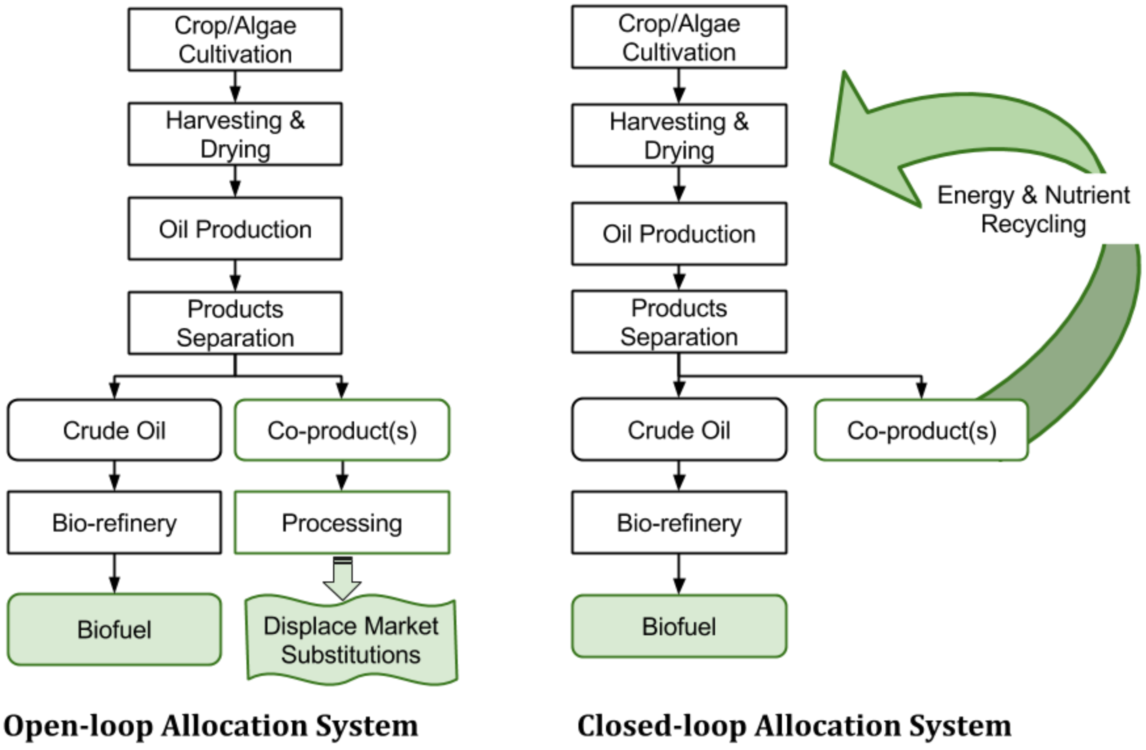

Figure 1-1Comparisons of Open-loop System and Closed-loop System

A closed-loop system reuses the co-product within the system and displaces input materials with no allocation approach needed. A closed-loop system recycles every co-product, avoiding entirely the allocation process and thus results in fewer uncertainties of environmental impacts. Its drawback is the loss of potential economic value from co-products. If the co-product is recycled or utilized outside the production system, an "open-loop" allocation problem occurs [8]. For example, biofuel co-products such as distiller's grains and solubles from corn ethanol, or algae cake from algae biodiesel, may create higher market value when used as animal feed than recycled within their respective production systems. Occasionally, higher-value co-products may also be generated. For example, pharmaceutical or nutraceutical co-products from algae could displace those originally produced from fish, e.g. omega-3 fatty acids for DHA, thus avoiding the environmental impacts from pelagic fisheries and aquaculture farming.

Instead of attributing environmental burdens solely to the biofuel, the environmental impacts should be re-evaluated and re-distributed between the biofuel and its co-products. We call the corresponding methods co-product allocation. In an open-loop system, various allocation approaches can be applied to estimate environmental impacts of the primary product. We describe them in following section.

1.2.2 Allocation Methodology

In the LCA of a biofuel production system, practitioners often face the challenge of choosing the right co-product allocation approach. While more than one method can be applied, it is unclear which method is the most applicable [9]. Allocation methods include partitioning methods and system expansion. The former divides the environmental flows for the system based on physical causality or property such as mass, energy content, or economic value. The latter (i.e., displacement method) expands the product system to include additional procedures related to the co-product [8]. Guidelines for selecting co-product allocation methods are given in ISO 14044 developed by The International Organization for Standardization (ISO) [10]. According to ISO 14044 (2006), the stepwise procedure for co-products handling is described below:

"Step 1: Wherever possible, allocation should be avoided by: 1) Dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes. 2) Expanding the product system to include the additional functions related to the co-products, taking into account the requirements of function, functional unit and reference flow.

Step 2: Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them, i.e., they shall reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system. The resulting allocation will not necessarily be in proportion to any simple measurement such as mass or molar flows of co-products.

Step 3: Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products." (ISO 14044, p. 14).

LCA results are significantly affected by the allocation methods used for partitioning environmental burdens to primary products (e.g., biofuels) and co-products and the assumption of co-product utilization [11]. Different allocation methods could be favored by different co-product utilization assumptions in a biodiesel production system [6]. But it is difficult to harmonize among different studies due to the differences in system boundaries, pathway designs, and quantities and quality of products. As recommended by the ISO standard, LCA practitioners have commonly adopted the displacement method. When system expansion cannot be used, and partitioning methods have to be used, several studies have advocated economic allocation that divides emissions and energy burdens to products based on economic revenue [12-15]. Value-based (economic) allocation and energy-based allocation tend to present similar results when the products are all energy or fuel based products [11, 16], because the market value of each product is priced roughly based on the energy content and results in similar impact values. In a mature market, the market price of one product should represent the manufacturing cost which is eventually the total input of material and energy of one product. Thus the value-based allocation should provide a rational basis for how the environmental impacts should be allocated among products. Other partitioning-based allocation methods, such as mass-based allocation, are less applicable to a biofuel LCA compared to energy-based and value-based allocation because energy is usually the output function [17]. Numerous studies have tested the weaknesses and advantages of each allocation method, and sometimes a hybrid allocation approach is employed to present a realistic utilization of the energy products and co-products. But there is no agreement on which allocation method is the best for biofuel LCA, and comparing several application approaches is recommended for case studies [17].

1.2.3 Displacement Method and Consequential Effects

Displacement methods examine the role of co-products in the market and attempt to quantify their value by modeling substitutable products. For example, if a biofuel production system generates a co-product used as feed, substitutable feed products on the market are used to estimate the environmental value of the generated co-product. This environmental value is then attributed to the producing system. Although the displacement approach is considered the default allocation method, it has been critiqued with two main challenges: 1) the difficulty of quantifying the amount of displaced conventional product and to assessing life cycle impacts of that conventional product; 2) the distorted impacts assigned to the fuel product when a co-product’s displacement credit is so high as to have net negative environmental impacts on the biofuel [12]. The latter is a particular challenge because there is no question that the biofuel production system has environmental impacts from an accounting perspective, but when a consequential approach is used like displacement (i.e. by providing a co-product to the market that in theory displaces some other substitutable product), an unrealistic outcome may occur. While this study does not definitively address and solve these problems, Chapter 2 and Chapter 3 attempt to improve displacement method, by better capturing market choices of displaced commodities and realistic quantification of displacement effects.

Along with displacement issues, the consequential effects of biofuels, have been discussed by recent researchers and recognized by policy regulations [18-20]. In particular, land use change effects, including direct land use change (DLUC) and indirect land use change (iLUC), have been particularly important consequential effects of biofuels, due to expansion of crop cultivation for biofuel production and competition for agricultural resources with food crops. The induced consequential land use change effects have ramifications for food security, GHG emissions, and other environmental impacts such as soil organic carbon (SOC) and biodiversity loss. Meanwhile, the use of biofuel co-products in various animal diets has mitigative effect for the competition between fuel crops and food crops, thus avoids some land use change by displacing livestock feeds [20].

The utilization of biofuel co-products as animal feeds has been researched and optimized for years [21]. Among the various types of biofuels, algae derived biofuels are considered one of the most promising petroleum fuel substitutes due to its advantage of few iLUC effects. It also avoids competition on fertile lands with food crops. The consequential impacts from algae biofuels have been ignored [22]. Consequential impacts on biodiversity reduction and SOC loss depending on DLUC of algae biofuel have been conducted and quantified in recent studies [22, 23]. However, research on the consequential impacts from biofuels have focused on terrestrial land and resources. Algae, however, may be more consequential for ocean resources.

Algae biomass has been used in fish feed for decades, and it has the potential for use as a fishmeal substitute and thus may reduce demand for wild fish catch. While impacts on ocean resources have been considered in LCAs of fisheries and aquaculture systems, they have not been previously considered in the context of algae-based production systems. This dissertation examines the consequential effects of algae-based biofuel systems on ocean resources using the cause-effect method commonly used to estimate DLUC in terrestrial biofuel assessments. A novel method for estimating consequential impacts on ocean resources is proposed and applied in Chapter 4.

1.3 Objectives and Organization of the Dissertation

The broad objectives of this dissertation are to analyze and compare effects of co-product handling strategies (where handling refers both to actual utilization of co-products and methodological choices for co-product allocation) in different biofuel production systems within harmonized system boundary and modeling assumptions, and to develop a new method and conduct consequential effect analysis on ocean resources due to co-products from algal biofuel production.

This study contributes to current knowledge and methodology in the following ways:

1) it develops a comprehensive life cycle energy, carbon and water model for microalgae biofuel production with the capability of capturing variability due to technology choices and co-product handling strategies;

2) it improves co-product allocation strategies in LCA for different biofuel production systems including first generation (corn ethanol), second generation (corn stover cellulosic ethanol) and advanced biofuels (algae based biofuels);

and 3) it explores the indirect impacts induced by algal oil production at large scale and expands the scope of relevant impact categories for algal biofuel LCAs.

This research is presented in the following order:

Chapter 2 presents a detailed model for two algal biofuel production pathways. The optimal algal oil production pathway is determined by comparing open-loop and closed-loop systems, considering not only the estimated net environmental impacts but also the confidence or uncertainty of those outcomes.

Chapter 3 deploys a retrofitted corn ethanol plant to simulate the effects of co-products. The model discusses existing co-product allocation methodologies and issues in an integrated biofuel system, and explores improved solutions for co-product allocation methods.

Chapter 4 presents a novel extension of existing environmental impact assessment for algae biodiesel production. The consequential impact on ocean resource depletion of algae production is evaluated using a midpoint indicator of net primary productivity.

1.4 References

1. Dafnomilis, I., et al., *Review of solid and liquid biofuel demand and supply in Northwest Europe towards 2030 – A comparison of national and regional projections.* Renewable and Sustainable Energy Reviews, 2017. **78**(Supplement C): p. 31-45.
2. EPA. *Overview for renewable fuel standard*. [cited 2017 Nov 10]; Available from: https://www.epa.gov/renewable-fuel-standard-program/overview-renewable-fuel-standard.
3. CARB, *Low Carbon Fuel Standard (LCFS) Final Regulation*, C.A.R. Board, Editor. 2006, Assembly Bill No.32: California.
4. Kendall, A. and J. Yuan, *Comparing life cycle assessments of different biofuel options.* Current opinion in chemical biology, 2013. **17**(3): p. 439-443.
5. Kendall, A. and B. Chang, *Estimating life cycle greenhouse gas emissions from corn–ethanol: a critical review of current US practices.* Journal of Cleaner Production, 2009. **17**(13): p. 1175-1182.
6. Zaimes, G.G. and V. Khanna, *The role of allocation and coproducts in environmental evaluation of microalgal biofuels: How important?* Sustainable Energy Technologies and Assessments, 2014. **7**: p. 247-256.
7. Canter, C., et al., *Policy Implications of Allocation Methods in the Life Cycle Analysis of Integrated Corn and Corn Stover Ethanol Production.* BioEnergy Research, 2015: p. 1-11.
8. ISO 14044, *Environmental management — Life cycle assessment — Requirements and guidelines*. 2006, International Standard: Switzerland.
9. Flysjö, A., et al., *How does co-product handling affect the carbon footprint of milk? Case study of milk production in New Zealand and Sweden.* The International Journal of Life Cycle Assessment, 2011. **16**(5): p. 420-430.
10. ISO, *ISO 14044 Environmental management — Life cycle assessment — Principles and framework*. 2006.
11. Hoefnagels, R., E. Smeets, and A. Faaij, *Greenhouse gas footprints of different biofuel production systems.* Renewable and Sustainable Energy Reviews, 2010. **14**(7): p. 1661-1694.
12. Wang, M., H. Huo, and S. Arora, *Methods of dealing with co-products of biofuels in life-cycle analysis and consequent results within the US context.* Energy Policy, 2011. **39**(10): p. 5726-5736.
13. Mendoza, A., et al., *The allocation problem in bio-electricity chains.* Report of a Project Group as part of the MSc. Leiden, The Netherlands: Industrial Ecology, Institute of Environmental Sciences (CML), 2008.
14. Lardon, L., et al., *Life-cycle assessment of biodiesel production from microalgae.* Environmental science & technology, 2009. **43**(17): p. 6475-6481.
15. Lam, M.K., K.T. Lee, and A.R. Mohamed, *Life cycle assessment for the production of biodiesel: a case study in Malaysia for palm oil versus jatropha oil.* Biofuels, Bioproducts and Biorefining, 2009. **3**(6): p. 601-612.
16. Wang, M., H. Lee, and J. Molburg, *Allocation of energy use in petroleum refineries to petroleum products.* The International Journal of Life Cycle Assessment, 2004. **9**(1): p. 34-44.
17. Cherubini, F., A.H. Strømman, and S. Ulgiati, *Influence of allocation methods on the environmental performance of biorefinery products—A case study.* Resources, Conservation and Recycling, 2011. **55**(11): p. 1070-1077.
18. Baral, A. and C. Malins, *Assessing the climate mitigation potential of biofuels derived from residues and wastes in the European context.* ICCT. Washington DC http://www/. theicct. org/sites/default/files/publications/ICCT_biofuels_wastes-residues_20140130. pdf, 2014.
19. Esteves, V.P.P., et al., *Assessment of greenhouse gases (GHG) emissions from the tallow biodiesel production chain including land use change (LUC).* Journal of Cleaner Production, 2017. **151**: p. 578-591.

20. Weightman, R., et al., *Opportunities for avoidance of land-use change through substitution of soya bean meal and cereals in European livestock diets with bioethanol coproducts.* Gcb Bioenergy, 2011. **3**(2): p. 158-170.
21. Shurson, G.C., *The Role of Biofuels Coproducts in Feeding the World Sustainably.* Annual Review of Animal Biosciences, 2017. **5**(1): p. 229-254.
22. Fortier, M.-O.P., et al., *Determination of the life cycle climate change impacts of land use and albedo change in algal biofuel production.* Algal Research, 2017. **28**(Supplement C): p. 270-281.
23. Correa, D.F., et al., *Biodiversity impacts of bioenergy production: Microalgae vs. first generation biofuels.* Renewable and Sustainable Energy Reviews, 2017. **74**(Supplement C): p. 1131-1146.

Chapter 2 Effects of System Design and Co-product Treatment Strategies on the Life Cycle Performance of Biofuels from Microalgae

2.1 Introduction

Interest in biofuels derived from microalgae as an alternative to traditional energy crops is growing because it may avoid some of the consequential effects of terrestrial oil crops [1]. Besides high productivity and oil content, microalgae require significantly less land area and do not require fertile cropland. However, microalgae require a large amount of fertilizer during cultivation to achieve high oil productivity. And the energy input during harvesting and dewatering of the biomass is intensive. Many life cycle assessment (LCA) studies of algal oil production have been done to evaluate environmental impacts and identify energy intensive processes of the system with various assumptions on growth parameters and oil extraction or conversion technologies, and results from these studies show greenhouse gas (GHG) emissions from algae biodiesel varied from 20 to 500 g CO_2e /MJ, while the energy return on energy investment (EROI) of algae biodiesel ranged from 0.2 to 6 [2]. This range of values is the result of both method- and model-induced variability and real variability in the performance of current and simulated future systems [3].

The sources of method and model-induced variability are many, and among them the methods used to treat co-products stand out as requiring additional study and guidance. Most biofuel production processes are multi-functional systems that produce biofuel products along with economically valuable co-products such as algal cake that may be used as animal feed and fertilizers. In the LCA of a biofuel production system, practitioners often face the challenge of co-product allocation, because usually more than one method can be used to handle co-products and there is no commonly shared understanding on when different methods are applicable [4]. Instead of assigning environmental burdens solely to the biofuel, some methods are required to represent impacts attributable solely to the biofuel, or distribute the environmental impacts between the biofuel and co-products.

The allocation methods used for partitioning environmental burdens to primary products such as biofuels and co-products and the assumption of how co-products are utilized can significantly affect the results of a LCA [5]. Moreover, different allocation methods might be favored by different co-product utilization assumptions, meaning the choice of allocation method might be affected by utilization choices [6]. While harmonizing allocation methods across different studies could address this, due to differences in system boundaries, pathway designs, and quantities and quality of products this is often impossible. Numerous studies have tested the weakness and advantages of each allocation method, and sometimes a hybrid allocation approach is employed to present a realistic utilization of the energy products and co-products. However, there is no agreement on which allocation method is the best for biofuel LCA, and comparing several allocation approaches is recommended for case studies [7, 8].

This research explores the real, method-induced, and model-induced variability of algal biofuels by comparing two algal fuel pathways, renewable diesel from hydrothermal liquefaction (HTL) and biodiesel from a solvent-based lipid extraction (LE) process. Each of these pathways generates different co-products that can be utilized in different ways, and which can be accounted for using different allocation methods.

2.2 Materials and Methodology

2.2.1 Goal and Scope

The objective of this study is to evaluate and compare the life cycle GHG emissions and energy performance of biodiesel and renewable diesel produced from microalgae through two technology pathways under different co-product treatment strategies using a process-based, prospective LCA approach. LCA is a technique for evaluating the environmental aspects and potential environmental impacts of a product throughout its life cycle, considering the full supply chain of inputs (14040, 2006). Life cycle energy and GHG assessments are a narrow application of the LCA method, since full LCA considers a suite of impact categories.

The research presented here applies this narrow form of LCA, accounting for energy, direct water consumption (meaning indirect and upstream water use are not accounted for) and global warming potential (GWP). Energy and water consumption are reported simply as inventory values (e.g. MJ of energy and liters of water). GHGs are reported in units of CO_2-equivalent (CO_2e). The IPCC's 100-year GWPs are used to convert non-CO_2 emissions into CO_2e (28 for biogenic CH_4, 30 for fossil CH_4, and 265 for N_2O) [9]. This means that 1 kg of methane released is equivalent to 30 kg of CO_2 released when assessed over a 100 year period.

2.2.2 System Definition and Boundary

The system boundary of the two pathways (the LE pathway and HTL pathway) is illustrated in Figure 2-1. The scope of this analysis is "cradle-to-gate," meaning that the analysis stops at the biorefinery gate. Thus, the life cycle stages included in the analysis are microalgae cultivation in open raceway ponds (ORPs), algae harvesting and dewatering, biocrude production via LE or HTL, conversion of bio-crude oil into the final energy product (biodiesel or renewable diesel), and utilization of co-products. Figure 2-1 describes the steps in each of the considered pathways.

The processes of algae cultivation, harvesting and dewatering, drying, oil extraction, and utilization of residual biomass occur within the same facility, from there the crude oil is transported to a nearby refinery for conversion to biodiesel or renewable diesel. Construction, repair and maintenance of infrastructure, production of equipment and waste management are excluded from the system boundary. The functional unit of analysis is 1 MJ of algal biofuel, although 1 kg of dry biomass is used as a modeling unit of analysis to assess the material and energy consumption in each unit process in the life cycle inventory (LCI) assessment.

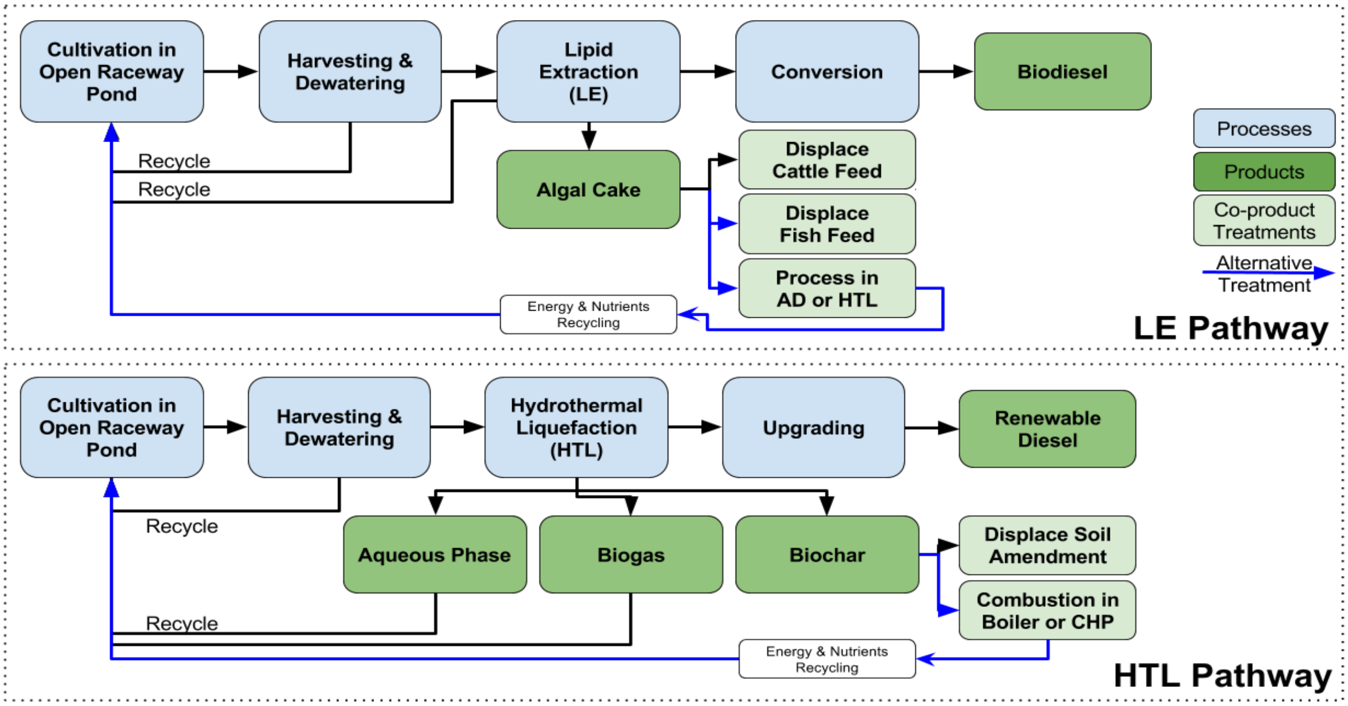

Figure 2-1System Description of Algal Biofuel Production through LE and HTL Pathway

2.2.3 The Microalgae Cultivation, Harvesting and Dewatering

The cultivation model of the microalgae Scenedesmus *dimorphus*, grown in ORPs, is adopted from previous work [10]. The production facility of 400 acres of open raceway ponds are assumed to be located in southern New Mexico (which determines water quality, groundwater depth for water pumping and evaporation rates), with pond dimensions of 100 meters by 10 meters and a water depth of 0.3 meters.

In previous research [10], four combinations of technologies for harvesting and dewatering were considered, including bioflocculation followed by dissolved air flotation (DAF) and centrifugation, flocculation with polymer followed by DAF and centrifugation, flocculation with alum followed by DAF and centrifugation, and centrifugation only. The most efficient harvesting and dewatering technology route was found to be bioflocculation following DAF and centrifugation, because bioflocculation required no chemical inputs. These are used in the current model as the default harvesting and dewatering route. We assume no chemicals are used for bioflocculation. After dewatering, the density of microalgae biomass is assumed to be 180 g/L. Table 2-1 summarizes key parameter assumptions, material inputs, and energy inputs during the algae cultivation and harvesting stage.

Table 2-1 Growth model assumptions and input summary for cultivation, harvesting and dewatering (all parameters are dry weight based)

Modified Growth Model			
Parameter settings	Unit	Input	Data Source
Growth rate	g/m^2/day	25.00	[10]
Lipid content	wt%	25.00	[10]
Protein	wt%	32.15	[10]
Carbohydrate	wt%	34.85	[10]
Ash	wt%	8.00	[10]
C	g/kg biomass	500.00	[10]
N	g/kg biomass	52.50	[10]
P	g/kg biomass	12.92	[10]
CO_2 requirement	kg/kg biomass	1.83	[10]
CO_2 use efficiency		0.87	[10]
Ammonium nitrate (NH_4NO_3) requirement	kg/kg biomass	0.15	modeled
Triple superphosphate ($Ca(H_2PO_4)_2$) requirement	kg/kg biomass	0.10	modeled
Energy for CO_2 injection	MJ/kg biomass	0.18	[10]
Energy for paddlewheel	MJ/kg biomass	0.68	[10]
Energy for water pumping	MJ/kg biomass	0.78	[10]
Energy for water pumping within the system	MJ/kg biomass	0.76	[10]
Mixing energy for flocculation	MJ/kg biomass	0.0032	[10]
Energy for DAF	MJ/kg biomass	0.1203	[10]
Biomass recovery from harvesting		90%	[10]
Biomass recovery from dewatering		96%	[10]
Electricity for centrifugation	MJ/kg biomass	0.576	[10]
Polymer Use for DAF	g/kg biomass	20	[10]
Water content after dewatering	L/kg biomass	5.56	[10]
Water Evaporation rate	L/m^2/day	5.97	[10]
Evaporation Loss	L/kg biomass	238.66	[10]
Pond Area	ha	400.00	[10]
Annual Biomass Yield	tonne/ha/yr	75.00	[10]

2.2.4 Algae Renewable Diesel Production through HTL Pathway

HTL is a thermochemical process involving the reaction of biomass in water at subcritical temperatures (below 374 °C) and high pressure (10–25 MPa) for a certain reaction time with or without the use of a catalyst [11]. Among the major thermochemical processing pathways, including HTL, HTG (hydrothermal gasification) and pyrolysis, HTL is considered the most promising technology for relatively high energy efficiency [12, 13]. HTL yields a product typically referred to as bio-crude or bio-oil along with gaseous, aqueous (liquid) phase, and solid phase (char) streams. Energy recovery may occur through the combustion of char and bio-crude to generate heat. The nutrient-rich liquid stream can be recycled into the cultivation pond as a nutrient supply for microalgae growth, while the gaseous fraction is composed mostly of CO_2 which can be reused for algae cultivation. In order to model the HTL process under different operation conditions, a mathematical kinetic HTL model was employed [14]. The LCA model includes nutrient recycling and six co-product allocation strategies.

2.2.4.1 HTL modeling

The kinetic HTL model developed by Valdez et al. (2014) estimates product quantities including crude oil, aqueous phase, gas phase and solid phase as a function of the characteristics of the algae feedstock [14]. The model provides four operating conditions, 250°C, 300°C, 350°C and 400°C, with retention times ranging from 1 to 90 minutes. The HTL product yields reflect the biochemical composition of microalgae and the operating conditions of the HTL system. Unfortunately, this kinetic model is not capable of defining the properties of each product. Instead the C and N content in each product are estimated from empirical data in the literature (as described in section 2.2.2.2).

Based on the kinetic modeling of HTL, operation conditions of 350°C for 15 minutes is the optimal scenario because it requires low energy inputs and yields a large amount of biocrude oil, thus it is used as the default condition for modeling. Detailed HTL production results can be found in the supplementary material. Below some of the key features and assumptions beyond the kinetic modeling of the HTL technology pathway are described:

- *HTL Process Model:* The HTL process energy demand is assumed to be equal to the energy needed to heat the medium to operation temperature from ambient temperature at 20°C [15]. A spiral tube heat exchanger is integrated in the system, to re-heat the incoming biomass with the outgoing streams from HTL reactor, assuming 80% of HTL heat can be recovered with 85% efficiency [16]. Additional energy is needed to meet process energy demands; grid electricity is used for pumping, and natural gas (NG) is used for the remaining heat demand not met by heat re-circulation. NG is assumed to be combusted in a boiler with 85% efficiency.

- *HTL Products Separation.* There is currently no consistent method used for separation of the HTL products [17]. Various methods including water separation, solvent separation, filtration, vacuum and centrifugation were reported to separate solid and oil under lab conditions [18, 19]. Due to the inconsistency and lack of data, the separation process is omitted in this analysis.
- *Bio-crude Upgrading.* Bio-crude from HTL has high potential for co-processing with petroleum crude oil in conventional refineries to produce renewable transportation fuels such as renewable diesel, which has the identical properties as conventional diesel [20, 21]. However, the bio-crude has higher oxygen, nitrogen and sulfur content than conventional crude oil. Because of the high oxygen content, an additional process for removing oxygen from the bio-crude, deoxygenation, is recommended before the co-processing [17]. However, we assume biocrude oil can be co-processed directly with petroleum crude in a refinery [20]. The upgrading process of biocrude oil to renewable diesel is modeled using the refinery process of crude oil from the GREET model [22]. Inputs and outputs of the HTL pathway are summarized in Table 2-2.

Table 2-2 Inputs and Outputs Summary of HTL Pathway at 350°C for 15 minutes (dry weight based)

Parameter	Unit	Value	Data source
HTL Electricity	MJ/kg biomass	0.001	modeled
HTL Natural Gas (NG)	MJ/kg biomass	0.003	modeled
Biocrude Oil	Kg/kg biomass	0.420	modeled
Gas Phase	Kg/kg biomass	0.014	modeled
Aqueous Phase	Kg/kg biomass	0.485	modeled
Solid Phase	Kg/kg biomass	0.081	modeled
Pumping Electricity	MJ/kg biomass	0.001	[10]
Oil Upgrading Electricity	MJ/kg biomass	0.05	[22]
Oil Upgrading NG	MJ/kg biomass	0.80	[22]
Oil Upgrading H_2	MJ/kg biomass	0.20	[22]
Oil Upgrading Gasoline	MJ/kg biomass	0.002	[22]
Oil Upgrading Water	Gallon/kg biomass	0.16	[22]
Renewable Diesel	MJ/kg biomass	15.05	modeled
N recycled from Aqueous phase	g/kg biomass	26.25	modeled
P recycled from Aqueous phase	g/kg biomass	10.33	modeled
Ammonium nitrate input after recycling	kg/kg biomass	0.08	modeled
Triple superphosphate input after recycling	kg/kg biomass	0.02	modeled

2.2.4.2 Co-products from HTL

When using HTL as the oil conversion technology, co-products including the nutrient-rich aqueous phase, gaseous phase and bio-char, can all be reused within the production system to reduce the primary fertilizer, CO_2 and energy inputs demand by the system [15, 23-26].

- *Gaseous Phase Product (Recirculated CO2).* Based on experimental studies, the gaseous stream separated from the HTL products is primarily composed of CO_2 [27-29]. We model that 90% of gaseous phase is CO_2 and 100% of the gaseous phase is recycled to cultivation pond.
- *Aqueous Phase Product (Recirculated Nutrients).* Nutrient recycling is accomplished by recirculating the aqueous phase HTL product to the ORPs. The recirculated fluid assumed to reduce fertilizer input. It is reported that 15% to 95% of input N and 20% to 95% of input P are

retained in the liquid phase and thus can be recycled for algae cultivation [24, 30-34]. This is an enormous potential range, and in this model 50% of input N and 80% of input P are assumed to be recycled. Uncertainty in nutrient reccyling rates are tested at three levels: low (15% of N, 20% of P), default (50% of N, 80% of P), and high (95% of N, 95% of P).

- *Solid Phase Product (Biochar)*. Biochar is the solid residue consisting of inorganics and the remaining organic matter after HTL of algae [29, 35]. Products obtained from the HTL model exclude ash content of the biomass, so ash is added to the solid phase and assumed to be part of biochar. Thus the biochar modeled in current research contains ash and is rich in inorganics. Biochar used as soil amendment has been investigated for soil fertility improvement and carbon sequestration in agricultural systems and forest systems by numerous studies [36]. Biochar additions were shown to increase growth-limiting nutrients to plants, such as phosphorus and calcium [36]. The composition of biochar varies with the operating conditions and feedstocks, but a typical N content of biochar is 0.5% [37]. Biochar can provide nutrients to soil, change the nutrient efficiency of cropping systems, but it is also found to result in adverse effects such as increased N leaching potential from soil as reported by Zhao et al. (2014) [38]. Because current study focuses on the displacement of fertilizers and GHG emissions from biochar, the effects on soil organic carbon and leaching of biochar are excluded from modeling. Wang et al. (2014) reported that the application of biochar from pyrolysis as soil amendment for corn cultivation increased fertilizer efficiency and crop yields, reduced N_2O emissions from soils by 20% to 80%, and increased soil organic carbon [37]. This study adopts the assumptions from Wang et al. (2014), assuming a onetime application of 30-tonne/ha biochar on a soil planted with corn would reduce fertilizer application by 10% in the year following and N_2O soil emissions by 30% [37].

2.2.5 Algae Biodiesel Production through the LE Pathway

Lipid extraction is a widely modeled microalgal biodiesel production pathway. In contrast to lipid extraction from dry biomass, a wet lipid extraction technology is preferred for microalga because it avoids extensive thermal input for drying while still yielding relatively high crude oil. The extracted lipid is assumed to be transported and processed in a biorefinery. The algal biomass remaining after LE (algal cake) and glycerol co-produced from transesterification are two co-products that can be used in various applications.

2.2.5.1 LE Pathway Modeling

The model of lipid extraction from wet algae biomass using hexane extraction is adopted from Yuan et al. 2014 [10]. Transesterification is the conversion technology used to convert crude algal oil to biodiesel. With production of 1 kg dry algae biomass, the yields of biodiesel, glycerol and algal cake are 5.75 MJ, 17 g and 0.84 kg, respectively.

2.2.5.2 Co-products from LE Pathway

Algal cake and glycerol are co-products from the LE and transesterification route. The modeled algal cake composes 8% lipid, 39% protein, 43% carbohydrate and 10% ash (dry weight based). This nutrient rich algal cake has great potential to be used for animal feed, fish feed or organic fertilizer; the energy and nutrients can also be recycled and reused in the microalgae cultivation processes through energy recycling technologies. Glycerol can displace synthetic glycerol with a 1:1 mass ratio [10], though currently glycerol from biodiesel production is the dominant source in the U.S. market.

Previous studies have considered the utilization and allocation strategies for coproducts generated from the LE pathway. Lardon et al. (2009) and Passell et al. (2013) partitioned environmental burdens between biodiesel, algal cake and glycerol using energetic allocation [39, 40]. Shirvani et al. (2011) and Batan et al. (2010) applied a displacement approach assuming the algal cake displaced animal or aquaculture feed and glycerol displaced glycerol production from other process [41, 42]. Other studies attempted to reuse and recycle nutrients and energy *within* the oil production system by applying additional treatments to the algal cake using anaerobic digestion (AD), hydrothermal gasification (HTG), gasification or direct combustion [10, 13, 25, 43, 44].

2.2.6 Co-product Treatment Methods

Allocation methods include partitioning methods and system expansion that expands the product system to include the displacement effects of a co-product on substitutable products in the market [45], where the displacement method and economic allocation are more recommended by several studies and economists than energy and mass based allocation methods [7, 39, 46-48]. An alternative to utilizing co-products in the market is the reuse and recycling co-products within the production system to reduce material inputs, leading to a closed-loop production system. A closed-loop system avoids uncertainties from co-product allocation issues and is advocated under the concept of circular economy [49]. We have considered potential applications of co-products from the two algae biofuel pathways, and investigated different treatment methods in the following section.

2.2.6.1 Co-product Treatment - HTL

Six co-product utilization scenarios and four co-product allocation strategies based on co-products of the HTL process are investigated (Table 2-3). Recycled nutrients are assumed to displace synthetic fertilizers. Recycled CO_2 gas for algae cultivation displaces CO_2 that would otherwise be piped in. The bio-char is the only co-product that requires allocation strategies. System expansion methods are the default co-product allocation approach, but economic allocation and energy allocation are also included.

Table 2-3 Scenario Description of Co-product Treatment for HTL Pathway

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
Bio-char	Economic Allocation	Energy Allocation	Mass Allocation	Soil Amendment Displacement	Combusted in CHP* to produce Heat and Electricity	Combusted in Boiler to produce Heat
Aqueous Phase	Recycled	Recycled	Recycled	Recycled	Recycled	Recycled
CO_2	Reused for Cultivation	Reused for Cultivation	Reused for Cultivation	Reused for Cultivation	Reused for Cultivation	Reused for Cultivation

*CHP=Combined heat and power system

Scenario 1: Economic Allocation

Economic allocation is an alternative approach to displacement calculations; it partitions the impacts of a production system among co-produced products based upon the economic value of each product. In this study, the price of renewable diesel is assumed to have the same market value of conventional diesel of $3.06/gallon [50].

The price of biochar is assumed to be equal to or less than agrichar and charcoal, reported in a large range from $0.08/kg to $13.5/kg. A mean value of $2.65/kg of biochar was used [51, 52].

Scenario 2: Energy Allocation

Energy allocation is similar to economic allocation, but partitions the impacts based on the energy value of each product. The higher heating value (HHV) of biochar and crude oil are used to calculate the energy content in each. In this scenario, the environmental impacts are allocation based on energy content divided between crude oil and biochar, and upgrading of crude oil to renewable diesel is included separately.

HHV of biochar is reported from 5 to 15 MJ per kg [53-55], the HHV of crude oil ranges from 33.6 to 37.3 MJ per kg [30, 54, 56], and the HHV of renewable diesel is assumed to be the same as conventional diesel at 37 MJ/kg. A conservative value as 7 MJ/kg is used for HHV of biochar and 35.7 MJ/kg is used for crude oil.

Scenario 3: Mass Allocation

The mass allocation method partitions environmental impacts based on mass of biochar and biodiesel. The mass of biochar and crude oil resulting from HTL varies under different operation conditions as modeled. The renewable diesel mass is estimated using bio-crude upgrading efficiency at 99% [22].

Scenarios 4: System Expansion

Biochar is used as a soil amendment that can reduce 10% of fertilizer application and 30% of N_2O emission from the field as described previously. Fertilizer inputs for California corn production are used for evaluating the environmental benefits of biochar as soil amendment. The GHG emission from fertilizer application on a typical California corn farm is 270 kg CO_2e per hectare with 4.54 kg N_2O emission per hectare [57]. Fertilizer input data are adopted from University of California–Davis (UCD) cost and return studies [58-61]. The potential for long-term carbon sequestration is not considered.

Scenario 5: Closed-loop co-product utilization

Biochar is combusted in a combined heat and power (CHP) unit and displaces natural gas and grid electricity. The efficiency of CHP to convert biochar into electricity and heat is 36% and 50%, respectively. The energy content in biochar is estimated using the HHV of biochar at 7 MJ/kg [53-55].

Scenario 6: Closed-loop co-product utilization

Biochar is combusted in a boiler to produce heat and displace natural gas use on site. The boiler operates at 85% efficiency.

2.2.6.2 Co-product Treatment - LE

Four utilization of algae biomass residual are modeled: displacement of dairy cattle feed, displacement of fishmeal, on-site anaerobic digestion (AD) for energy and nutrient recycling, and on-site HTL of biomass residual for energy and nutrient recycling. Table 2-4 describes the LE scenarios considered.

Table 2-4 Scenario Description of Co-product Treatment for LE Pathway

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Glycerol	Economic Allocation Glycerol Price	Displace Glycerol 1:1 mass	Displace Glycerol 1:1 mass	Displace Glycerol 1:1 mass	Displace Glycerol 1:1 mass
Algal Cake	Economic Allocation Cattle Feed Price	Displace CA Dairy Cattle Feed PCDairy Model	Displace Fishmeal Protein Based	Recycle Nutrients and Energy in AD	Recycle Nutrients and Energy in HTL

Glycerol is treated simply in these scenarios; either through economic allocation in Scenario 1, or displacement assuming one to one substitution for synthetic glycerol. The treatment of algal cake is described for each scenario below.

Scenario 1: Economic Allocation

Economic allocation is based on the market price of biodiesel and glycerol, which are biodiesel and glycerol use \$3.77/gallon [50] and \$0.11/kg [10], respectively. The market price of algal cake is estimated based on the Feed Value Calculator developed by Saskatchewan Ministry of Agriculture assuming the algal cake is used as cattle feed [62]. The Feed Value Calculator calculates the relative value of crude protein, total digestible nutrients (TDN), phosphorus, calcium and moisture content based on the market price of reference feeds. In the current estimation, the 2015 average price of canola meal in California was used as reference. The algal cake was assumed to be sun dried to 40% moisture content before transportation and use. A TDN value for algal cake of 78% was used for price estimation [63]. The market value of algal cake is estimated as \$199 per metric tonne based on its biomass substrate characteristics.

Scenario 2: System Expansion - Displacement of California Dairy Cow Feedstuffs

Based on review of the existing literature, no research or assessment of the displacement value for algal cake in California exists. To conduct this calculation a feed optimization tool tailored to California is identified, PCDAIRY_2015_USA (Least Cost and Ration Analysis Programs for Dairy Cattle), referred to hereafter as PCDAIRY [64]. PCDAIRY uses an economic optimization based on the price of available feeds to recommend a balanced ration at lowest cost. To identify feedstuffs likely to be displaced by the introduction of algal cake, PCDAIRY is run with and without algal cake. By doing so, the consequential change induced by introducing algal cake into the feed market in California can be estimated. Of course if algal cake is introduced in very large volumes, the price of algal cake and competing feeds could change; these displacement calculations implicitly assume that the introduction of algal cake from the simulated facility will not have a significant effect on the price of other feeds. Assumptions and operating parameters that were used in the PCDAIRY tool can be found in appendix.

Table 2-5 was calculated using PCDAIRY, it reflects a model run with an optimization goal of milk sale profit given fixed nutrient composition and prices for each feed. Based on PCDAIRY calculations, the addition of algal cake in a standard dairy cattle feed ration would result in small changes to all ration constituents but notable increases in corn silage, and decreases in alfalfa hay and dry distiller's grains and soluble (DGS).

These changes constitute the effects of adding algal cake to a dairy feed ration and will be used to calculate its displacement value.

Table 2-5 California Dairy Feed Rations with Algal Cake Addition (Dry Matter Based)

	No Algal Cake	Algal Cake $175/ton	Unit
Algal Cake	0.00	2.99	lb/day
Corn Silage	8.58	9.78	lb/day
Wet DGS	8.36	8.39	lb/day
Barley	12.12	12.96	lb/day
Alfalfa Hay	10.32	9.12	lb/day
Almond Hulls& Shell	6.68	6.71	lb/day
Dry DGS	6.00	0.50	lb/day
Beet Pulp	0.00	1.77	lb/day
Dicalcium Phosphate	0.15	0.00	lb/day
Limestone	0.11	0.24	lb/day

Scenario 3: System Expansion- Displacement of Fishmeal

Lipid-extracted algal biomass is a suitable candidate to partially replace the use of fishmeal in fish farming. It is found that replacing up to 10 percent of the crude protein in fishmeal and soybean protein by lipid-extracted algal biomass (including species *Navicula sp*., *Chlorella sp*. and *Nannochloropsis salina*) residual does not lower the growth rate or the feed efficiency in fish farming applications [65]. The displacement ratio of algal biomass to fishmeal in this study is estimated at 1.04 based on protein content (42% for algal biomass residual and 40% for fishmeal). Based on previous LCAs, a primary energy requirement of 19.85 MJ and emissions of 1.35 kg CO_2e are associated with the production of 1 kg of fishmeal [66, 67].

Scenario 4 and 5: Recycling and Reuse in a Closed-loop System

Two recycling technologies, AD and HTL, are tested for scenarios 4 and 5. AD produces biogas, suitable for use in a CHP unit, and digestate, from which the liquid fraction is recovered and fed into the ORPs for water and nutrient recycling, and the solid fraction is composted and used off-site as a nutrient-rich soil amendment.

Just as when HTL is used to process whole algae, HTL applied to algal cake produces a CO_2-rich gaseous stream, a nutrient-rich aqueous stream, a biochar and a biocrude product. The nutrient rich stream is used for nutrient recycling while biocrude and biochar are combusted in a boiler for heat generation. The results for Scenario 4 and 5 are adopted from previous study by Zhang et al. [13].

2.2.7 Data Sources

The primary data for modeling parameters such as the algae growth model, energy inputs for cultivation, harvesting and HTL and upgrading inputs, are based on peer-reviewed literature as described in each section. The reference LCI data including fertilizer production, gasoline production, grid electricity and natural gas production and related emissions come from the ecoinvent Database, the Gabi Professional database and the U.S. LCI database accessed through Gabi 6 software [68, 69]. LCI data are provided in appendix.

2.3 Results and Discussion

2.3.1 LCA Results without Co-product Allocation

2.3.1.1 Effects of HTL Operation Conditions

The lowest GHG emissions from 1 MJ renewable diesel production occurred at temperatures of 300°C and 350°C with retention time from 15 minutes to 60 minutes. Operating at 350°C for 15 minutes is used as the optimal condition because a shorter retention time is preferred for lower cost at industrial facilities. The following sections report results using this operation condition as default. The effects of operation conditions are shown in the Appendix.

Table 2-6 shows results for the default conditions. Cultivation and harvesting of microalgae is the most energy intensive stage for renewable diesel production, predominately due to the electricity use for pumping. These values reflect reduced fertilizer inputs due to nutrients recycling from the aqueous phase. The upgrading stage has higher GHG emissions and energy use than HTL processing.

Table 2-6 Life Cycle GHGs and Energy by Process per MJ Renewable Diesel Production[*]

	Cultivation & Harvesting	HTL processing	Upgrading
Primary Energy (MJ/MJ)	2.23E+00	4.66E-04	1.05E-01
Fossil Energy (MJ/MJ)	2.03E+00	4.12E-04	1.02E-01
GWP_{100} (kg CO_2e/MJ)	1.12E-01	2.26E-05	4.31E-03
GWP_{20} (kg CO_2e/MJ)	1.30E-01	2.60E-05	5.18E-03

[*] HTL was modeled at 350°C for 15 minutes.

2.3.1.2 Comparison of LE and HTL Pathways

The GHG emissions and total energy input for biodiesel and renewable diesel produced from microalgae before allocation of co-products are shown in table 2-7. Overall, biodiesel production from LE requires much higher energy than renewable diesel from HTL, because the yield of crude oil from 1 kg biomass under the LE pathway is less than the crude oil produced under HTL.

Table 2-7 GWP and Total Energy of Algal Biofuel from LE and HTL[*] *Pathways*

	Biodiesel (LE Pathway)	**Renewable Diesel (HTL Pathway*)**	**Unit**
GWP_{100}	225	55	g CO_2e/MJ
Total Primary Energy	3.52	0.95	MJ/MJ

[*]HTL was modeled at 350°C for 15 minutes.

2.3.2 Results with Co-product Allocation

2.3.2.1 Effects of Co-product Treatment on the HTL Pathway

Table 2-8 reports the results for un-allocated energy and emissions from the HTL pathway along with results from the six co-products treatment scenarios in terms of kg of algal biomass produced and MJ of renewable diesel. Because of the high value estimated for biochar, economic allocation leads to the lowest energy and life cycle GHG intensity (or carbon intensity) for renewable diesel among all allocation approaches. When the price of biochar is set at $0.5/kg instead of $2.65/kg (default value), the economic allocation results in equal carbon intensity of biochar to other allocation methods. Second to economic allocation in terms of favorable carbon intensity is the substitution of biochar for soil amendments. Depending on the long term carbon sequestration potential of biochar in soils, this use could result in even lower carbon intensity. In terms of closed-loop utilization, combustion in a CHP is slightly preferable to combustion in a boiler for heat generation only. Overall, the allocation approach has relatively small effects on the final results due to the small yield of biochar from HTL (Table 2-8). This suggests the findings for renewable diesel produced through the HTL pathway are reasonably robust to changes in the value of co-products and the allocation method chosen.

Table 2-8 Effects of co-product treatment on Algal Renewable Diesel when HTL is operated at 350 °C and 15 minutes retention time

	Primary Energy (MJ/kg dry biomass)	GWP_{100} (kg CO_2e/kg dry biomass)	Primary Energy (MJ/MJ)	Carbon Intensity (g CO_2e/MJ)
Economic Allocation	9.33	0.54	**0.62**	**35.64**
Energy Allocation	14.07	0.81	**0.93**	**53.75**
Mass Allocation	14.07	0.81	**0.93**	**53.76**
Soil Amendment	11.43	0.82	**0.76**	**54.49**
CHP for heat and power	13.25	0.77	**0.88**	**51.16**
Boiler for heat generation	13.44	0.78	**0.89**	**52.13**
Before Allocation	14.29	0.82	**0.95**	**54.59**

2.3.2.2 Effects of Co-product Treatment on Biodiesel Performance

Using algal cake as feed (scenarios 1, 2 and 3) show higher environmental benefits than closed-loop nutrient and energy recycling scenarios (scenario 4 and 5) (Table 2-9). However, biodiesel is very sensitive to the treatment of algal cake and allocation strategies, which means there are large uncertainties related to the algal cake treatment, such as the price, the nutrient content, the feasibility to use as animal feed, and perhaps additional processing.

Table 2-9 Effects of Co-product Treatments on GWP and Total Energy of Biodiesel

Co-product Treatment Scenario	GWP_{100} (g CO_2e/MJ)	Primary Energy (MJ/MJ)
Before Allocation	226	3.52
Displace Cattle Feed & Glycerol	-58.80	-1.24
Displace Fishmeal & Glycerol	-9.88	0.05
Recycled with AD	84.77	1.06
Recycled with HTL	124.73	1.77
Economic Allocation	2.89	0.05

2.3.3 Production Pathway Comparisons

Comparing the recycling strategies of co-products in a closed-loop and selling co-product in an open-loop system, a closed-loop system design avoids the allocation process and results in fewer uncertainties of environmental impacts, while the drawback is the loss of potential economic value (as well as the environmental best-use) from co-products (Figure 2-2 and Figure 2-3).

In general, the HTL pathway results in more consistent environmental performance results and is subject to fewer effects from co-product treatment strategies (Figure 2-2 and Figure 2-3). This is because HTL yields a very small quantity of co-product (biochar) that can be used outside the production system, reusing most non-fuel products within the system.

While the LE pathway exhibits higher uncertainty, it may also hold promise for higher profits from selling the high value algal cake as animal feed, as illustrated in Figure 2-3 under the bars for Economic Allocation.

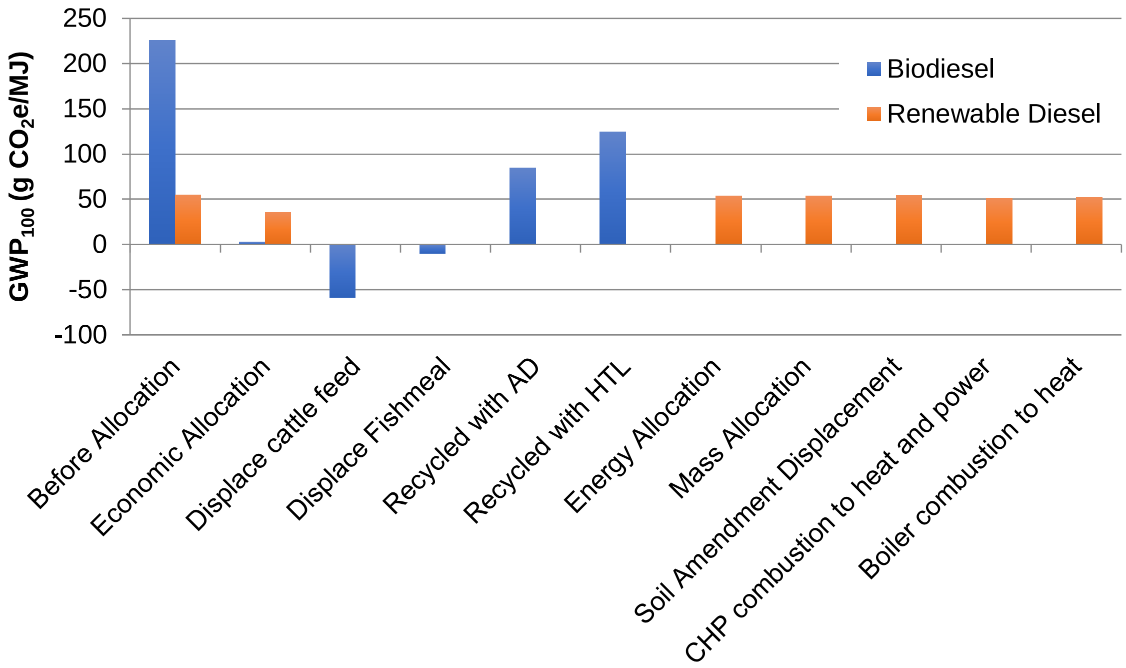

Figure 2-2 GHG emissions from Biodiesel and Renewable Diesel Production with Co-product Treatment. For reference, petroleum diesel is approximately 95 g CO$_2$e/MJ

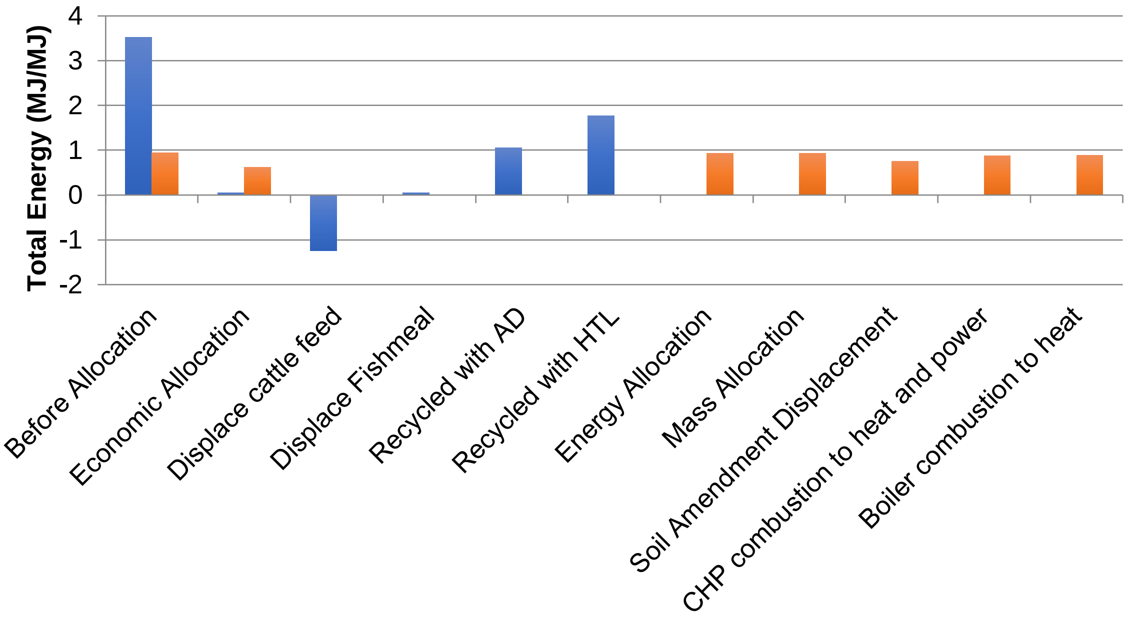

Figure 2-3 Total Primary Energy of Biodiesel and Renewable Diesel Production with Co-product Treatment

2.4 Uncertainties and Discussion

2.4.1 Uncertainty of Nutrient Recycling Capacity on HTL Pathway

Microalgae cultivation with recycling of the aqueous phase and gases from HTL may introduce heavy metals and inorganic contaminants into the growth media. However, there are no consistent estimates of nutrient content in the aqueous phase, nor are there studies that have definitively proven the feasibility of recycling the aqueous product to the ORP without affecting algae growth performance due to different experimental conditions and limited data [24, 30-34]. To better estimate the effects of nutrient recycling rates used in the ORP, three recycling rates for N and P from the HTL aqueous phase are tested: the low rate assumes 15% of total input N and 20% of total P can be reused for cultivation and the high recycling rate assumes 95% of total N and 95% of total P can be reused for cultivation. Effects on the HTL production system (before co-product treatments) are shown in table 2-10.

Without allocation of co-products, HTL system GHG emissions range from 44.2 g CO_{2e} to 67.2 g CO_{2e} to produce 1 MJ renewable diesel from the low rate case to high rate case; while the total energy input ranges from 1.10 MJ/MJ to 0.85 MJ/MJ.

Table 2-10 Effects of Nutrient Recycling Capacity on GHGs and Energy per MJ Renewable Diesel Production (Before co-product treatments)*

	Low 15%N, 20%P	**Default 50%N, 80%P**	**High 95%N, 95%P**
GWP_{100} (g CO_{2e}/MJ)	67.3	55.9	44.3
Total Primary Energy (MJ/MJ)	1.10	0.96	0.85

*HTL was modeled at 350°C for 15 minutes.

The impact of heavy metals and inorganic contaminants on algae growth and the fate of heavy metals need to be better understood in order to evaluate the potential or limits on recycling HTL products.

2.4.2 Uncertainty of Algal Cake Price on LE Pathway

Sensitivity analysis of life cycle displacement credits of algal cake at different prices is conducted to understand the potential effect. At lower prices, algal cake offsets more GHG emissions and energy inputs, meaning the credit attributed to the algal biodiesel production system is higher (Table 2-11). At a lower price, algal cake displaces larger quantities of dry DGS in the feed ration, which has a higher market price and involves higher environmental impacts to produce (as shown in Appendix). This sensitive response of environmental impacts to prices is critical to the life cycle performance of biodiesel produced from LE pathway. However, estimating the market price of algal cake as feed is challenging to this research, because algal cake is not yet a commercial product in the feed market. Moreover, algal cake may concentrate chemical elements which can be toxic to animal and human health, depending on algae species, cultivation or conversion processes. Thus, the feasibility of using algal cake used for feed still requires further research.

Table 2-11 Sensitivity Analysis of Avoided CO_2e Emissions and Total Energy by 1 kg Algal Cake at Different Prices

Price of algal cake	**\$150/kg**	**\$175/kg**	**\$199/kg**
GWP_{100} (kg CO_{2e}/kg algal cake)	-1.65	-1.63	-1.30
Total Primary Energy (MJ/kg algal cake)	-27.77	-27.25	-14.72

2.5 Conclusion

This study conducted a LCA model to examine life cycle GHG emissions and energy use of biofuel production from microalgae via two pathways, a HTL renewable diesel and a LE biodiesel. Before co-product allocation, the GHG emissions from renewable diesel (HTL) and biodiesel (LE) were 55 gCO_2e/MJ and 226 gCO_2e/MJ, respectively. After allocation, the carbon intensity of renewable diesel varied from 36 gCO_2e/MJ to 54 gCO_2e/MJ, while the carbon intensity of biodiesel had a dramatic range from -59 gCO_2e/MJ to 125 gCO_2e/MJ. Not surprisingly, a comparison of these two pathways subject to a variety of scenarios that varied the co-product utilization strategies and allocation methods, suggest that more robust carbon intensity estimates are achievable when co-products have little contribution to the performance of the biofuel, or when they are internally recycled.

2.6 Acknowledgement

This work was supported by the U.S. Department of Energy (Grant #:DE-EE0003373) and Consortium for algal biofuel commercialization (CAB-Comm) program.

2.7 Reference

1. Chisti, Y., *Biodiesel from microalgae.* Biotechnol Adv, 2007. **25**(3): p. 294-306.
2. Quinn, J.C. and R. Davis, *The potentials and challenges of algae based biofuels: A review of the techno-economic, life cycle, and resource assessment modeling.* Bioresource Technology, 2015. **184**: p. 444-452.
3. Kendall, A. and J. Yuan, *Comparing life cycle assessments of different biofuel options.* Current opinion in chemical biology, 2013. **17**(3): p. 439-443.
4. Flysjö, A., et al., *How does co-product handling affect the carbon footprint of milk? Case study of milk production in New Zealand and Sweden.* The International Journal of Life Cycle Assessment, 2011. **16**(5): p. 420-430.
5. Hoefnagels, R., E. Smeets, and A. Faaij, *Greenhouse gas footprints of different biofuel production systems.* Renewable and Sustainable Energy Reviews, 2010. **14**(7): p. 1661-1694.
6. Zaimes, G.G. and V. Khanna, *The role of allocation and coproducts in environmental evaluation of microalgal biofuels: How important?* Sustainable Energy Technologies and Assessments, 2014. **7**: p. 247-256.
7. Cherubini, F., A.H. Strømman, and S. Ulgiati, *Influence of allocation methods on the environmental performance of biorefinery products—A case study.* Resources, Conservation and Recycling, 2011. **55**(11): p. 1070-1077.
8. 14040, I., *Environmental management — Life cycle assessment — Principles and framework.* 2006.
9. IPCC, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. 2013, Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. 1535.
10. Yuan, J., A. Kendall, and Y. Zhang, *Mass balance and life cycle assessment of biodiesel from microalgae incorporated with nutrient recycling options and technology uncertainties.* GCB Bioenergy, 2014.
11. Ross, A., et al., *Hydrothermal processing of microalgae using alkali and organic acids.* Fuel, 2010. **89**(9): p. 2234-2243.
12. Bennion, E.P., et al., *Lifecycle assessment of microalgae to biofuel: Comparison of thermochemical processing pathways.* Applied Energy, 2015(0).
13. Zhang, Y., A. Kendall, and J. Yuan, *A comparison of on-site nutrient and energy recycling technologies in algal oil production.* Resources, Conservation and Recycling, 2014. **88**: p. 13-20.
14. Valdez, P.J., V.J. Tocco, and P.E. Savage, *A general kinetic model for the hydrothermal liquefaction of microalgae.* Bioresour Technol, 2014. **163**: p. 123-7.
15. Fortier, M.-O.P., et al., *Life cycle assessment of bio-jet fuel from hydrothermal liquefaction of microalgae.* Applied Energy, 2014. **122**(0): p. 73-82.
16. Delrue, F., et al., *Comparison of various microalgae liquid biofuel production pathways based on energetic, economic and environmental criteria.* Bioresource Technology, 2013.

17. Xiu, S. and A. Shahbazi, *Bio-oil production and upgrading research: A review.* Renewable and Sustainable Energy Reviews, 2012. **16**(7): p. 4406-4414.
18. Huang, H.-j., et al., *Comparative studies of thermochemical liquefaction characteristics of microalgae, lignocellulosic biomass and sewage sludge.* Energy, 2013. **56**: p. 52-60.
19. Zacher, A.H., et al., *A review and perspective of recent bio-oil hydrotreating research.* Green Chemistry, 2014. **16**(2): p. 491-515.
20. Jensen, C.U., J. Hoffmann, and L.A. Rosendahl, *Co-processing potential of HTL bio-crude at petroleum refineries. Part 2: A parametric hydrotreating study.* Fuel.
21. Pegallapati, A.K., et al., *Supply Chain Sustainability Analysis of Whole Algae Hydrothermal Liquefaction and Upgrading*. 2015, Argonne National Laboratory (ANL).
22. Palou-Rivera, I. and M.Q. Wang, *Updated estimation of energy efficiencies of US petroleum refineries*. 2010, Argonne National Laboratory (ANL).
23. Grierson, S., V. Strezov, and J. Bengtsson, *Life cycle assessment of a microalgae biomass cultivation, bio-oil extraction and pyrolysis processing regime.* Algal Research, 2013. **2**(3): p. 299-311.
24. Liu, X., et al., *Pilot-scale data provide enhanced estimates of the life cycle energy and emissions profile of algae biofuels produced via hydrothermal liquefaction.* Bioresour Technol, 2013. **148**: p. 163-71.
25. Frank, E.D., et al., *Life cycle comparison of hydrothermal liquefaction and lipid extraction pathways to renewable diesel from algae.* Mitigation and Adaptation Strategies for Global Change, 2013. **18**(1): p. 137-158.
26. Ponnusamy, S., et al., *Life cycle assessment of biodiesel production from algal bio-crude oils extracted under subcritical water conditions.* Bioresource technology, 2014. **170**: p. 454-461.
27. Jazrawi, C., et al., *Pilot plant testing of continuous hydrothermal liquefaction of microalgae.* Algal Research, 2013. **2**(3): p. 268-277.
28. Brown, T.M., P. Duan, and P.E. Savage, *Hydrothermal Liquefaction and Gasification of Nannochloropsis sp.* Energy & Fuels, 2010. **24**(6): p. 3639-3646.
29. Tian, C., et al., *Hydrothermal liquefaction for algal biorefinery: A critical review.* Renewable and Sustainable Energy Reviews, 2014. **38**: p. 933-950.
30. Biller, P., et al., *Nutrient recycling of aqueous phase for microalgae cultivation from the hydrothermal liquefaction process.* Algal Res, 2012. **1**(1): p. 70-76.
31. Jena, U., et al., *Evaluation of microalgae cultivation using recovered aqueous co-product from thermochemical liquefaction of algal biomass.* Bioresource technology, 2011. **102**(3): p. 3380-3387.
32. Valdez, P.J., et al., *Hydrothermal liquefaction of Nannochloropsis sp.: Systematic study of process variables and analysis of the product fractions.* Biomass and Bioenergy, 2012.
33. Yu, G., et al., *Distributions of carbon and nitrogen in the products from hydrothermal liquefaction of low-lipid microalgae.* Energy & Environmental Science, 2011. **4**(11): p. 4587-4595.
34. López Barreiro, D., et al., *Assessing microalgae biorefinery routes for the production of biofuels via hydrothermal liquefaction.* Bioresource Technology, 2014. **174**: p. 256-265.
35. López Barreiro, D., et al., *Hydrothermal liquefaction (HTL) of microalgae for biofuel production: State of the art review and future prospects.* Biomass and Bioenergy, 2013. **53**(0): p. 113-127.
36. Sackett, T.E., et al., *Soil and greenhouse gas responses to biochar additions in a temperate hardwood forest.* GCB Bioenergy, 2014.
37. Wang, Z., et al., *Effects of co-produced biochar on life cycle greenhouse gas emissions of pyrolysis-derived renewable fuels.* Biofuels, Bioproducts and Biorefining, 2014. **8**(2): p. 189-204.
38. Zhao, X., S. Wang, and G. Xing, *Nitrification, acidification, and nitrogen leaching from subtropical cropland soils as affected by rice straw-based biochar: laboratory incubation and column leaching studies.* Journal of Soils and Sediments, 2014. **14**(3): p. 471-482.
39. Lardon, L., et al., *Life-cycle assessment of biodiesel production from microalgae.* Environmental science & technology, 2009. **43**(17): p. 6475-6481.
40. Passell, H., et al., *Algae biodiesel life cycle assessment using current commercial data.* Journal of environmental management, 2013. **129**: p. 103-111.

41. Batan, L., et al., *Net energy and greenhouse gas emission evaluation of biodiesel derived from microalgae.* Environmental science & technology, 2010. **44**(20): p. 7975-7980.
42. Shirvani, T., et al., *Life cycle energy and greenhouse gas analysis for algae-derived biodiesel.* Energy & Environmental Science, 2011. **4**(10): p. 3773-3778.
43. Brentner, L.B., M.J. Eckelman, and J.B. Zimmerman, *Combinatorial life cycle assessment to inform process design of industrial production of algal biodiesel.* Environ Sci Technol, 2011. **45**(16): p. 7060-7.
44. Woertz, I.C., et al., *Life cycle GHG emissions from microalgal biodiesel--a CA-GREET model.* Environ Sci Technol, 2014. **48**(11): p. 6060-8.
45. ISO 14044, *Environmental management — Life cycle assessment — Requirements and guidelines*. 2006, International Standard: Switzerland.
46. Wang, M., H. Huo, and S. Arora, *Methods of dealing with co-products of biofuels in life-cycle analysis and consequent results within the US context.* Energy Policy, 2011. **39**(10): p. 5726-5736.
47. Mendoza, A., et al., *The allocation problem in bio-electricity chains.* Report of a Project Group as part of the MSc. Leiden, The Netherlands: Industrial Ecology, Institute of Environmental Sciences (CML), 2008.
48. Lam, M.K., K.T. Lee, and A.R. Mohamed, *Life cycle assessment for the production of biodiesel: a case study in Malaysia for palm oil versus jatropha oil.* Biofuels, Bioproducts and Biorefining, 2009. **3**(6): p. 601-612.
49. Murray, A., K. Skene, and K. Haynes, *The Circular Economy: An Interdisciplinary Exploration of the Concept and Application in a Global Context.* Journal of Business Ethics, 2017. **140**(3): p. 369-380.
50. DOE, *Clean cities alternative fuel price report*, E.E.R. Energy, Editor. 2015, Department of Eenergy: Washington, D.C.
51. Kulyk, N., *Cost-benefit analysis of the biochar application in the US cereal crop cultivation.* 2012.
52. Jirka, S. and T. Tomlinson, *State of the Biochar Industry—A survey of commercial activity in the biochar field.* A report by the International Biochar Initiative. Available at: www. biochar-international. org/sites/default/files/State_of_the_Biochar_Industry_2013. pdf, 2013.
53. Jena, U. and K. Das, *Comparative evaluation of thermochemical liquefaction and pyrolysis for bio-oil production from microalgae.* Energy & fuels, 2011. **25**(11): p. 5472-5482.
54. Barreiro, D.L., et al., *Hydrothermal liquefaction (HTL) of microalgae for biofuel production: state of the art review and future prospects.* biomass and bioenergy, 2013. **53**: p. 113-127.
55. Neveux, N., et al., *Biocrude yield and productivity from the hydrothermal liquefaction of marine and freshwater green macroalgae.* Bioresource technology, 2014. **155**: p. 334-341.
56. Vardon, D.R., et al., *Thermochemical conversion of raw and defatted algal biomass via hydrothermal liquefaction and slow pyrolysis.* Bioresource Technology, 2012. **109**: p. 178-187.
57. Zhang, Y. and A. Kendall, *Life Cycle Performance of Cellulosic Ethanol and Corn Ethanol from a Retrofitted Dry Mill Corn Ethanol Plant.* BioEnergy Research, 2016: p. 1-16.
58. Brittan, K.L., et al., *Sample Costs to Produce Field Corn Sacramento Valley*. 2004, University of California Cooperative Extension: Department of Agricultural and Resource Economics, UC Davis.
59. Brittan, K.L., et al., *Sample Costs to Produce Field Corn on Mineral Soils in the Sacramento Valley*. 2008, University of California Cooperative Extension: Department of Agricultural and Resource Economics, UC Davis.
60. Frate, C.A., et al., *Sample Costs to Produce Grain Corn San Joaquin Valley-South 2008*. 2008, University of California Cooperative Extension: Department of Agricultural and Resource Economics, UC Davis.
61. Vargas, R.N., et al., *Sample Costs to Produce Grain Corn San Joaquin Valley*. 2003, University of California Cooperative Extension: Department of Agricultural and Resource Economics, UC Davis.
62. *Feed Value Calculator*, M.o. Agriculture, Editor. 2012, Government of Saskatchewan: Regina, SK, Canada.

63. MišurCoVá, L., et al., *Nitrogen content, dietary fiber, and digestibility in algal food products.* Czech J. Food Sci, 2010. **28**: p. 27-35.
64. Robinson, P.H. and A. Ahmadi, *PCDAIRY Least Cost and Ration Analysis Programs for Dairy Cattle* U.o.C.D. Department of Animal Science, CA 95616 USA, Editor. 2015: Davis, California, USA.
65. Patterson, D. and D.M. Gatlin, *Evaluation of whole and lipid-extracted algae meals in the diets of juvenile red drum (Sciaenops ocellatus).* Aquaculture, 2013. **416**: p. 92-98.
66. Papatryphon, E., et al., *Environmental impact assessment of salmonid feeds using life cycle assessment (LCA).* AMBIO: A Journal of the Human Environment, 2004. **33**(6): p. 316-323.
67. Pelletier, N., et al., *Not all salmon are created equal: life cycle assessment (LCA) of global salmon farming systems.* Environmental science & technology, 2009. **43**(23): p. 8730-8736.
68. PE International, G.P. Database, Editor. 2012: Leinfelden-Echterdingen.
69. Ecoinvent, *Gabi 6*, G. 6, Editor. 2011.

Chapter 3 Life Cycle Performance of Cellulosic Ethanol and Corn Ethanol from a Retrofitted Dry Mill Corn Ethanol Plant

3.1. Introduction

Ethanol has been produced predominately from corn starch in the U.S.; nearly 34% of corn (5175 out of 15414 million bushels) was used for ethanol production for fuel use in 2015 [1]. The environmental shortcomings of corn ethanol production have been widely discussed in the literature, often highlighting competition with food and feed resources and land use change effects as particularly harmful. Fuel policies such as California's Low Carbon Fuel Standard (LCFS) and the federal Renewable Fuel Standard (RFS2) attempt to promote fuels with lower greenhouse gas (GHG) emissions, often looking to second generation (2G) ethanol produced from cellulosic feedstock such as corn stover to avoid the disadvantages first generation (1G) fuel such as corn grain-derived ethanol [2].

Despite years of development, barriers persist for scaling up cellulosic ethanol production. As of 2015, only four commercial cellulosic ethanol facilities (DuPont, POET, Abengoa, and Quad County Corn Processors) operated in the U.S. [3]. The challenges of commercial scale production of cellulosic ethanol include technology improvement to efficiently convert cellulose to fermentable sugars; high capital cost; and the supply, transportation and storage of a large amount of often low-density feedstock.

To address these challenges, an emerging technology trend is to retrofit existing corn starch ethanol facilities with a cellulosic ethanol process train, a so-called "bolt-on" technology which produces sugar from corn stover to blend with sugar from corn grain. The bolt-on technology partially displaces demand for sugars from corn starch, and the facility yields a combination of cellulosic ethanol and corn ethanol. Although only a small amount of cellulosic ethanol may be processed from the bolt-on equipment, it helps facilities gain experiences with cellulosic materials and avoids high capital investment of building stand-alone plants [4]. Moreover, corn ethanol facilities can benefit more generally from retrofits that introduce cellulose feedstocks because they produce lignin as a residual product, which can be combusted for electricity and heat generation, reducing demand for process fuels.

As early as 2005, the economic feasibility of co-locating 1G and 2G ethanol production facilities was illustrated by Wallace et al. [5]. Several techno-economic assessment (TEA) and LCA studies have been done on co-located 1G and 2G ethanol production facilities from sugarcane and bagasse. Compared to a stand-alone 2G ethanol facility, co-located 1G and 2G ethanol shows lower production cost and environmental advantages, namely reduced GHG emissions [6-8]. Similar conclusions were found in a TEA of co-located 1G and 2G ethanol plants using corn grain and stover feedstock by Ou et al. 2014 [9].

A limited number of life cycle GHG intensity estimates and LCAs have been conducted on co-located 1G and 2G ethanol products. A 2015 LCA study modeled the POET company's Project LIBERTY facility which uses corn and stover feedstocks [10]. The carbon intensity (CI) for corn and stover ethanol was estimated at 57 and 25 g carbon dioxide equivalent (CO_2e) per MJ, respectively with land use change (LUC) GHG emissions for corn grain ethanol and stover ethanol of 7.6 and -0.6 g CO_2e/MJ. The study focused on the allocation of energy produced from lignin combustion in a combined heat and power (CHP) unit between the corn ethanol plant and stover ethanol plant. Distiller's grains and solubles (DGS) were handled using the displacement allocation method and led to a credit of 15 g CO_2e/MJ corn ethanol.

In previous studies, the energy generated from stover or bagasse combustion has been treated carefully while the co-product DGS (in either wet or dry form) seems to have been treated without considering regional market conditions and uses.

This study makes two particular contributions that address deficiencies in the existing literature; it adds to the limited LCA literature on co-located 1G and 2G production facilities, and advances methods and knowledge related to allocation of livestock feed co-products by considering the influence of dairy ration science, regional feedstuff availability and real-world market conditions on co-product displacement calculations.

3.2. Materials and methods

3.2.1 LCA, scope and system boundary

LCA is a technique for evaluating the environmental flows and potential environmental impacts of a product throughout its life cycle, from “cradle to grave,” and considers the full supply chain of inputs or processes used in the product’s life cycle [11]. This LCA model assesses field-to-factory-gate environmental flows and impacts including global warming potential (GWP), select air pollutants, fossil fuel use, total energy use, direct water use, direct land use, and indirect land use change (considering GHG effects only) for the production of corn ethanol and cellulosic ethanol in a California facility using a process-based, prospective LCA approach. The system boundary (illustrated in Figure 3-1) includes the agricultural production of corn grain in the Midwest and corn stover in California, transportation of feedstocks from farms to the ethanol facility, and ethanol conversion processes for the two feedstocks. Equipment fuel use and emissions, agrochemical production and application, and field biochemical emissions from nitrogen (N) fertilizer are included in the assessment of both corn grain and stover production. Production of equipment, construction of the ethanol facility, and transport of ethanol from the ethanol facility to blending terminals are excluded from the system boundary. A functional unit of one MJ ethanol is used in this study.

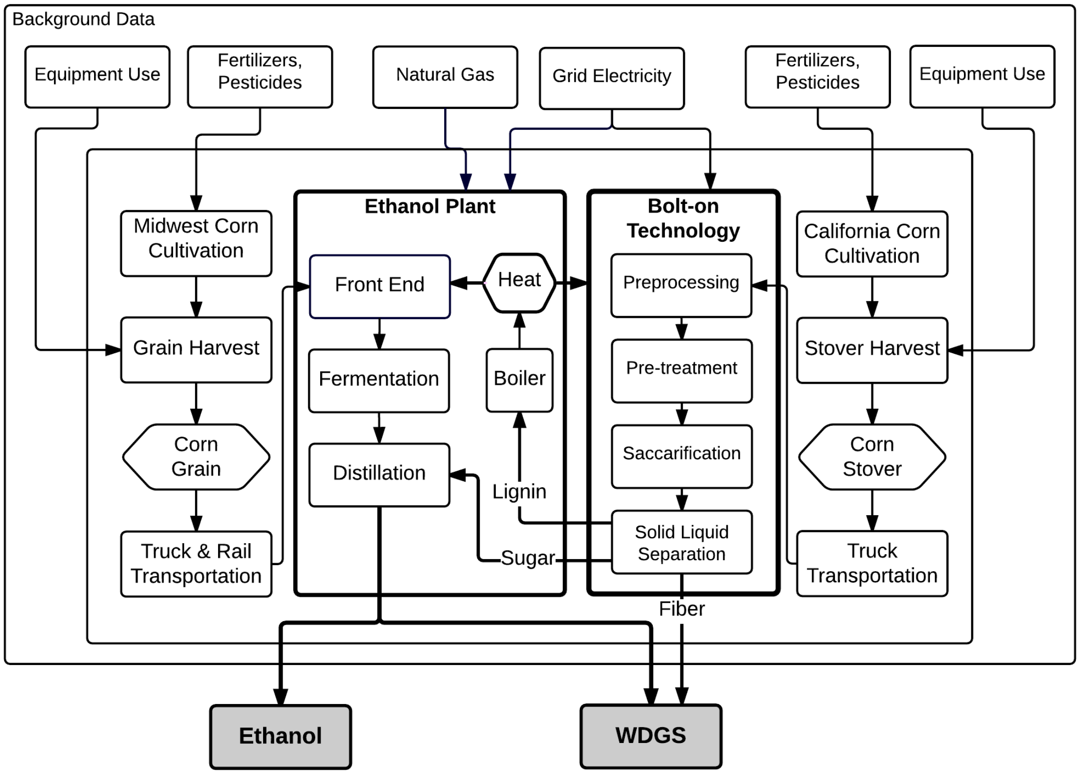

Figure 3-1 System boundary of retrofitted ethanol production system (WDGS = Wet Distillers Grains and Solubles)

All LCA results are reported as an inventory, except for GHGs where GWPs are used to convert non-CO_2 GHGs to CO_2e. GWPs use time-integrated radiative forcing over a specific time horizon to estimate the equivalence of non-CO_2 GHGs to CO_2 on a mass basis. GHGs converted using a 100-year integration period (GWP_{100}) and using a 20-year integration period GWP_{20} are both reported in the results. Whenever carbon intensities (CIs) or CO_2e results are reported without specification of a GWP time horizon they refer to GWP_{100}. The GWPs of methane (CH_4) and nitrous oxide (N_2O) for 100 years are 25 and 298, and for 20 years are 72 and 289, as defined by IPCC's 2007 Fourth Assessment report [12]. The 2007 GWPs are used to enable comparison with existing CI calculations for other biofuel pathways. Results using updated GWPs in IPCC's Fifth Assessment are included in the Appendix.

3.2.2 System definition

The simulated facility draws on the conditions of Pacific Ethanol's factory in Stockton, California, which imports Midwestern corn as a feedstock. California is not a major corn producing state. The benefit of producing ethanol in California from imported corn (rather than shipping corn ethanol from the Midwest) includes a proximal market for wet distiller's grains and solubles (WDGS), the primary co-product from dry mill corn ethanol facilities. California is a large dairy producer, and importing dried Midwestern DGS is a common practice, thus by producing ethanol close to the DGS market, no drying is required. When the bolt-on technology is added to the facility, corn stover produced locally in California, is assumed to be used. The market of corn grain produced from California is assumed to remain not changed. A 60 million gallon per year (MGY) corn ethanol plant is modeled. Three ethanol production cases are included as baseline case, low stover case and high stover case.

- **Baseline case**: 100% ethanol production from corn starch, all corn grain is from the Midwest and a typical dry mill facility using natural gas and California grid electricity is assumed.
- **Low stover case**: 3.3% of total feedstock by dry mass is from California corn stover, and the remainder is from Midwestern corn. The facility is modeled to include an additional pre-processing step (compared to the baseline facility) that provides a 3% increase in corn grain ethanol production as a result of improved starch conversion. This pre-processing step targets the cellulosic fiber contained in the corn kernel. It reduces the particle size of corn fiber which is then sent to saccharification and converted to ethanol. This enhancement subsequently decreases the mass of co-product generated from corn grain, WDGS, and increases the protein concentration of DGS (i.e., from 25.9% for a typical facility's WDGS to 28.1% protein for the modeled facility) due to reduced starch mass. To make up this loss of co-product the residual fiber, namely lignin and non-fermentable hemicellulose sugars, remaining after hydrolysis of sugars from the stover

are added to the WDGS. The stover feedstock mass was selected to ensure that the WDGS co-product achieves a protein composition of 25.9%, matching that of WDGS from a typical corn ethanol facility. The solid content of WDGS is 37% by weight.

- **High stover case**: 16.7% of total feedstock by dry mass is California corn stover, the remainder is Midwestern corn grain. The enhanced starch ethanol production is included, as described for the low stover case. However, since the high stover case yields much greater quantities of residual fiber, the residual fiber's suspended solids mass (primarily lignin in composition) is combusted in a boiler, displacing natural gas demand in the boilers. Because criteria air emissions from a biomass fired boiler is higher than those form a natural gas fired boiler, the differences in criteria air emissions are accounted. The residual fiber's dissolved solids mass (primarily non-fermentable xylose from hemicellulose) is added to the WDGS in the post fermentation solubles stream. Adding the dissolved solids mass achieves approximately the same protein content as the previous cases, 25.9%, for the WDGS product.

Facility energy consumption, water use, enzyme inputs, ethanol production and WDGS production data are provided by Edeniq and listed in Table 3-1. Edeniq, a commercial collaborator that developed the bolt-on technology, provided these facility-level data for analysis.

Table 3-1 Assumptions and parameters of modeled ethanol facility

Model Inputs				
Feedstocks	**Baseline**	**Low Stover**	**High Stover**	**Unit**
Corn grain dry	1,393	1,315	1,265	dry metric tonne/day
Corn Stover	0	45	253	dry metric tonne/day
Transportation				
Corn Grain to Elevator	32	32	32	Truck distance-km
Elevator to Ethanol Plant	2829	2829	2829	Rail distance- km
Enzymes				
Alpha-Amylase	724.55	683.64	657.57	kg/day
Gluco-Amylase	1,379.42	1,301.55	1,251.92	kg/day
Cellulase	0	826.36	4,562.21	kg/day
Yeast	68.09	68.09	68.09	kg/day
Facility Utility				
Ethanol Plant Electricity	96,004	99,265	98,089	kWh/day
Bolt-on Electricity	0	10,261	51,715	kWh/day
Ethanol Plant Natural Gas	3,220	3,242	3,217	MMBtu/day
Bolt-on Natural Gas	0	93	0 (-741) *	MMBtu/day
Bolt-on Biomass Energy	0	0	1255	MMBtu/day
Ethanol Plant Water	171,375	173,946	210,118	gallon/day
Ethanol Plant Outputs				
Mixed Ethanol Production	172,160	172,159	172,159	gallon/day
Total WDGS Delivered	484	457	445	dry metric tonne/day
Corn Ethanol (proportion of mixed ethanol)	172,160 (100%)	170,130 (98.82%)	162,064 (94.14%)	gallon/day
Corn WDGS	484	423	412	dry metric tonne/day
Stover Ethanol (proportion of mixed ethanol)	0 (0%)	2,029 (1.18%)	10,095 (5.86%)	gallon/day
Stover WDGS	0	34	34	dry metric tonne/day

**0 MMBtu natural gas is used in the high stover case bolt-on system and the (-741) indicates the heat surplus produced from bolt-on system. In the high stover case, the bolt-on system requires 514 MMBtu heat per day, while the heat generated from stover combustion is 1255 MMBtu/day (biomass energy). So the heat requirement for the bolt-on system is fulfilled by the stover combustion and 741 MMBtu heat surplus is produced which can be used to displace the natural gas use in the ethanol plant.*

3.2.3 Life cycle inventory development

Life cycle inventories (LCIs) are required to model the inputs to a production system in LCA. For example, an LCI of nitrogen fertilizer production and transport is required to model the full life cycle of fertilizer used in the production system. The LCI of a product or process quantifies the environmental flows (inputs and outputs) associated with the provision of a product or process.

This research required the development of new LCIs for a number of products and processes, including California stover, and various California feeds (used in co-product allocation calculations). Other LCIs, such as those for chemicals, fuels, electricity, natural gas, agricultural products and equipment use were taken directly or adapted from commercial databases and publicly available models. These are reported in Table 3-2. The LCI of corn production in the Midwest is adopted from previous work [13]. Equipment operation and vehicle use, comprised of fuel use and combustion emissions, are modeled using California's official air emissions models, OFFROAD (for non-road vehicles) and EMFAC (for on-road vehicles) [14,15]. Enzymes and yeast are assumed produced on-site at the ethanol facility and their transportation is excluded. Fuel production LCIs are then linked with the operational fuel use and emissions derived from these models resulting in a "well-to-wheels" LCI for equipment and vehicle use.

Table 3-2 LCI data source

Category	**Name**	**Source (Software, Database)**
Agricultural Chemical	Monoammonium phosphate	Gabi 6, Ecoinvent 2011 database
Agricultural Chemical	UAN32	Gabi 6, Ecoinvent 2011 database
Agricultural Chemicals	Liquid Ammonia	Gabi 6, Ecoinvent 2011 database
Agricultural Chemicals	Pesticide	Gabi 6, Ecoinvent 2011 database
Agricultural Chemicals	Herbicide	Gabi 6, Ecoinvent 2011 database
Cultivation	Corn Seed	Gabi 6, Ecoinvent 2011 database
Cultivation	Midwestern Corn Grain	[13]
Cultivation	California Corn Stover	Developed based on corn cultivation cost and return studies and a study on lignocellusic biomass study by Idaho National Labs [16-18]
Irrigation	Water	Kendall et al. [19]
Equipment Emissions	Heavy-duty Tractor	EMFAC 2011
Equipment Emissions	Pick-up Truck	EMFAC 2011
Equipment Emissions	Tractors	OFFROAD 2007
Equipment Emissions	Balers	OFFROAD2007
Equipment Emissions	Corn stover fired boiler	CA-GREET 1.8
Transportation	Rail	Gabi 6, PE 2012 database
Energy Inputs	Diesel	Gabi 6, PE 2012 database
Energy Inputs	Gasoline	Gabi 6, PE 2012 database
Energy Inputs	Electricity	Gabi 6, PE 2012 database
Energy Inputs	NG	Gabi 6, USLCI/PE2012 database
Facility Inputs	Cellulase	GREET 2013
Facility Inputs	Alpha-amylase	GREET 2013
Facility Inputs	Gluco-amylase	GREET 2013
Facility Inputs	Yeast	GREET 2013
Facility Inputs	Water	Gabi 6, PE 2012 database
Dairy Cattle Feedstuff	Corn Silage	LCI developed based on Sample Cost and Return study for corn silage production in California [20]
Dairy Cattle Feedstuff	Beet pulp	Beet cultivation and transportation is from [21], beet pulp processing is taken from Gabi 6, Ecoinvent 2011
Dairy Cattle Feedstuff	Alfalfa Hay	LCI developed based on Sample Cost and Return study for alfalfa hay production in California [22]
Dairy Cattle Feedstuff	California Corn Grain	[23,17,24,16]
Dairy Cattle Feedstuff	Cottonseed Meal	LCI developed based on Sample Cost and Return study for cotton production in California with economic allocation to cottonseed [25]
Dairy Cattle Feedstuff	Almond Hulls& Shell	[19]
Dairy Cattle Feedstuff	Salt	Gabi 6, PE 2012 database
Dairy Cattle Feedstuff	Dicalcium Phosphate	Gabi 6, PE 2012 database
Dairy Cattle Feedstuff	Soybean Meal	Gabi 6, PE 2012 database

3.2.3.1 Development of California Corn Stover LCI

California corn and stover production was modeled based on typical inputs, equipment usage, and yield as defined by published *Cost and Return* studies available for different regions of production in the state from UC Davis's Agricultural and Resource Economics Department [23, 17, 24, 16]. Results (yields and inputs) from the Cost and Return studies for the San Joaquin Valley and Sacramento Valley are averaged because they are the corn-producing regions most proximal to the production facility and they are also the two major corn-production regions in California. Assuming stover is produced at a 1:1 dry weight ratio to grain yield [26], an average of 11.65 metric tonne per hectare (5.2 ton/acre) corn stover can be produced in California. However, stover is typically left on the field or incorporated into the soil to return nutrients and carbon and improve soil fertility. Many studies have shown that high stover harvest rates decrease soil quality [27], but not all studies agree. For example, a study by Moebius-Clune et al. found that stover removal has no effect on soil quality under no-till production practices [28].

Usually a harvesting rate less than 40% of stover by mass for biofuel production is considered to be sustainable under typical practices, as little soil organic carbon is thought to be lost at and below 40% removal [13]. Although Blanco-Canqui [29] conclude that only 25% or less of stover removal has little impact on soil organic carbon (SOC) and total N in soil. Lugato and Jones suggested that large scale and long term stover removal could lead to SOC loss even at low removal rate [30].

In addition to disagreement among studies, none consider California conditions of soil and climate, and focus instead on the U.S. Corn Belt. Thus, the applicability of their findings to California conditions is not known, but soil, climate, and distinct crop rotations in California are all likely to change the effects of stover removal. For these reasons this study does not include possible SOC loss caused by stover removal, but considers the stover supply availability at high and low harvest rates:

High harvest scenario: Assumes stover harvesting at 40%, yielding 4.66 tonnes per hectare. Nutrients (N and P) removed in stover are assumed to be replaced with synthetic fertilizers. Replacement of N and P fertilizers are calculated using nutrient compositions in the stover from Murphy and Kendall [13]. Ammonium polyphosphate and urea ammonium nitrate (UAN32) are modeled as the N and P fertilizers as reported in *Cost and Return Studies* by California corn farms [23, 17, 24, 16]. The environmental impacts of the additional synthetic fertilizer production and application are allocated to corn stover. The emission factor of N_2O volatilization from N fertilizer was estimated as 1.525% of applied N as adopted from the GREET model [2].

The stover harvest radius is 80 km (50 miles) which means the one way transport of corn stover from farm to ethanol plant is 50 miles because corn farms in Sacramento County and San Joaquin County are able to meet the stover demand of the ethanol facility.

Low harvest scenario: Assumes stover harvesting at 25% (2.91 tonne/hectare) so that nutrients removed from stover do not need replacement, thus no additional fertilizers are required [29]. When the stover removal rate is reduced to 25%, the corn stover supply from Sacramento and San Joaquin counties is not sufficient to meet demand in the high stover case, and a wider radius is required. The harvest radius increases from 80 km to 322 km (200 miles), according to the corn cultivation acreage data in California [31]. Equipment usage hours increase as well since average stover yield decreases per hectare. The horsepower of harvesting equipment is assumed to be the same as the 40% harvest case. The accuracy of this assumption is unknown since very limited information is available for the equipment speeds, efficiencies, and power ratings at different stover harvesting rates.

These two scenarios do not include a full spectrum of possible stover collection circumstances in terms of removal fraction and nutrient replacement. For example, it is possible that at 40% removal, less than 100% of the removed nitrogen needs replacement. Moreover, some studies report reductions in post-harvest N_2O field emissions after stover removal [32]. The complex interactions of stover removal, N_2O emissions, and SOC changes are not addressed in this modeling due to a lack of data, and should be researched if the implications of stover removal and stover removal rates are to be better understood. In addition, the economics of low stover harvest rates, have not been examined, and such low harvest rates may not be economically viable.

Stover harvesting equipment activities are adopted from Hess et al. [18] as listed in table 3-3. The fuel consumption and air emissions from stover harvesting equipment, including a shredder, windrow, baler, stacker and telehandlers for upload and download are modeled from OFFROAD [15]. Corn stover is harvested and transported at 15% moisture content.

Table 3-3 Equipment usage for stover harvesting (adopted from Hess et al. 2009 [18])

Category	Equipment	HP	Use	Unit
Stover Harvest	Shred / Windrow (15ft flail shredder w/ windrow)	240	0.34	hour/hectare
Stover Harvest	Bale tractor	225	0.11	hour/hectare
Stover Harvest	Baler	180	0.11	hour/hectare
Stover Harvest	Stacker (roadside)	240	0.10	hour/hectare
Stover Harvest	Telehandlers (Load and Unload)	100	0.10	hour/hectare

Overall, higher GHG emissions, higher energy consumption and more pollutants occur per kg of stover harvested at a high rate than at a low harvest rate (Table 3-4). Under the high harvest rate (40% removal) corn stover generates higher GHG emissions than under low harvest rates due to emissions for fertilizer production and onsite N_2O emissions from N-fertilizer. Because no additional fertilizer is required for stover production, the significant impacts that result from fertilizer use are avoided. All emissions and energy input for stover production in the low harvest scenario are from harvesting equipment use (which includes longer equipment use times to obtain the same amount of stover compared to the high stover harvest scenario). A more detailed LCI for California corn stover production is reported in the Appendix which includes a breakdown by process.

Table 3-4 LCI of corn stover (with 15% moisture content) production in California under two harvest rates

	High Harvest Scenario	**Low Harvest Scenario**	Unit
CO_2	1.70E-02	1.60E-02	kg/kg
CH_4	3.43E-05	2.16E-05	kg/kg
N_2O	1.54E-06	6.05E-08	kg/kg
NMVOC	9.11E-06	9.54E-06	kg/kg
CO	3.46E-05	3.90E-05	kg/kg
NO_x	2.22E-04	1.00E-04	kg/kg
SO_x	3.10E-05	1.12E-05	kg/kg
PM_{10}	5.41E-06	3.58E-06	kg/kg
$PM_{2.5}$	4.61E-06	1.02E-07	kg/kg
Fossil Fuel	**0.46**	**0.23**	**MJ/kg**
Total Energy	**0.50**	**0.24**	**MJ/kg**
GWP_{100}	**0.018**	**0.017**	**kg CO_2e/kg**
GWP_{20}	**0.020**	**0.018**	**kg CO_2e/kg**

3.2.4 Transportation of feedstocks

Corn kernels are imported from the Midwest via rail. Rail miles are estimated using the BNSF 6003 Rail Miles Inquiry [33] the rail distance from Grand Island, Nebraska to Stockton, CA is 2829 km. Heavy duty trucks are used to transport corn from farms to rail elevator stations in Nebraska assuming 32 km (20 miles) average distance because the average length of truck transportation from farm to elevator is 21 km in north-central plains region and 32 km radius covers 75% of grains in the region [34]. The estimation is close to the results reported by Vachal (2015), which estimated average corn delivery distance for the Corn Belt at 35 km [35]. Corn kernels are delivered to the modeled ethanol facility by train directly.

Corn stover is transported from California farms to the ethanol facility at Stockton, CA using heavy duty trucks. The distance of stover transportation is determined by the stover harvest rate, as described in the section 2.3.1. Inputs for stover production in California are described in table 3-5.

Table 3-5 Inputs for stover production in California

	High Harvest	Low Harvest
Stover Harvested (kg/hectare)	4669	2918
Diesel Use for Harvest Equipment (liter/kg corn stover)	1.06E-02	1.69E-02
Truck Transport Distance (round-trip) (km/kg corn stover)	160	644
Fertilizers		
Monoammonium phosphate (kg/kg corn stover)	3.85E-03	0
UAN32 (kg/kg corn stover)	2.37E-02	0

3.2.5 Allocation of Impacts

An allocation process is required to assign life cycle impacts to each of the two ethanol types produced when the bolt-on technology is added to the system. Two occasions require allocation: first, allocation of facility operations among corn and stover ethanol; and second, allocation among the co-products of corn ethanol, cellulosic ethanol, and DGS. The decision basis for allocation method selection follows the International Organization for Standardization (ISO) 14040 standard's hierarchy of preference; where possible subdivision is used to avoid allocation, followed by system expansion (displacement), with value-based allocation (e.g. based on energy content or economic value) as the least preferred allocation method [36]. The ISO standard also recommends testing multiple allocation methods, which is done for allocation among ethanol and WDGS. Sensitivity analysis is also applied to examine the effect of price on displacement and economic allocation outcomes.

3.2.5.1 Allocation of facility operation

Facility operations are allocated among corn ethanol and stover ethanol using a multi-step process whereby a subdivision method is applied to those processes, which can be wholly attributed to either of the products, followed by an energy-based allocation of shared facility processes, and then a displacement calculation for the generated co-product of WDGS used as livestock feed.

For the facility operations suitable for subdivision, stover ethanol is allocated 100% of the bolt-on energy consumption and generation, and corn ethanol is allocated 100% of front-end processes. In the high stover case, the credit of heat production from lignin combustion is allocated entirely to cellulosic ethanol, which is a major contribution to the lower life cycle GHG emissions, or CI, compared to the low stover case. Corn ethanol is allocated 100% of the alpha-amylase and gluco-amylase enzymes used in the system.

The energy consumption, utilities, water, and yeast used in the shared processes cannot be subdivided and consequently are allocated in proportion to the production of each ethanol type based on their energy content. The lower heating value of 80.5 MJ/gallon is assumed for both corn ethanol and cellulosic ethanol.

3.2.5.2 Allocation of co-product WDGS

WDGS is assumed to be used as dairy cattle feed in California. Most displacement calculations for DGS products in the U.S. are based on modeling conducted for the U.S. Corn Belt, yet the availability of feedstuff varies significantly across the U.S. Here, common displacement values used in LCA of corn ethanol for WDGS are used for comparability with other studies, but original displacement calculations tailored to the California dairy feed market are also calculated to test whether regional specificity is important in WDGS displacement calculations.

A common source for displacement values is the GREET model, developed at Argonne National Labs and used in California's Low Carbon Fuel Standard to estimate the carbon intensity of fuels. GREET assumes that DGS (in either wet or dry form) displaces dairy cattle feed. Dairy cattle feed is modeled as a combination of corn grain and soybean meal. This model is used extensively by researchers and policymakers and is widely cited as a source for DGS displacement calculations. GREET credits the ethanol production system with avoiding emissions from corn and soybean meal production; one kilogram of WDGS displaces 0.445 kg of corn grain and 0.545 kg of soybean meal for dairy cattle feed (all dry matter based) [37].

While some feed rations (particularly those in the U.S. Corn Belt) might be reasonably defined by this substitution, California feed rations are not because of the different feedstuffs available in the state. Thus, while GREET's default assumptions are used as the baseline value, additional scenarios are tested where feed assumptions tailored to California are modeled and new displacement calculation conducted, along with a scenario for economic allocation.

Based on review of the existing literature, no research or assessment of the displacement value for WDGS (or other dairy cattle feeds) in California exists. To develop regional values, a feed optimization tool tailored to California was identified, *PCDAIRY_2005_USA (Least Cost and Ration Analysis Programs for Dairy Cattle)*, referred to hereafter as PCDAIRY [38]. PCDAIRY uses an economic optimization based on the price of available feeds and their nutritional profiles to recommend a balanced ration at lowest cost. To identify feedstuffs likely to be displaced by the introduction of WDGS, PCDAIRY is run with and without WDGS. By doing so, the consequential change induced by introducing local WDGS into the feed market in California can be estimated. The displacement calculations implicitly assume that the introduction of WDGS from the simulated facility will not have a significant effect on the price of other feeds.

The required input data for PCDAIRY, which include California dairy feedstuffs, their prices, and the price of milk, are from the California Department of Food and Agriculture (CDFA) [39, 40]. Based on PCDAIRY calculations, the addition of 1 kilogram WDGS in a standard dairy cattle feed ration would result in increases of 0.037 kg of corn silage and 0.0007 kg of dicalcium phosphate, while reducing 0.06 kg of beet pulp, 0.04 kg of alfalfa hay, 0.63 kg of corn grain, 0.24 kg of cottonseed meal, 0.22 kg of almond hulls and 0.001 kg of salt, in an optimal ration. These changes constitute the effects of adding WDGS to a dairy feed ration and will be used to calculate its displacement value (LCI of California feedstuffs are reported in Appendix).

Table 3-6 compares the credits generated by the displaced feeds described above and the displacement value from the GREET model.

Table 3-6 Displacement credits of 1 kg WDGS (dry mass basis)

	GREET Displacement	California Displacement	
CO_2	1.68E-01	1.28E-01	kg/dry kg
CH_4	1.10E-04	2.48E-04	kg/dry kg
N_2O	1.83E-04	3.45E-04	kg/dry kg
NMVOC	2.41E-05	3.76E-03	kg/dry kg
CO	2.97E-04	4.27E-04	kg/dry kg
NO_x	2.28E-04	5.26E-04	kg/dry kg
SO_x	6.01E-03	3.39E-03	kg/dry kg
PM_{10}	1.24E-05	1.02E-04	kg/dry kg
$PM_{2.5}$	9.68E-06	9.58E-05	kg/dry kg
Fossil Energy	**3.00**	**2.75**	**MJ/dry kg**
Primary Energy	**3.42**	**3.27**	**MJ/dry kg**
GWP_{100}	**0.22**	**0.24**	**kg CO_2e/dry kg**
GWP_{20}	**0.23**	**0.25**	**kg CO_2e/dry kg**

Economic allocation is an alternative approach to displacement calculations, it partitions the impacts of a production system among co-produced products based upon the economic value of each product. In this study, corn ethanol and cellulosic ethanol are assumed to have the same market value of $2.44 per gallon, the average monthly price of ethanol from 2012 to 2014 [41]. The average 2012 to 2014 monthly price of dried DGS (or DDGS) is $316 per dry tonne. This value is used to represent WDGS value (on a dry basis) because of a lack of historical market prices for WDGS [42]. Table 3-7 shows allocation ratios between ethanol and WDGS based on market values.

Table 3-7 Assumptions and calculations for economic allocation between ethanol and WDGS

		Baseline	Low Stover Case	High Stover Case
WDGS Price	$/dry metric tonne	316.42		
Ethanol Price	$/Gallon Ethanol	2.44		
Mixed (Corn and Stover) Ethanol	WDGS Delivered (dry kg/MJ_{EtOH})	0.035	0.033	0.032
	Allocation to Ethanol	73%	74%	75%
	Allocation to WDGS	27%	26%	25%
Corn Ethanol Only	DGS from corn (dry kg/MJ_{EtOH})	0.035	0.031	0.032
	Allocation ratio to Ethanol	73%	76%	75%
	Allocation ratio to WDGS	27%	24%	25%
Stover Ethanol Only	DGS from Stover (dry kg/MJ_{EtOH})	--	0.207	0.042
	Allocation ratio to Stover Ethanol	--	32%	70%
	Allocation ratio to Stover WDGS	--	68%	30%

3.2.6 Sensitivity Analysis

A sensitivity analysis is performed on various parameters to test the sensitivity of the resulting CI of corn ethanol and stover ethanol. The baseline assumptions for all variables are described in previous sections using the high harvest rate and high stover capacity case. Each input is varied separately by ±10% with all other parameters held constant to its baseline value. Although this one-at-a-time sensitivity analysis approach cannot detect the interactions among variables, it is chosen because it avoids complicated computations and is capable of comparing effects of parameters under different scenarios simultaneously, e.g. price effects on economic allocation and displacement calculations. The parameters tested include ethanol price, WDGS price, the co-product displacement credit as function of price, yeast and enzyme (alpha-amylase, gluco-amylase, and cellulase) dosing rates, transportation distances for corn grain and stover, Midwest corn yield and California stover yield. Parameters that cause more than 0.01% change in model results per 1% change in parameter value are reported.

3.3. Results and Discussion

LCA results for corn ethanol and cellulosic ethanol are described in the following sections by impact category. Complete results for GHG emissions, energy inputs, non-GHG air pollutants, land use, and water use results for mixed ethanol, corn ethanol and stover ethanol under the three facility cases, two harvest scenarios, and using the three co-product allocation strategies are reported in the online supplementary material available for this article (tables S1 and S2).

3.3.1 GHG emissions

The CI of corn ethanol ranges from 41.5 to 49.1 g CO_2e/MJ (with no iLUC emissions) when the three facility designs and multiple allocation methods are considered. Because corn ethanol production is expected to induce iLUC, while stover-derived ethanol is not, it is important to only compare the CI of these fuels when iLUC is accounted for. Results shown in figures 2 and 3 include the iLUC emissions estimate of 19.8 g CO_2e/MJ for corn ethanol, the ilUC emissions estimate used in California's LCFS [43]. Stover harvest rates have no effect on the CI of corn ethanol because stover does not contribute to corn ethanol production based on the methodology used. The CI of corn ethanol does not seem to be affected by the incorporation of the bolt-on technology. Overall, the CI of corn ethanol remains steady in the three facility designs.

The CI of stover ethanol, however, ranges from 14.58 to 109.21 g CO_2e/MJ. In the low stover case, facility utility and enzyme use are the most GHG-intensive processes for cellulosic production; while enzyme and feedstock transportation are the two highest contributors of GHG emissions of cellulosic ethanol in the high stover case (figure 3-2). In the high stover case, stover residuals are combusted in the boiler to generate heat and displace natural gas demand. The large amount of heat provided by residuals combustion leads to a negative emission (meaning it avoids more emissions that it produces) and thus reduces the net CI of cellulosic ethanol.

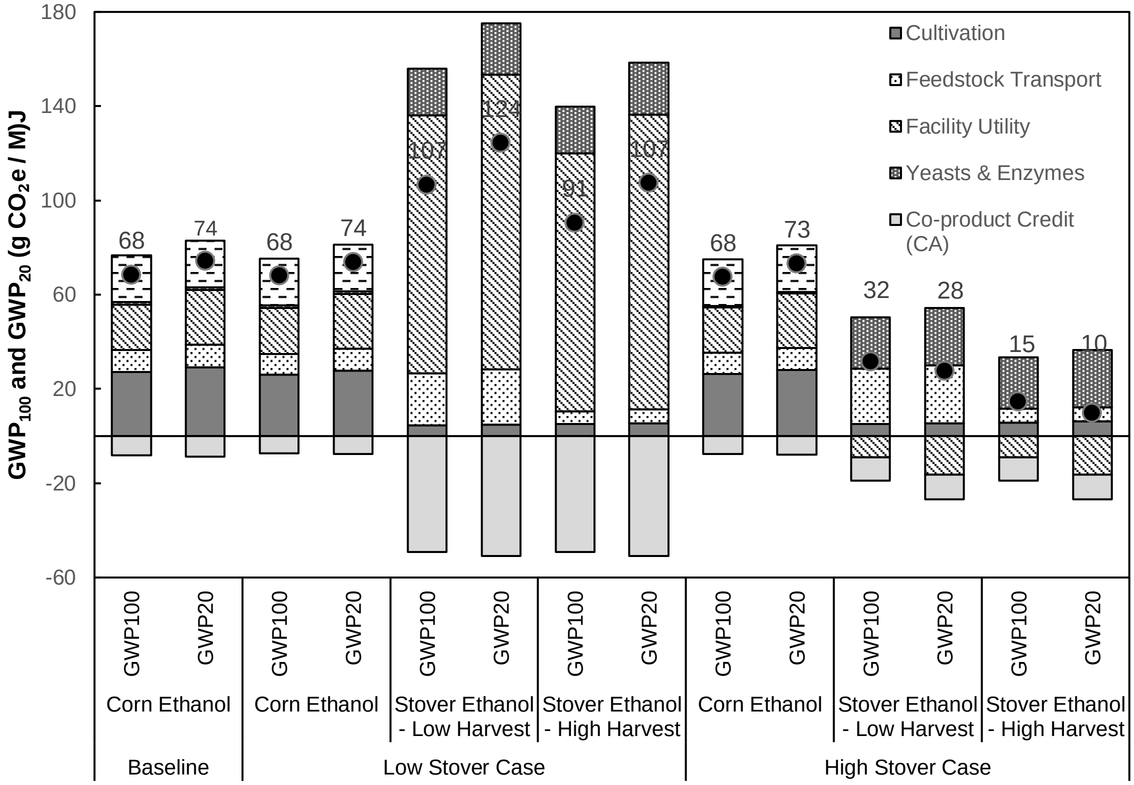

Figure 3-2 GWP100 and GWP20 from corn and stover ethanol with California displacement method

Other significant differences between the low stover case and high stover case result from WDGS displacement credits and energy credits. The low stover case benefits from WDGS contributed by corn stover, but the electricity consumption of the bolt-on system is significant and cellulosic ethanol production is relatively low compared to the energy consumption from the facility. Therefore, the CI of cellulosic ethanol from the low stover case is much higher than that from high stover case.

The WDGS credit for the low stover case is much larger than the WDGS credits from any other facility cases due to the small amount of cellulosic ethanol production and relatively high WDGS contribution from corn stover. One MJ of cellulosic ethanol produced from the low stover case associates with 0.21 kg of WDGS produced from stover while only 0.03 kg to 0.04 kg WDGS is produced from other facility cases per MJ ethanol production.

Stover harvest rates also have significant effects on the CIs of cellulosic ethanol. Because the low harvest rate requires a larger stover collection radius, emissions and energy use from transportation increase. Therefore, although GHG emissions of stover production are lower at low harvest rate, the high harvest rate performs better once transportation to the facility is accounted for (figure 3-2).

The CI of corn ethanol and cellulosic ethanol based on both GWP_{100} and GWP_{20} are presented in figure 2 (and use the California displacement calculations). The GWP_{20} of stover ethanol is higher than GWP_{100} in the low stover facility, while the situation is the opposite in the high stover facility. The low stover facility design requires large amount of energy, provided by natural gas, which causes CH_4 emissions due to leakage over the fuel cycle and increases GWP_{20} relative to GWP_{100}. In the high stover facility stover residuals provide most facility energy needs and thus receives a credit by avoiding natural gas usage, reducing methane emission.

The effects of allocation strategies on GHG emissions of corn and stover ethanol are shown in figure 3-3, assuming the high stover harvest rate. Results from the two displacement methods lead to similar results. In general, GHG emissions with economic allocation are lower than those from displacement methods. But in the low stover facility, the choice of allocation strategies has a significant effect on the result; GHG emissions from stover ethanol are much lower with economic allocation than with displacement methods. This is because in the low stover case, stover ethanol is produced in small quantities compared to its co-product of residuals used in WDGS, and the contribution of residuals to WDGS dominates the economic allocation, and to a lesser extent in displacement calculations.

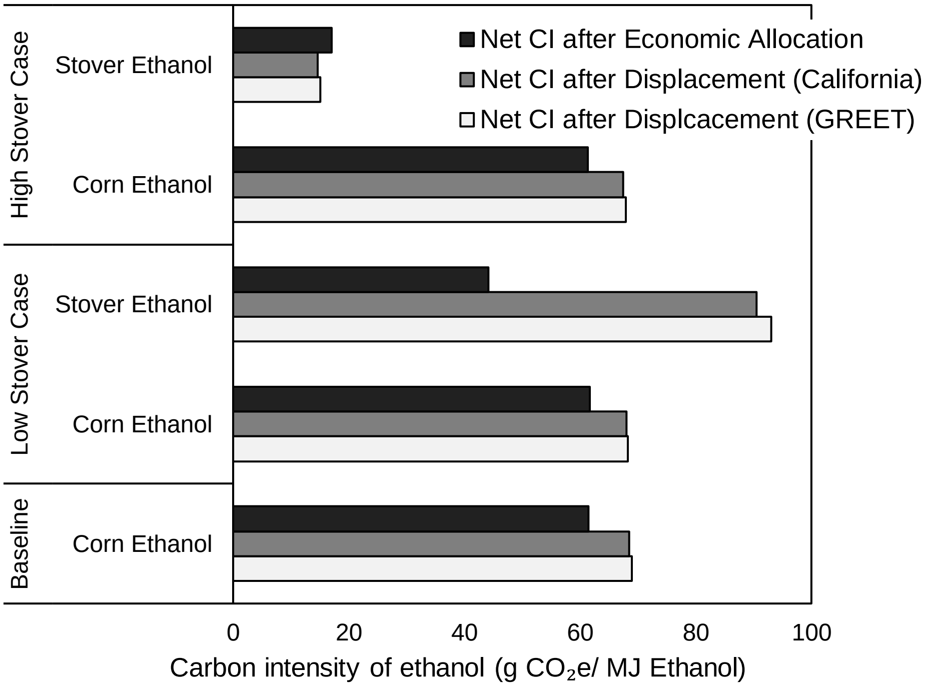

Figure 3-3 Effects of allocation strategies on carbon intensity results for corn and stover ethanol at high stover harvest rate (iLUC emissions of 19.8 g CO2e/MJ included in corn ethanol results)

3.3.2. Total energy and fossil energy

Biomass energy is produced and consumed within the ethanol production system, so the biomass energy is not included in the total fuel consumption values reported. Total fuel and fossil fuel consumption are relatively consistent (0.58 – 0.70 MJ fossil energy per MJ and 0.60 – 0.71 MJ total energy per MJ) for corn ethanol across the three cases with different allocation strategies (table 3-8). Stover harvest scenarios have no effect on energy consumption of corn ethanol because only stover harvest and transportation are affected.

For cellulosic ethanol, the fossil fuel consumption and total energy consumption ranges from -0.19 to 1.98 MJ fossil fuel/MJ and 0.13 to 2.29 MJ total energy/MJ, respectively, among all facility cases, harvest scenarios and allocation methods. Energy consumption of each ethanol are found to be lower with economic allocation than with the two displacement methods. Stover ethanol can achieve high energy efficiency in the high stover case.

Table 3-8 Fossil energy and total energy consumption by ethanol (MJ/ MJ Ethanol)

			Corn Ethanol		**Stover Ethanol**	
	(MJ/MJ)		Fossil Energy	Total Energy	Fossil Energy	Total Energy
High Harvest Scenario	Economic Allocation	Baseline	0.58	0.60	--	--
		Low Stover	0.59	0.61	0.76	0.89
		High Stover	0.58	0.61	-0.04	0.19
	GREET Displacement	Baseline	0.69	0.70	--	--
		Low Stover	0.69	0.70	1.78	2.12
		High Stover	0.68	0.70	-0.19	0.13
	California Feed Displacement	Baseline	0.70	0.71	--	--
		Low Stover	0.69	0.71	1.83	2.15
		High Stover	0.69	0.70	-0.18	0.14
Low Harvest Scenario	Economic Allocation	Baseline	0.58	0.60	--	--
		Low Stover	0.59	0.61	0.81	0.94
		High Stover	0.58	0.61	0.07	0.30
	GREET Displacement	Baseline	0.69	0.70	--	--
		Low Stover	0.69	0.70	1.93	2.26
		High Stover	0.68	0.70	-0.03	0.28
	California Feed Displacement	Baseline	0.70	0.71	--	--
		Low Stover	0.69	0.71	1.98	2.29
		High Stover	0.69	0.70	-0.02	0.29

Cellulosic ethanol performs best for the high stover case because of the natural gas displacement from lignin combustion. The fuel consumption in the low stover case is high due to the bolt-on electricity consumption, and the small amount of cellulosic ethanol produced.

Total energy consumption is higher for cellulosic ethanol in the low harvest rate scenario, due to the higher fuel consumption for stover transport (figure 3-4).

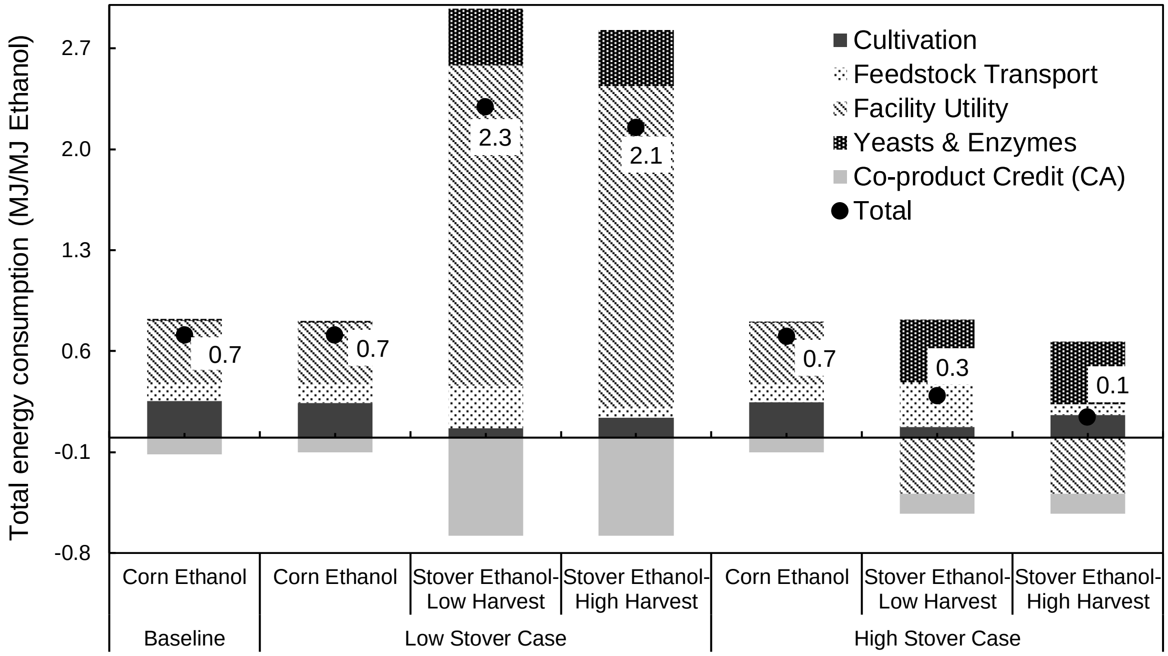

Figure3-4 Total energy consumption from ethanol with California displacement method

3.3.3 Criteria pollutants

Air pollutants including NMVOC, CO, NO_x, SO_x, PM_{10} and $PM_{2.5}$ from corn and stover ethanol are reported in figure 3-5 under the high stover harvest scenario with two co-product allocation methods, economic allocation and displacement with California feeds.

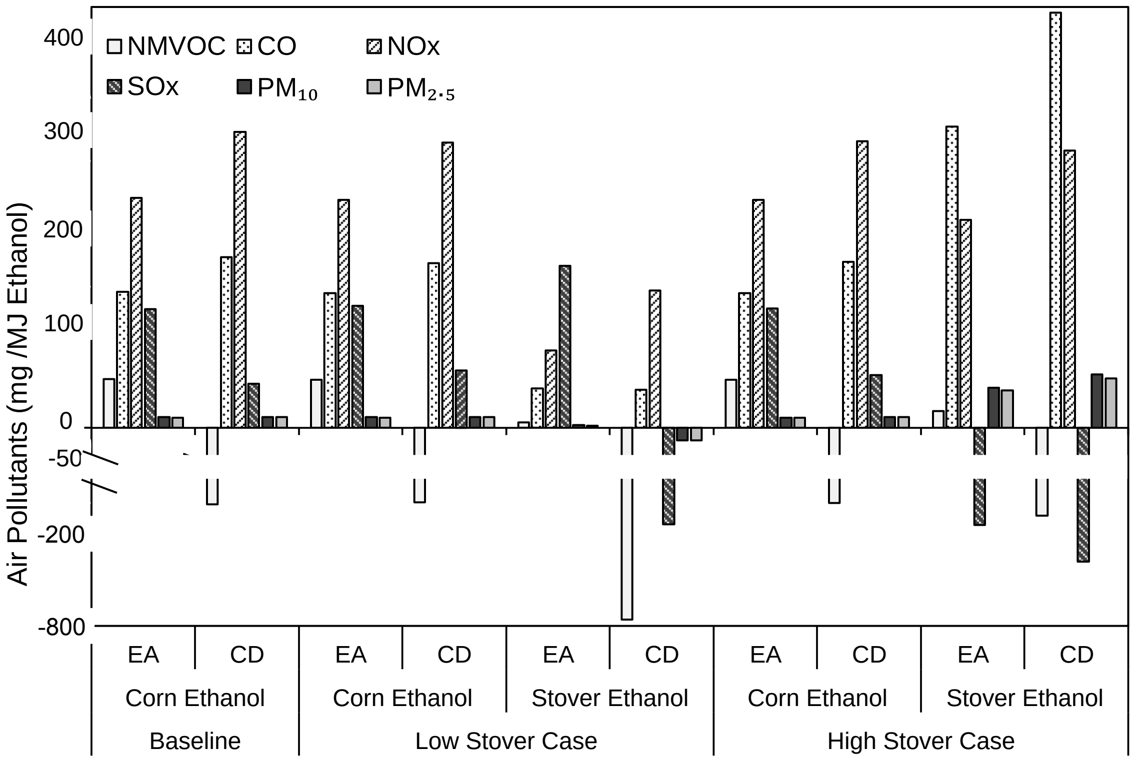

Figure 3-5 Criteria air pollutants from corn and stover ethanol at high stover harvest rate with economic allocation and California displacement (EA= economic allocation; CD= California displacement)

Air pollutants from corn ethanol are relatively constant among three facility cases. Stover ethanol has higher air emissions in the high stover facility compared to stover ethanol from the low stover facility because lignin combusted in a biomass boiler generates higher air emissions than those from natural gas fired boilers. Air emissions of an industrial biomass boiler using corn stover as feedstock are based on the values from CA-GREET 1.8b [44]. CO and PM emissions are particularly high for stover ethanol in the high stover facility. Co-product allocation has significant impact on the results. The California displacement method assumes WDGS displaces local feedstuffs (e.g. corn and cottonseed) and thus avoids farming emissions from crop cultivation. The displacement results show lower NMVOC and SO_x pollutants but higher CO, NO_x and PM pollutants compared with economic allocation. The air pollutants are spatially sensitive (e.g. air emissions may have higher impacts in California than in the Midwest), and thus the allocation methods need to be carefully selected for policy decisions. Note that displacement methods tend to result in negative values, which indicate the significant emission reduction potential by displacing local feeds.

The definition of reactive organic gases (ROG) in OFFROAD2007 and EMFAC2011 is similar to the EPA’s definition of volatile organic compounds (VOC) but not identical, methane and ethane are excluded in that air emission group. In this study, non-methane VOCs (NMVOCs) are reported as the ROG value from OFFROAD2007 and EMFAC2011.

3.3.4 Water Use and Land Use

California corn grain requires 100 cm (40 inches) of irrigation water, while corn in Nebraska requires an average of 25 cm (10 inches) irrigation water [45]. However, none of the irrigation water applied in California is allocated to corn stover production because stover harvesting does not affect irrigation water demand. Facility water use is partitioned to corn ethanol and stover ethanol using energy-based allocation. In the facility, cellulosic ethanol consumes more water than corn ethanol because the pre-processing of cellulosic feedstock requires steam explosion (table 3-1). But cellulosic ethanol has lower life cycle water consumption due to zero water input for corn stover cultivation (table 3-9).

Similar to water consumption, no land use is allocated to corn stover production because the primary purpose of corn farming is to produce corn, not stover. In theory an economic allocation could be applied to estimate a land use value for stover, but it is not tested here. Table 3-9 shows the direct water and land use for ethanol production with no allocation to WDGS.

Table 3-9 Direct water use and direct land use for ethanol production (without allocation to WDGS)

	Baseline	**Low Stover Case**	**High Stover Case**	**Unit**
Midwest Corn Irrigation	1088912	1027449	988266	m^3/day
CA Stover Irrigation	--	0	0	m^3/day
Facility Water Use	649	658	795	m^3/day
Total Water Use	1089561	1028107	989061	m^3/day
Mixed Ethanol Water	**7.86E-02**	**7.42E-02**	**7.14E-02**	**m^3/MJ**
Corn Ethanol Water	**7.86E-02**	**7.51E-02**	**7.58E-02**	**m^3/MJ**
Cellulosic Ethanol Water	**--**	**4.75E-05**	**5.74E-05**	**m^3/MJ**
Midwest Corn Land	428.71	404.51	389.08	hectare/day
CA Stover Land	--	0.00	0.00	hectare/day
Total Land Use	428.71	404.51	389.08	hectare/day
Mixed Ethanol Land Use	**3.09E-05**	**2.92E-05**	**2.81E-05**	**hectare/MJ**
Corn Ethanol Land Use	**3.09E-05**	**2.95E-05**	**2.98E-05**	**hectare/MJ**
Cellulosic Ethanol Land Use	**--**	**0.00**	**0.00**	**hectare/MJ**

3.3.5 Sensitivity Analysis

Among the parameters tested in sensitivity analysis, GHG emissions of corn ethanol are most sensitive to co-product price, ethanol price, corn yield, transportation distances and gluco-amylase dosing; and GHG emissions of stover ethanol are most sensitive to prices of WDGS and ethanol, cellulase dosing, transportation distances and feedstock yield, as illustrated in figure 3-6. Sensitivity results are reported as percent change in ethanol CI per one percent change in parameter values.

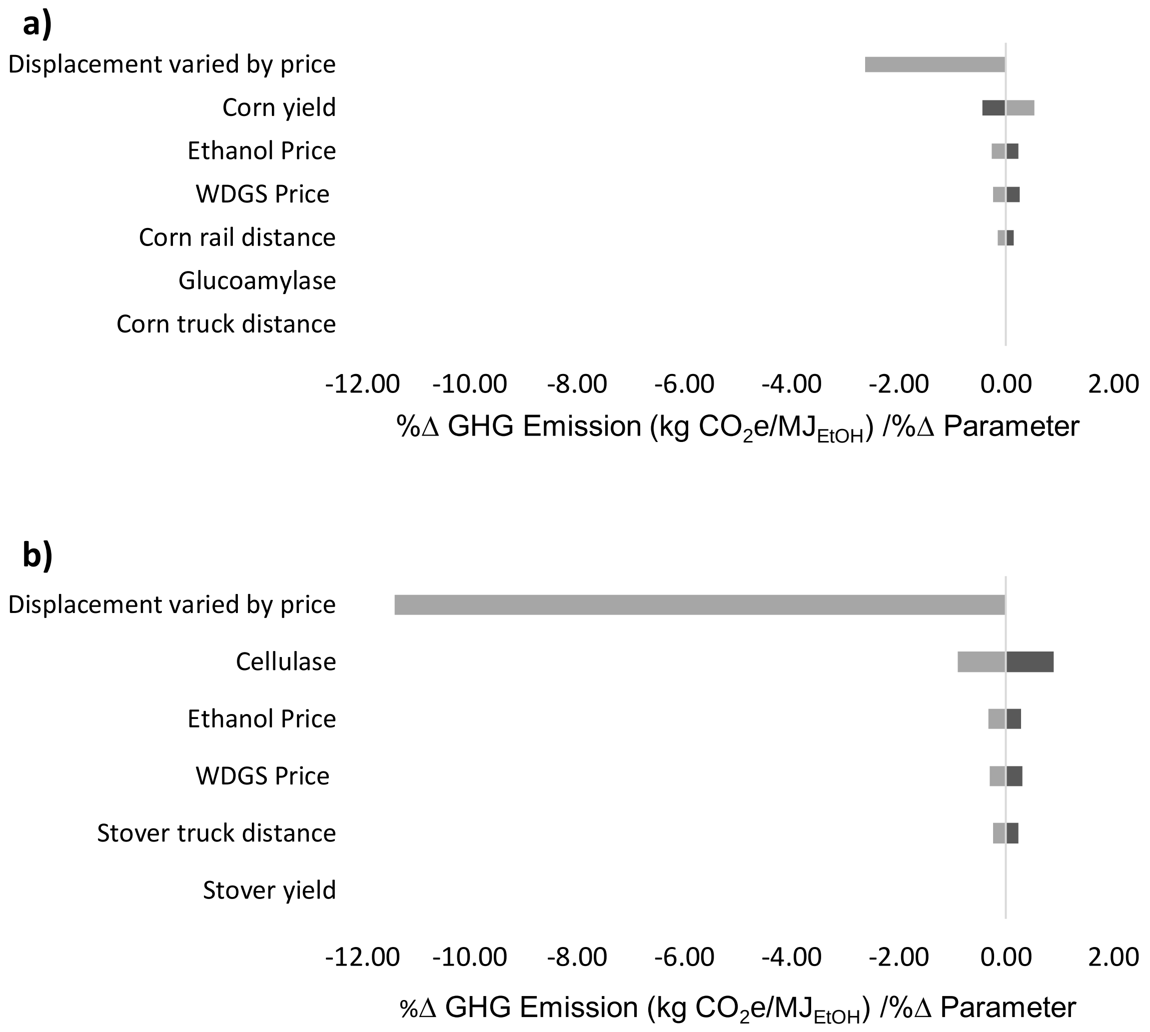

Figure 3-6 Sensitivity analysis for CI of (a) corn ethanol and (b) stover ethanol. Black bars indicate a 1% increase in parameter value, and grey bars indicate a 1% decrease in parameter value

3.3.5.1 Co-product Allocation

Both displacement calculations and economic allocation methods are sensitive to feedstuff price volatility. The price of ethanol also has strong effects on the CI of ethanol when economic allocation is used.

Price fluctuations of WDGS have significant effects of the CI for corn ethanol and stover ethanol using displacement methods. A 1% of price reduction in WDGS results in 2.6% and 11.4% reduction of GHG emissions from corn ethanol and stover ethanol, respectively. Only a lower price is tested for WDGS because higher prices for WDGS exceed the price limit for displacing other feedstuffs. Thus the market would not bear a higher WDGS price. Seasonal changes in the market value of feedstuffs will affect the composition of feed rations, resulting in a non-linear variation of the displacement credit from WDGS over the period of a year. More seasonal or monthly data on the historical prices for dairy cow feedstuffs in California would help quantify potential variability in displacement calculations for WDGS. Year-to-year price has fluctuated in recent years as well for both DDGS and ethanol. For example, during the three years from 2012 through 2014, the price of dried distiller's grain and solubles (DDGS) varied from $117 per ton to $280 per ton, and the price of ethanol fluctuated from $1.6 to $2.9 per gallon [41, 42]. As with the intra-annual volatility, improved data and modeling could help estimate the expected variability in WDGS displacement credits over time.

Another important consideration is the nutrient contribution of stover to WDGS; it is primarily lignin (though dissolved solids such as xylose are also included) instead of protein, fat, or starch. The nutrient values of these cellulosic residuals for dairy cattle are not as high as whole WDGS. This study assumes the qualities of WDGS from the combined stover and grain facility are identical to WDGS from a corn grain-only facility. A more detailed assessment could examine the nutrient contribution of each source (corn grain and stover) to WDGS. This seems most important for the low stover case, because the WDGS co-product credit is extremely important to the performance of the stover ethanol, while in the high stover case most of the co-product credit for stover ethanol comes from displacement of natural gas when residuals are used as boiler feed and thus the methods used to calculate dairy feed displacement credits do not have a significant effect on stover ethanol CI.

3.3.5.2 Enzymes

Enzyme dosing rates have significant effects on the model outcomes as shown in the sensitivity analysis. However, there are limited sources of LCIs or other relevant data for LCI development for enzymes. In the GREET model, the LCIs of yeast and alpha-amylase are collected from Dunn et al. [46] and the LCI of cellulase is from Wang et al. [2]. One challenge of using existing data is that the active ingredients in cellulase products can be very different, and may result in variations in dosing rates and efficiency. A review of previous literature and sources show significant differences in enzyme dosage among studies, as shown in table 3-10, suggesting differences in the cellulase products, yet these studies do not provide detailed information on the products they model.

Table 3-10 Comparison of enzymes dosing rates from different studies

Enzyme or Yeast	Unit	This study	Dunn 2012, Industry [46]	Maclean & Spatari 2009 [47]	Wang 2012 [2]
Alpha-amylase	kg solution/dry tonne corn	0.52	0.36	0.80	1.04
Gluco-amylase	kg solution/dry tonne corn	0.99	0.61	1.10	1.04
Cellulase	kg solution/dry tonne stover	13.40	10-100	9.2-9.6	15.50
Yeast to propagation	Kg dry/dry tonne substrate	0.035	--	--	0.358 (corn)
Yeast to propagation	Kg dry/dry tonne substrate	0.045-0.048	--	--	2.49 (cellulosic)

3.3.5.3 Feedstock Supply

GHG emissions of ethanol are highly sensitive to corn yield and stover yield. A 1% increase of feedstock yield results in reductions of 0.15% to 0.53% in the CI of ethanol. While increasing yield will reduce the GHG emissions from corn ethanol and stover ethanol, the assumption of fertilizer replacement in the corn stover supply scenarios significantly influences the CI, fossil fuel and air pollutant emissions of cellulosic ethanol. This study only tests two simple scenarios, 100% replacement of fertilizer at a 40% harvest rate and no replacement of fertilizer at a 25% harvest rate. However, if 50% of total fertilizer is replaced in the 40% harvest case, the CI of cellulosic ethanol could be reduced by 15% to 40% (depending on other scenario assumptions). In addition, the assumption that increased synthetic fertilizer application after stover harvest increases N_2O emissions may be incorrect, given previous studies that show a reduction in N_2O after stover harvest [32]. Finally, the climate and soil conditions in California are so distinct from the

U.S. Corn Belt, where nearly all stover research has been conducted, that the findings may not be applicable.

Further research is needed on corn stover farming and harvesting for California to test the optimized harvest rate that minimizes life cycle impacts. The harvest rate affects the transport distance of feedstocks and thus its environmental performance. A more sophisticated optimization-based analysis could provide an optimum recommendation for harvest rate and transport distance that is specific to the region analyzed and that reflects corn planting density and road networks.

3.4. Conclusions

This study evaluates impacts of facility design, feedstock supply scenarios and co-product allocation strategies on GHG emissions, energy consumption, criteria air emissions, water use, and land use of ethanol production from corn and corn stover in California.

Stover ethanol produced from the examined scenarios has lower CI, lower fossil energy consumption and less air pollutant emissions than corn ethanol, and stover production seems to avoid key sustainability issues that affect biofuel feedstocks, like water and land use. However, the sustainability of stover removal from the standpoint of soil carbon and the effect of stover removal on fertilizer demand and other farming practices are uncertain and require additional research.

Co-product credits are important for the performance of both stover and corn ethanol in this production system. The co-product allocation method selected (e.g. economic allocation or displacement methods) do not result in significant effects on the CI of stover or corn ethanol except for the case of stover ethanol from the low stover facility. However, as indicated in the sensitivity analysis, a nutrient-based co-product allocation process for WDGS could change these results significantly. The high stover case does not face the same uncertainty with regard to co-product allocation methods.

The displacement credit from co-products reflects real world market conditions for California, which likely improves the representativeness of results, but requires careful validation by policymakers if incorporated in policy-relevant life cycle methods. The use of the solid residual byproduct as boiler feed (a use that is internal to the production facility) eliminates much of the uncertainty introduced by co-product uses outside the production system, which require allocation calculations. Thus, the results for the CI of stover ethanol from this case are consistent across co-product allocation methods.

3.5. Acknowledgements

The authors would like to acknowledge financial support from California Energy Commission, contract grant award number ARV-11-018. We are also grateful to Lily Wachter, Tom Griffin, Richard Woods and Cameron Cast at Edeniq, Inc for providing valuable data and helpful discussions.

3.6. References

1. Feed Grains: Yearbook Tables (2016) United States Department of Agriculture Economic Research Service. http://www.ers.usda.gov/data-products/feed-grains-database/feed-grains-custom-query.aspx#ResultsPanel. Accessed December 16, 2015
2. Wang M, Han J, Dunn JB, Cai H, Elgowainy A (2012) Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. Environmental Research Letters 7 (4):045905
3. Looker D (2015) World's Largest Cellulosic Ethanol Plant Opens in U.S. http://www.agriculture.com/news/business/wlds-largest-cellulosic-ethol-plt-opens_5-ar51218. Accessed Dec 12 2015
4. Morrison GM, Witcover J, Parker NC, Fulton L (2016) Three routes forward for biofuels: Incremental, leapfrog, and transitional. Energy Policy 88:64-73. doi:http://dx.doi.org/10.1016/j.enpol.2015.10.014
5. Wallace R, Ibsen K, McAloon A, Yee W (2005) Feasibility Study for Co-Locating and Integrating Ethanol Production Plants from Corn Starch and Lignocellulosic Feedstocks (Revised). National Renewable Energy Laboratory. Golden, CO, US
6. Dias MOS, Junqueira TL, Cavalett O, Cunha MP, Jesus CDF, Rossell CEV, Maciel Filho R, Bonomi A (2012) Integrated versus stand-alone second generation ethanol production from sugarcane bagasse and trash. Bioresource Technology 103 (1):152-161. doi:http://dx.doi.org/10.1016/j.biortech.2011.09.120
7. Dias MOS, Junqueira TL, Cavalett O, Pavanello LG, Cunha MP, Jesus CDF, Maciel Filho R, Bonomi A (2013) Biorefineries for the production of first and second generation ethanol and electricity from sugarcane. Applied Energy 109:72-78. doi:http://dx.doi.org/10.1016/j.apenergy.2013.03.081
8. Gnansounou E, Vaskan P, Pachón ER (2015) Comparative techno-economic assessment and LCA of selected integrated sugarcane-based biorefineries. Bioresource Technology 196:364-375. doi:http://dx.doi.org/10.1016/j.biortech.2015.07.072
9. Ou L, Brown TR, Thilakaratne R, Hu G, Brown RC (2014) Techno-economic analysis of co-located corn grain and corn stover ethanol plants. Biofuels, Bioproducts and Biorefining 8 (3):412-422
10. Canter C, Dunn J, Han J, Wang Z, Wang M (2015) Policy Implications of Allocation Methods in the Life Cycle Analysis of Integrated Corn and Corn Stover Ethanol Production. Bioenerg Res:1-11. doi:10.1007/s12155-015-9664-4
11. Technical Committee ISO/TC207 (2006) ISO 14044 International Standard: Environmental management – Life cycle assessment – Principals and framework. International Organization for Standardization. Geneva
12. Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz M, Dorland RV (2007) Changes in Atmospheric Constituents and in Radiative Forcing. Climate Change 2007: The Physical Science Basis. Press CU, Cambridge, United Kingdom and New York, NY
13. Murphy CW, Kendall A (2013) Life cycle inventory development for corn and stover production systems under different allocation methods. Biomass and Bioenergy 58 (0):67-75. doi:http://dx.doi.org/10.1016/j.biombioe.2013.08.008
14. Mobile Source Emission Inventory (2011) California Environmental Protection Agency. http://www.arb.ca.gov/msei/modeling.htm
15. Off-Road Mobile Source Emission Inventory (2007) California Environmental Protection Agency. http://www.arb.ca.gov/msei/modeling.htm

16. Brittan KL, Schmierer JL, Munier DJ, Klonsky KM, Livingston P (2008) Sample Costs to Produce Field Corn on Mineral Soils in the Sacramento Valley. University of California Cooperative Extension. Department of Agricultural and Resource Economics, UC Davis
17. Frate CA, Marsh BH, Klonsky KM, De Moura RL (2008) Sample Costs to Produce Grain Corn San Joaquin Valley-South 2008. University of California Cooperative Extension. Department of Agricultural and Resource Economics, UC Davis. http://coststudies.ucdavis.edu
18. Hess JR, Kenney KL, Ovard LP, Searcy EM, Wright CT (2009) Commodity-Scale Production of an Infrastructure-Compatible Bulk Solid from Herbaceous Lignocellulosic Biomass. Idaho National Laboratory. Idaho Falls, ID. https://bioenergy.inl.gov/Reports/Uniform%20Format%20Bioenergy%20Feedstock.pdf
19. Kendall A, Marvinney E, Brodt S, Zhu W (2015) Life Cycle–based Assessment of Energy Use and Greenhouse Gas Emissions in Almond Production, Part I: Analytical Framework and Baseline Results. Journal of Industrial Ecology 19 (6):1008-1018
20. Mitchell J, Klonsky K, Stewert D (2015) Sample Costs to Produce Silage Corn: Conservation Tillage Practices San Joaquin Valley – North. University of California Cooperative Extension. Davis, California http://coststudyfiles.ucdavis.edu/uploads/cs_public/a9/c5/a9c55e16-83cf-46f3-86b8-436ae2deb41f/15ctsilagecornsanjoaquinvalleyfinaldraftjuly20.pdf
21. Alexiades A (2014) Applying Adaptive Agricultural Management & Industrial Ecology Principles to Produce Lower-Carbon Ethanol from California Energy Beets. University of California Davis
22. Long R, Leinfelder-Miles M, Putnam D, Klonsky K, Stewart D (2015) *Sample Costs To Establish And Produce Alfalfa Hay In The Sacramento Valley And Northern San Joaquin Valley Flood Irrigation* University Of California Cooperative Extension Davis, California, USA. http://coststudyfiles.ucdavis.edu/uploads/cs_public/39/f2/39f29aa5-b991-4a13-816e-c695ed243249/alfalfa-flood-sv-2015.pdf
23. Vargas RN, Frate CA, Canevari WM, Campbell-Mathews M, Klonsky KM, De Moura RL (2003) Sample Costs to Produce Grain Corn San Joaquin Valley. University of California Cooperative Extension. Department of Agricultural and Resource Economics, UC Davis. http://coststudies.ucdavis.edu
24. Brittan KL, Munier DJ, Klonsky KM, Livingston P (2004) Sample Costs to Produce Field Corn Sacramento Valley. University of California Cooperative Extension. Department of Agricultural and Resource Economics, UC Davis. http://coststudies.ucdavis.edu
25. Hutmacher RB, Wright SD, Godfrey L, Munk DS, Marsh BH, Klonsky KM, De Moura RL, Tumber KP (2012) *Sample Costs To Produce Cotton – Pima Variety-San Joaquin Valley*. UC Cooperative Extension. Davis, California, US. http://cottoninfo.ucdavis.edu/files/150403.pdf
26. Graham RL, Nelson R, Sheehan J, Perlack R, Wright LL (2007) Current and potential US corn stover supplies. Agronomy Journal 99 (1):1-11
27. Laird DA, Chang C-W (2013) Long-term impacts of residue harvesting on soil quality. Soil and Tillage Research 134:33-40
28. Moebius-Clune BN, van Es HM, Idowu OJ, Schindelbeck RR, Moebius-Clune DJ, Wolfe DW, Abawi GS, Thies JE, Gugino BK, Lucey R (2008) Long-term effects of harvesting maize stover and tillage on soil quality. Soil Science Society of America Journal 72 (4):960-969
29. Blanco-Canqui H, Lal R (2009) Corn stover removal for expanded uses reduces soil fertility and structural stability. Soil Science Society of America Journal 73 (2):418-426

30. Lugato E, Jones A (2015) Modelling Soil Organic Carbon Changes Under Different Maize Cropping Scenarios for Cellulosic Ethanol in Europe. Bioenerg Res 8 (2):537-545. doi:10.1007/s12155-014-9529-2
31. California Corn for Grain County Estimates (2012) National Agriculture Statistics Service. http://nass.usda.gov/Statistics_by_State/California/Publications/County_Estimates/2012corngrnF.pdf
32. Kim S, Dale BE, Jenkins R (2009) Life cycle assessment of corn grain and corn stover in the United States. The International Journal of Life Cycle Assessment 14 (2):160-174
33. BNSF 6003 Rail Miles Inquiry (2013) BNSF Railway Company. http://www.bnsf.com/bnsf.was6/RailMiles/RMCentralController. Accessed 2014/08/05
34. Vachal K (2012) Regional Elevator Transportation: Market Decisions and Rail Service. Upper Great Plains Transportation Institute. North Dakota State University, Fargo, ND. http://www.ugpti.org/resources/reports/details.php?id=732
35. Vachal K (2015) Northern Plains Grain Farm Truck Fleet & Marketing Patterns. Upper Great Plains Transportation Institute. North Dakota State University, Fargo, ND. http://www.ugpti.org/resources/reports/details.php?id=821#citation
36. ISO (2006) 14040:2006. Environmental management - Life cycle assessment - Principles and framework. International Organization for Standardization (ISO), Geneva.
37. Arora S, Wu M, Wang M (2010) Estimated displaced products and ratios of distillers' co-products from corn ethanol plants and the implications of lifecycle analysis. Biofuels 1 (6):911-922
38. Robinson PH, Ahmadi A (2005) PCDAIRY Least Cost and Ration Analysis Programs for Dairy Cattle vol 2005 USA. Davis, CA
39. CDFA (2015) California Dairy Statistics and Trends Mid-Year Review January-June 2015 Data. Dairy Marketing Branch, California Department of Food and Agriculture. Sacramento, CA. https://www.cdfa.ca.gov/dairy/pdf/Annual/2015/MidYear2015.pdf
40. California Dairy Review Newsletters (2015) California Department of Food and Agriculture. http://www.cdfa.ca.gov/dairy/uploader/postings/dairyreview/Default.aspx. Accessed 09/08/2015
41. U.S. Bioenergy Statistics Overview Prices Table 14--Fuel ethanol, corn and gasoline prices, by month (2014) United States Department of Agriculture Economic Research Service. http://www.ers.usda.gov/data-products/us-bioenergy-statistics.aspx#30039
42. U.S. Bioenergy Statistics Overview Co-products Table 8--Dried distillers grain with solubles: supply and disappearance (2014) Economic Research Service. http://www.ers.usda.gov/data-products/us-bioenergy-statistics.aspx#30039
43. Californi Air Resources Board (2015) Staff Report: Calculating Carbon Intensity Values from Indirect Land Use Change of Crop-Based Biofuels. California Environmental Protection Agency Air Resource Board. Sacramento, California. http://www.arb.ca.gov/fuels/lcfs/peerreview/050515staffreport_iluc.pdf
44. California Air Resources Board (2015) CA-GREET model documentation. http://www.arb.ca.gov/fuels/lcfs/ca-greet/ ca-greet.htm
45. Nebraska Department of Natural Resources (2013) Annual Evaluation of Availability of Hydrologically Connected Water Supplies. http://www.dnr.ne.gov/iwm/annual-report-2014-final
46. Dunn JB, Mueller S, Wang M, Han J (2012) Energy consumption and greenhouse gas emissions from enzyme and yeast manufacture for corn and cellulosic ethanol production. Biotechnology letters 34 (12):2259-2263
47. MacLean HL, Spatari S (2009) The contribution of enzymes and process chemicals to the life cycle of ethanol. Environmental Research Letters 4(1):014001

Chapter 4 Impact on Ocean Biotic Resources

4.1 Background and Rationale

Human population growth and changing diets across the world have led to increasing demand for food, and particularly for nutrient and protein rich animal products, including fish and shell fish. As a result, ocean resources have been exploited at unprecedented rates [1], leading to marine biodiversity loss, food web changes, and other alternations of ocean structure [2]. According to FAO (Food and Agriculture Organization) review of world fish stocks, of which 17% are over-exploited and over 52% are with risk of population decline [3]. Fishery and aquaculture activities are primary drivers of ocean resource depletion, because wild fish are captured for both direct human consumption and as feed for cultured fish [4]. Historically, fishmeal from low-value pelagic fish was an inexpensive primary protein source for cultured fish. However rapid growth of the aquaculture industry has resulted in an increased demand for, and increased price of, these fish, and a decreased availability of fishmeal.

Total fish[1] supply from ocean catch fisheries is projected to slow down as a result of more strict controls in many countries that are intended to prevent fishery depletion and collapse [6, 7], this in turn leads to reductions in the catch for high-value fish intended for human consumption, as well as the low value fish which would be used to produce fish for human consumption in an aquaculture system. The increasing demand for fish, concurrent with concern for the sustainability of extensively fished marine fish, has led to investigation of substitutions for low-value fish as a protein source [8]. Researchers have been seeking less expensive plant-based meals as fishmeal replacement, but unfortunately, they often result in reduced fish growth performance or require large amounts of other dietary supplements to achieve high growth rates [9]. Algae is a natural food source for many aquatic animals, and may provide an alternative to

---

[1] Definitions apply for catch fish categories from 5. FAO, *Aquaculture development. 5. Use of wild fish as feed in aquaculture.* , in *FAO Technical Guidelines for Responsible Fisheries*. 2011, FAO: Rome. p. 79.):
Fish (= all aquatic animal species): Literally, a cold-blooded lower vertebrate that has fins, gills and scales (usually) and lives in water. Used as a collective term and includes molluscs, crustaceans and any aquatic animal that is harvested (FAO Glossary of Aquaculture, available at: www.fao.org/fi/glossary/aquaculture/default.asp). **Fishmeal**: Protein-rich meal derived from processing whole fish (usually small pelagic fish and bycatch) as well as residues and by-products from fish processing plants (fish offal) (FAO Glossary of Aquaculture, available at: www.fao.org/fi/glossary/aquaculture/default.asp).

terrestrially-source feeds (e.g. soy meal) that better meets the requirements of aquatic organisms. If essential nutrients can be provided by algae-based fish feed, algae-based fishmeal could substitute for materials from wild capture fisheries in proportion with their nutrient content or market value, and could potentially reduce withdrawals and related impacts on ocean ecosystems [10].

De-fatted algae[2] meal is produced as a co-product of algal oil, which has long been investigated as a potential source of biofuel. Microalgae avert some of the most challenging problems of terrestrial bioenergy crops, such as direct and indirect land use change, and in some cases can be grown on low-quality water sources that are unfit for terrestrial crops. The potential of using defatted microalgae meal as a replacement for fishmeal for farmed fish species has been studied with various fish species and microalgae strains, and many of these studies show great potential to effectively provide protein, lipids, vitamins and energy to cultured fish [11]. In some cases, microalgae-based feeds proved to improve the weight, growth, health and immune system of both fish and animals when used as livestock feed [12-15]. This may be due in part to the fact that microalgae can be a source of fatty acids that essential to fish growth [16].

Thus, when microalgae-based meal is used as fish feed to avoid fish catching for substitute species, there is a potential consequential environmental effect on ocean fisheries, which is described in Figure 1. Figure 4-1 also includes the potential effect on terrestrial resources if microalgae-based meals displace crop-based feeds (either for aquaculture or livestock).

---

[2] Algae is used in this study instead of microalgae for short. Note all strains discussed in later sections are microalgae strains.

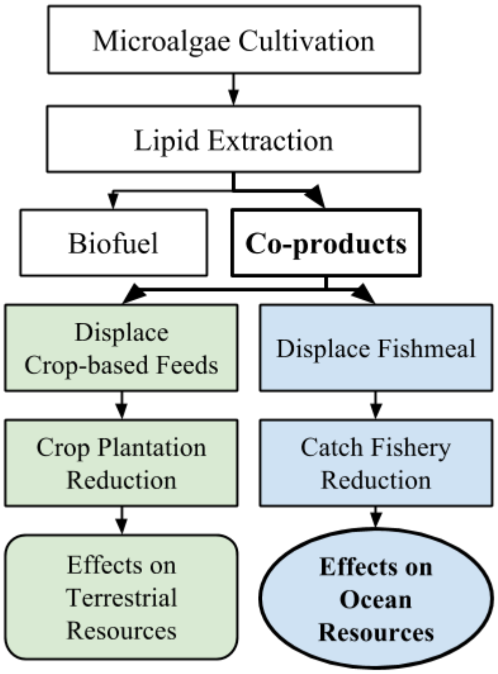

Figure 4-1 Direct and indirect impacts on land and ocean resources

This study aims to evaluate consequential impacts on ocean resources induced by co-product products from algal oil production systems using available models and applicable impact factors. The productivity of marine fisheries, environmental impacts from marine fish capturing, quality and quantity of fishmeal produced from microalgae, substitution potentials and ecological consequences are investigated.

4.2 Methodology and Rationale

4.2.1 Review of Methods: Consequential analysis in Life Cycle Assessment

There are two different approaches for performing LCA: attributional and consequential. Attributional LCA (ALCA) describes information on energy and material flows for a chosen system including a product's production, use phase and disposal or recycling [17, 18]. ALCA generally provides information on the average unit of a product and is commonly used to identify direct life cycle impacts of products [19]. The indirect effects induced from changes in the output of a product are not considered in an ALCA.

Consequential LCA (CLCA) investigates the consequences of changes to a product output, including effects both inside and outside the life cycle of the product [19]. Causal relationships are modeled between the change of the product output (sometimes framed as a *decision*, e.g. to produce more or less of a product) in CLCAs to estimate environmental impacts of potential decisions [17]. These two approaches aim to answer different questions. ALCA may reasonably be used to identify opportunities for reducing environmental impacts in different processes of the life cycle (e.g. hotspot analysis) or inform comparisons between products [19], while CLCA is designed to capture marginal environmental consequences of production systems and indirect effects on affected systems and inform decision makers on the broader impacts of policies that are intended to change levels of production [17, 20]. In CLCA, co-products are always handled with the displacement approach. This study takes a CLCA perspective, and application of the displacement approach is the primary mechanism whereby indirect effects are captured.

The principal consequential effect of terrestrial crops used as biofuel feedstocks, such as corn, soybean and sugarcane, is indirect land use change (iLUC), which has been extensively studied and modeled [21-24]. However, the indirect effects from microalgae cultivation and co-products produced from microalgae biofuel production system have rarely been discussed. While many researchers have pointed out the benefits of avoiding iLUC, in fact, consequential effects from microalgae-based fuels, have not been studied or discussed, and, may be more relevant for ocean resources, than terrestrial ones. While the indirect effects of microalgae biofuel production may be positive or negative, and may be relevant for ocean resources, the basic economic mechanisms at work that drive iLUC are similar for those that drive indirect effects on ocean resources. Therefore, it is neccessery to review existing methods for evaluating consequential changes from crop biofuels and apply the method to current approach.

4.2.2 Methods Used for Assessing Consequential Impacts

The iLUC hypothesis assumes biofuel production competes for agriculture resources resulting in higher prices of agricultural products. The increased prices cause alternate lands such as forest and grassland to shift into farmlands, and in the end cause carbon losses from converted ecosystems. The modeling process usually starts with an assumed biofuel production increase and a cropland increase for the biofuel feedstock crop cultivation. Sanchez et al. categorized the methodology for modeling iLUC as economic (market-based) methods (economic equilibrium models) and cause-effect methods [25].

Economic Methods

Many economic equilibrium models have been developed, including FAPRI-CARD, GTAP, IMPACT, and LEI-TAP [23, 26], that have been used for iLUC modeling. These economic models can be distinguished into two groups, partial equilibrium (PE) models, and computable general equilibrium (CGE) models. PE modeling determines substitutable and complementary goods based on the price elasticity of supply and demand and maximize net social payoff, CGE models (such as GTAP) include all sectors of the economic system and are usually more comprehensive than PE models [20]. The economic models, which either include only agricultural markets (PE models) or the global economy (CGE models), generally establish relationships between demand for land and crops by biofuel production and the effects on crop area, deforestation, and consumption reduction based on historical price data of crops, land types and fuels. Uncertainties and significant variation among iLUC estimates for ethanol production were generated from economic modeling due to different assumptions on the structures of causal relationships between crop and land conversion, yield change of crops, geographical boundaries and temporal scenarios [25].

Cause-effects Models

Compared to economic models, a cause-effect model usually establishes the link between the demand of crop and land, and land conversion based on statistical data on land use changes and physical data on crop yields [25]. Cederberg et al. (2011) applied a simple method to evaluate indirect carbon emissions from deforestation resulting from beef production. The modeling process included estimation of land productivity of cows, estimation of GHG emissions from deforestation and the distribution of emissions over time and products [27]. Bird et al. (2013) created a deterministic model to identify the amount of indirect land use change when agricultural crops were used for energy production. The model used the demand and supply for worldwide food and estimated that every additional 1 TJ bioenergy could result in 18 hectares of deforestation. The model can be used to determine deforestation rates for different crops based on the yield and energy productivity [28]. Audsley et al. (2010) assigned a single emission factor for agricultural land used by evenly distributed global annual GHG emissions from land use change on all agricultural lands, assuming commercial agriculture was one driving factor of land use change [29].

4.2.3 Indirect resource change modeling for ocean resources

Both CGE and PE models require historical market and price elasticity data for production sectors. Existing models have not previously included ocean resources in their assessments, and in fact historical market and price elasticity data are not available for relevant ocean products (e.g. high and low value pelagic fish). Thus, rather than adopting an economic modeling approach, this project adopts a cause-effect method to assess the indirect effects of generating co-products that affect ocean resources.

4.2.4 Choice of impact assessment - Ocean Biotic Resource Depletion

Like land use impacts, human activities such as fishing, aquaculture, shading, and seafloor destruction lead to significant impacts on marine ecosystems. Although impacts on marine ecosystems have been poorly addressed by the scope of life cycle impact assessment (LCIA) [30], various characterization factors have been discussed to represent “sea use” impacts for LCIA.

For wild fish catching activities, the environmental impact of biomass removal can be quantified through the amount of primary organic carbon required to sustain the production of one unit harvested fish [31]. Among different characterization factors, biotic primary carbon requirement, so called net primary production (NPP, kg carbon) has been used as an ecological impact measure in fishery and aquaculture LCAs [2, 32, 33]. NPP stands for the mass of carbon originally derived from photosynthesis that is required to meet the specific production of a product of biological origin. The NPP method estimates the primary production required to yield marine biomass consumption at a tropic level of the catch (TL) through estimating the carbon content in the target species and the energy loss based on understanding of the transfer efficiency (TE) between two adjacent trophic levels [32]. To implement this as an indicator of impact in LCA, the effects of human interventions on the stock of marine biomass present within the ecosystem is quantified at the midpoint level with primary production required (PPR), a common unit of kg of primary carbon equivalent per kg removed biomass (kg carbon/kg biomass) [34].

4.2.5 The displacement of fishmeal by algae biomass

The performance of defatted algae meal (algal cake, the biomass left from lipid extraction during biodiesel production) displacing fishmeal has been studied with different fish species. Table 4-1 summarizes previous research on the effects of displacing fishmeal with defatted algae biomass from different strains on the growth of particular fish.

Table 4-1 Empirical data for defatted algae meal effects on fishmeal reduction in fish feeds

Reference	[35]	[36]	[37]	[38]	[39]	[40]	[40]	[40]
Algae strain	Chlorella vulgaris	Desmochloris sp.	Haematococcus	*Haematococcus pluvialis*	*Desmodesmus* sp.	*Tetraselmis*	*Tetraselmis*	*Tetraselmis*
Location	Korea	Hawaii	Hawaii	Hawaii	Norway	Norway	Norway	Norway
Fed species	Olive flounder	Juvenile Nile tilapia	Juvenile tilapia	Longfin yellowtail	Atlantic salmon	Atlantic salmon	Common carp	Shrimp
Feed conversion ratio (FCR)	0.97	1.16	1.72	0.8	0.9	1.125	1.7	1.81
Functional unit	1 kg Fed Fish							
Fishmeal reduction (kg)	0.10	0.88	0.26	0.20	0.23	0.11	0.43	0.72
Algae meal inclusion (kg)	0.15	0.67	0.21	0.12	0.18	0.20	0.34	0.64

As shown in table 4-1, effects of algal cake inclusion in fish feed have been tested on certain fed fish species including olive flounder, Nile tilapia, longfin yellowtail, Atlantic salmon, carp, Atlantic cod and shrimp. These fish species can be fed with algal cake in place of a portion of the fishmeal in their diet. Different fish species have different tolerance to algae biomass, e.g. shrimp can have 0.64 kg algae for 1 kg weight gain without impacts on growth performance, while longfin yellowtail only tolerates 0.18 kg algae biomass for 1 kg weight gain. The proportion of fishmeal in the diet that can be displaced by algal cake are different to each fish species, too. Fishmeal inputs for olive flounder and juvenile Nile tilapia are reduced by 0.1 kg and 0.88 kg, respectively.

Due to the variation in response of different fed species to algae biomass, the data listed in table 1 are used for modeling displaced PPR in the following sections. The feed conversion ratio (FCR, kg feed/kg fish), as listed in table 4-1, stands for the dry mass of feed inputs to produce one unit weight gain of fed fish. High FCR indicates low efficiency of feed use. FCR data are adopted from each study for each fed fish (table 4-1).

4.2.6 PPR Modeling

The quantification of PPR follows the methodology described by Pauly and Christensen (1995) and Cashion et al. (2016). The reduction fishery PPR is the kg of marine carbon inputs to grow 1 kg catch fish (equation 1). A reduction fishery is a fishery targeted for reduction of catch for fishmeal or fish oil used for compound animal and aquaculture feeds [5].

Equation 1 (Adapted from [32, 34]):

$$Reduction\ Fishery\ PPR\ \ (kg\ C/kg\ fish) = \frac{1}{M} * \ TE^{(1-TL)}$$

In the equation, TL is the trophic level of the fish of interest, a low TL value means the fish is lower on the aquatic food chain. TE is trophic transfer efficiency of the ecosystem, and M is the ratio of wet weight biomass to carbon content (kg fish wet weight/kg C) of the species of interest. Specific ecosystem TE values were obtained from literature [32, 41]. A general TE of 10% is also tested for comparison.

Fishmeal production in the Americas is used for modeling the fishmeal PPR because only countries in the Americas reported fishmeal production at species level, and Peru and Chile dominated 87% of global fishmeal production, according to the FAO [3]. Data of major reduction fisheries in the Americas and the geographic production for each species are defined in accordance with FAO reports [42]. Production data in 2004 are used for estimating the general fish meal PPR calculation due to the limitation of data availability. A conservative ratio 9:1 is used for M as in previous LCA studies [31, 32, 43].

The fishmeal PPR for each reduction fishery is proportional to the specific fish species, as shown in equation 2, where meal yield efficiency (kg fishmeal/kg fish) is the mass of fishmeal production from a unit mass of fish.

Equation 2:

$$Fishmeal\ PPR\ (\ kg\ C\ /\ kg\ fishmeal) = \frac{Reduction\ Fishery\ PPR}{Meal\ Yield\ Efficiency}$$

General fishmeal PPR in the Americas is the weighted average value calculated using specific fishmeal PPRs. As expressed in equation 3, the unit of general fishmeal PPR is kg carbon per kg of fishmeal.

Equation 3:

$$General\ Fishmeal\ PPR\ in\ the\ Americas\ (\ kg\ C\ /\ kg\ fishmeal\ )$$

$$= \sum (Fish\ Production\ Weight * Fishmeal\ PPR)$$

where

$$Fish\ Production\ Weight\ (\%) = \frac{Production\ of\ Single\ Reduction\ Fish\ Species\ (kg)}{Sum\ Production\ of\ Reduction\ Fish\ Species\ (kg)} * 100\%$$

Fishmeal PPR in the Americas is weighted by the production of each reduction fish species captured in the Americas (table 4-2). Reduction fishery production in the Americas is obtained from the FAO [3], and only dominant reduction species (>1% of total) are included in the current model. Only one year of data (2004) is applied to the calculation due to limited data quality and availability. TE and TL values for specific fish in relevant marine ecosystem are obtained from Libralato et al. (2008) [41]. Fishmeal yield rates are adopted from Cashion et al. 2016, except for the jumbo flying squid, which uses an estimation of 0.2 kg meal per kg fish.

Table 4-2 Fishmeal production in the Americas

Large Marine Ecosystem (LME)	Humboldt current	Humboldt current	Humboldt current	Pacific central	Eastern Pacific Ocean	Gulf of Mexico	Humboldt current	North Sea	North Sea
Main Fishing Nations	Peru	Chile	Chile	Mexico	Peru, Chile	US	Chile	Canada &US	US
Reduction Fisheries	Anchoveta	Jack mackerel	Chub mackerel	Pilchard	Jumbo flying squid	Gulf menhaden	Araucanian herring	Atlantic Herring	Atlantic menhaden
Specific Transfer Efficiency (TE)	6.60%	6.60%	6.60%	6.60%	12.97%	9.70%	6.60%	11.60%	10.90%
General TE	10%	10%	10%	10%	10%	10%	10%	10%	10%
Fish Trophic Level (TL)	3	3.5	3.5	3.1	2.5	2.2	3.2	3.2	2.92
Meal Yield (kg fishmeal/kg fish)	0.23	0.194	0.2	0.23	0.2	0.24	0.204	0.204	0.24
2004 Fish Production (thousand tonnes)	10679	1638	730	683	556	464	356	269	215
Wet weight to Carbon (M, kg fish/kg carbon)	9	9	9	9	9	9	9	9	9

Displaced PPR is the PPR saving from reduced wild fish in feed for each fed fish species, expressed as kg of carbon saved in the production of 1 kg fish (equation 4). Fishmeal reduction proportion (kg reduced fishmeal/kg feed) is the displaced fishmeal mass from 1 kg fish feed by the addition of algae. This value is different for each fed species as indicated in table 4-1. Therefore, the effect of fishmeal substitution by algal cake on each fed fish species is different. Data of FCR of each fed species are shown in table 4-1. The projected production from fed fisheries are obtained from an FAO report [6].

Equation 4:

$$\begin{aligned} &Displaced\ PPR\ (kg\ C/kg\ \ fed\ fish) \\ &\qquad = Fishmeal\ reduction\ proportion * FCR * General\ Fishmeal\ PPR \end{aligned}$$

Assuming algae biomass will substitute fishmeal for fed fish species (olive flounder, Nile tilapia, longfin yellowtail, Atlantic salmon, carp, Atlantic cod and shrimp) as listed in table 4-1, we can calculate the mass of reduced fishmeal at global scale knowing the production of interested fed fish species. And a reduced global net primary production (NPP) can be estimated (equation 5). The reduced global marine carbon (reduced NPP) is calculated with the reduced fishmeal inputs for modeled fed species. Projection of each fish species production in 2020 is adopted from FAO [5]. Fed fish production data in 2008 is also adopted from FAO [5] to compare with the 2020 projection of potential effects on NPP from algae. The unit of reduced NPP is kg carbon.

Equation 5:

$$Algae\ Effects\ on\ Global\ Marine\ Carbon\ Input\ (Reduced\ NPP, kg\ C) = \sum (Production\ of\ Fed\ Fish\ Species * Displaced\ PPR)$$

4.3 Results and Discussion

4.3.1 Fishmeal PPR (the Americas data)

The result of fishmeal PPR produced in the Americas is shown in table 4-3, specific PPR stands for PPR using specific TE while general PPR is calculated using the general TE. There is substantial variation in the PPR of different fish and fishmeal and of PPR using different TEs. The meal yield determines the allocation of PPR into the meal and rest of the fish by mass. The weighted averaged PPR for 1 kg of fishmeal produced from the Americas is estimated to be 166 kg carbon using the specific PPR, and 67 kg carbon using general PPR. Among estimated reduction fisheries, jack mackerel meal has the highest PPR of 512 kg C per kg fishmeal, while Gulf menhaden meal has the lowest PPR of 8 kg C/kg fishmeal using specific TE. If the general TE is used, jack mackerel still shows the highest PPR of 181 kg C/kg fishmeal and menhaden remains similar PPR at 7.34 kg C/kg fishmeal. The resolution of global data used for modeling makes obvious differences in results. Given the high variability between general and specific PPR, fine resolution spatial data of specific TE and TL for different species is desired for accurately estimating the ocean impacts.

Table 4-3 PPR of 1 kg Fishmeal production in the Americas

Reduction Fisheries	Anchoveta	Jack mackerel	Chub mackerel	Pilchard	Jumbo flying squid	Gulf menhaden	Araucanian herring	Atlantic Herring	Atlantic menhaden
General Fishmeal PPR (kg C/kg fishmeal)	48.31	181.12	175.68	60.82	17.57	7.34	86.32	86.32	86.32
Specific Fishmeal PPR (kg C/kg fishmeal)	110.90	511.79	496.44	145.54	11.89	7.61	215.34	62.28	62.28
Production weights (%)	68%	11%	5%	4%	4%	3%	2%	2%	1%
Average Specific PPR	**166.00**	kg C/kg fishmeal in America							
Average General PPR	**67.32**	kg C/kg fishmeal in America							

4.3.2 PPR Displaced for each Fed fish species using in the Americas

Effects of 1 kg algae meal on marine biotic resources are shown in figure 4-2. Depending on different algae species, 1 kg of algae meal displaces different amounts of primary production due to the different performances as fish feed. Algae strain Haematococcus *pluvialis* shows the highest potential in PPR conservation (200 kg C/kg algae) as fish feed because of its high displacement ratio of fishmeal when feeding longfin yellowtail (as shown in table 4-1). The Teraselmis with lowest PPR displacement value is due to the low displacement ratio when feeding Atlantic salmon, which requires 0.2 kg algae meal addition to make up the deduction of 0.1 kg fishmeal in feed.

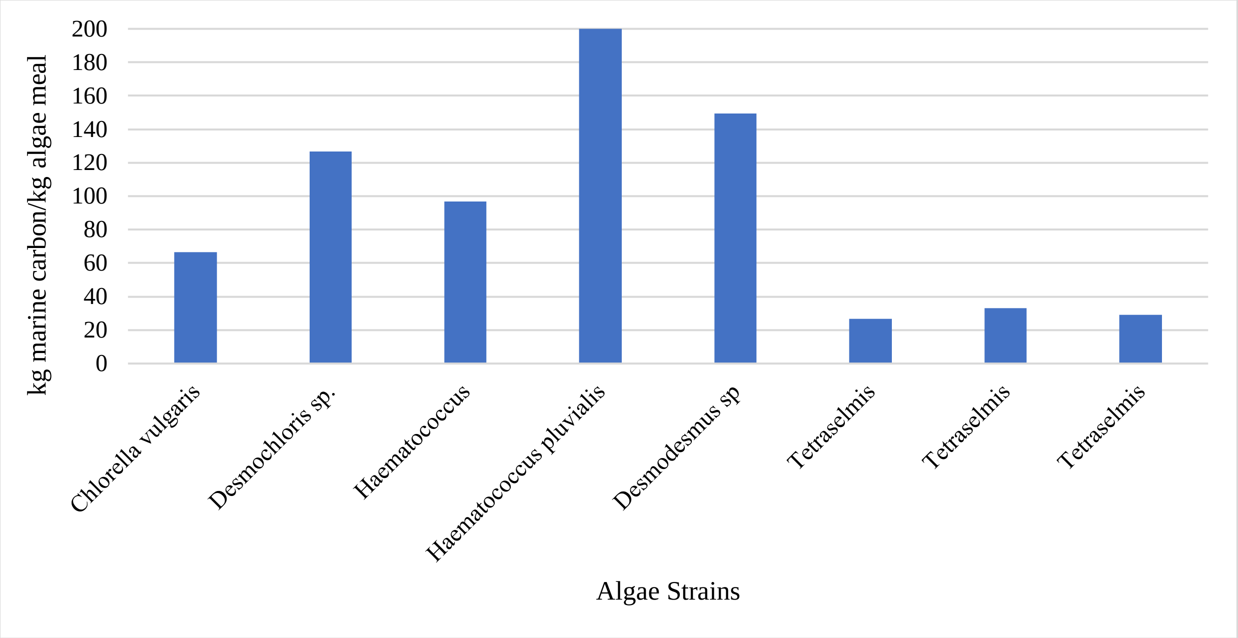

Figure 4-2 Displaced fishmeal PPR by 1 kg defatted algae meal

Differences in the fed fish result in different levels of tolerance for algae meal and feed conversion efficiency. Figure 4-3 shows the marine carbon inputs to grow 1 kg of fed fisheries. The blue bar is the initial PPR of fishmeal inputs for 1 kg fish growth, the orange bar is the reduction of PPR by inclusion of algae meal in feed to replace fishmeal, and the black dot represents the PPR of using reduced fishmeal amount for feeding 1 kg of fish by using algae meal. The effect of PPR reduction by algae meal is the most significant for Nile tilapia fishery because 75% of fishmeal inputs can be replaced by algae meal. Atlantic salmon shows low tolerance to algae meal, so only 10% of fishmeal is replaceable. Therefore, the effect of algae meal on the marine resource conservation for Atlantic salmon is relatively small.

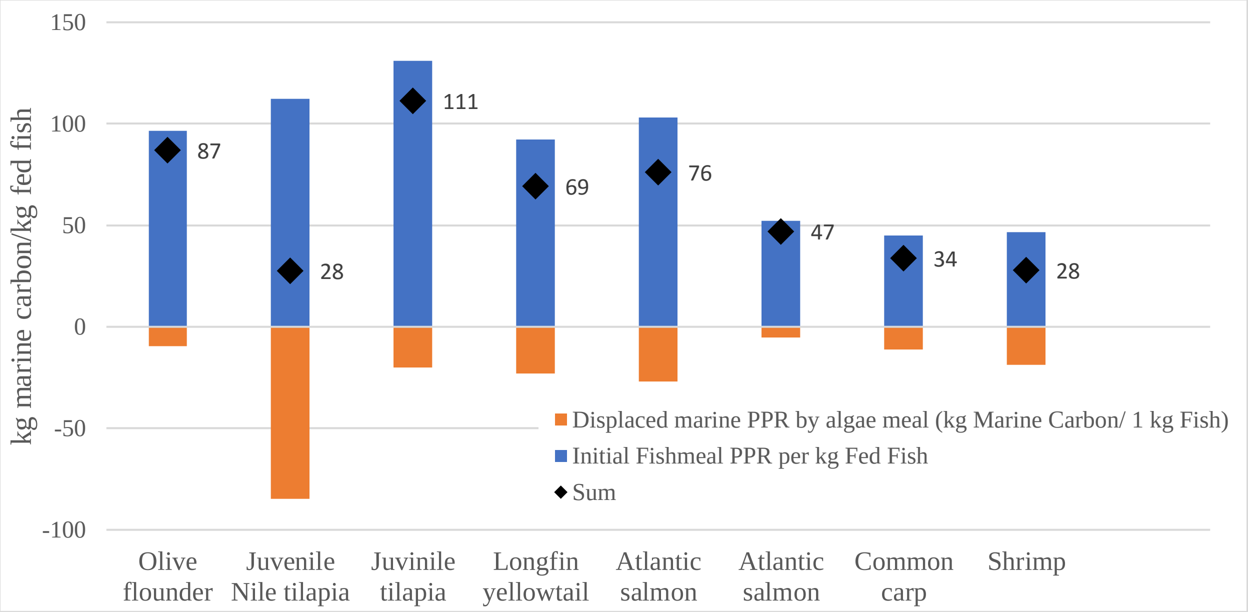

Figure 4-3 PPR of growing 1 kg fed fish by feeding algae meal

4.3.3 Projection of Global NPP Displaced by Algal Meal

Aquaculture production of tilapia, salmon, shrimp, carp, flounder, and longfin yellowtail in 2008 and 2020 (projected) is used to estimate the marine carbon resource depletion (table 4-4). An estimated 238 and 681 million tonnes of carbon can be conserved by using algae meal in fish feed for the listed 6 types of aquaculture farms in 2008 and 2020. To meet this NPP reduction for fish feed, 17 million tonnes of algae biomass will be required in 2020. Assuming the biodiesel yield from algae is 75 tonne/hectare/yr, to produce the targeted fish feed, the biodiesel produced from algae would be 1.2 billion gallons. The land input of 0.35 million hectares for open pond algae cultivation would be required to meet the feed demand as well.

Table 4-4 Projected global NPP savings from algae displacing fishmeal fed for tilapia, salmon, shrimp, carp, flounder, yellowtail and cod

Fed Species	**Unit**	**Tilapia**	**Salmon**	**Shrimp**	**Carp**	**Flounder**	**Longfin Yellowtail**
Displaced PPR	kg C/kg fish	84.84	26.86	18.63	11.27	10	23
Production in 2008	1000 tonnes	2798	1573	3399	10585	78	78
2008 Fishmeal Displacement	1000 tonnes	1432	255	382	720	5	11
2008 Algae Meal Required	1000 tonnes	1875	283	2185	3626	11	9
2008 NPP Reduction	Million tonnes C	**238**	**42**	**63**	**119**	**0.76**	**1.81**
Estimated Production in 2020	1000 tonnes	8012	2825	8087	16459	204	204
2020 Fishmeal Displacement	1000 tonnes	4100	458	909	1119	12	28
2020 Algae Meal Required	1000 tonnes	5368	509	5198	5638	30	24
2020 NPP Reduction	Million tonnes C	**681**	**76**	**151**	**186**	**2**	**5**

4.4 Conclusion and future research

This study estimates the potential impacts of supplying algae meal, a coproduct of algal-based fuels, on ocean primary production depletion effects. NPP offers an innovative and useful indicator for understanding the influence of algal biofuel production on marine ecosystems.

When algae biomass is used as a fishmeal substitute, reduction fishery can be reduced, ocean resources are then conserved but terrestrial resources are used. To resolve the trade-off between ocean and land resources revealed in results, reuse of waste resources is recommended for algae cultivation which reduces raw material inputs and decreases discharges into the ocean.

Maintaining the productivity of ocean ecosystem is important for humans' growing population and demand for protein. It is necessary to look for fish species that can accept high proportions of algae meal as feed, and which have a good feed conversion ratios. Additional scenarios with different substitution rates between marine fishery and fishmeal from algae should be tested. Cultivation of such fish with algae biomass would result in improved ocean resource conservation. Other mechanisms for improving consumer choice could include pricing fishmeal and fish species with higher PPR at higher prices than those with lower PPR, which could encourage ocean resource conservation.

This study models the consequential displacement effects in a very simple way; problems such as spatial and temporal limitations of algae biomass availability are excluded in current estimation. Aquaculture in

Asia is expanding rapidly with exclusive feeding of low-value fish in whole fish form with a high FCR [42]. However, because data are limited for this region, this study focused on the Americas. The implications of understanding the impacts of biofuel production are significant at the global scale, and particularly for Asia. More interesting issues such as using innovation in gene-modified algae for specific fish ingredient supply and human nutrition additives, and the impacts on displacing fish oil and fishmeal are future research that should be investigated to understand the potential role of algae and algae biofuels and their potential effects on aquaculture, the food system, and ocean resources.

4.5 References

1. Foley, J.A., et al., *Solutions for a cultivated planet.* Nature, 2011. **478**(7369): p. 337-342.
2. Avadí, A. and P. Fréon, *Life cycle assessment of fisheries: A review for fisheries scientists and managers.* Fisheries Research, 2013. **143**(Supplement C): p. 21-38.
3. Tacon, A.G., *Use of wild fish and other aquatic organisms as feed in aquaculture–a review of practices and implications in the Americas.* Fish as feed inputs for aquaculture: practices, sustainability and implications, 2009: p. 159-207.
4. Hasan, M., *Transition from low-value fish to compound feeds in marine cage farming in Asia*. 2012: Food and Agriculture Organization of the United Nations.
5. FAO, *Aquaculture development. 5. Use of wild fish as feed in aquaculture.* , in *FAO Technical Guidelines for Responsible Fisheries*. 2011, FAO: Rome. p. 79.
6. Tacon, A.G., et al., *Demand and supply of feed ingredients for farmed fish and crustaceans: trends and prospects*. 2011.
7. Metian, A.G.T.M., *Fishing for feed or fishing for food: increasing global competition for small pelagic forage fish.* AMBIO: A Journal of the Human Environment, 2009. **38**(6): p. 294-302.
8. Olsen, R.L. and M.R. Hasan, *A limited supply of fishmeal: Impact on future increases in global aquaculture production.* Trends in Food Science & Technology, 2012. **27**(2): p. 120-128.
9. Shurson, J., *Maize dried distillers grains with solubles (DDGS)-a new alternative ingredient in aquafeeds.* World Aquaculture, 2012. **43**(3): p. 54-58.
10. Miara, A., et al., *Planning for Algal Systems: An Energy-Water-Food Nexus Perspective.* Industrial Biotechnology, 2014. **10**(3): p. 202-211.
11. Shah, M.R., et al., *Microalgae in aquafeeds for a sustainable aquaculture industry.* Journal of Applied Phycology, 2017.
12. Muller-Feuga, A., *The role of microalgae in aquaculture: situation and trends.* Journal of Applied Phycology, 2000. **12**(3-5): p. 527-534.
13. Spolaore, P., et al., *Commercial applications of microalgae.* Journal of Bioscience and Bioengineering, 2006. **101**(2): p. 87-96.
14. Pulz, O. and W. Gross, *Valuable products from biotechnology of microalgae.* Applied microbiology and biotechnology, 2004. **65**(6): p. 635-648.
15. Brennan, L. and P. Owende, *Biofuels from microalgae—a review of technologies for production, processing, and extractions of biofuels and co-products.* Renewable and sustainable energy reviews, 2010. **14**(2): p. 557-577.
16. Qiao, H., et al., *Effects of dietary fish oil replacement by microalgae raw materials on growth performance, body composition and fatty acid profile of juvenile olive flounder, Paralichthys olivaceus.* Aquaculture nutrition, 2014. **20**(6): p. 646-653.
17. Plevin, R.J., M.A. Delucchi, and F. Creutzig, *Using attributional life cycle assessment to estimate climate-change mitigation benefits misleads policy makers.* Journal of Industrial Ecology, 2014. **18**(1): p. 73-83.
18. Thomassen, M.A., et al., *Attributional and consequential LCA of milk production.* The International Journal of Life Cycle Assessment, 2008. **13**(4): p. 339-349.
19. Brander, M., et al., *Consequential and attributional approaches to LCA: a guide to policy makers with specific reference to greenhouse gas LCA of biofuels.* Technical paper TP-090403-A, Ecometrica Press, London, UK, 2009.

20. Earles, J.M. and A. Halog, *Consequential life cycle assessment: a review.* The International Journal of Life Cycle Assessment, 2011. **16**(5): p. 445-453.
21. Hertel, T., et al., *Global land use and greenhouse gas emissions impacts of US Maize ethanol: the role of market-mediated responses*. 2009, Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University.
22. Gnansounou, E., et al., *Accounting for indirect land-use changes in GHG balances of biofuels: Review of current approaches*. 2008.
23. Edwards, R., D. Mulligan, and L. Marelli, *Indirect land use change from increased biofuels demand.* Comparison of models and results for marginal biofuels production from different feedstocks., EC Joint Research Centre, Ispra, 2010.
24. Lapola, D.M., et al., *Indirect land-use changes can overcome carbon savings from biofuels in Brazil.* Proceedings of the national Academy of Sciences, 2010. **107**(8): p. 3388-3393.
25. Sanchez, S.T., et al., *Accounting for indirect land-use change in the life cycle assessment of biofuel supply chains.* Journal of The Royal Society Interface, 2012: p. rsif20110769.
26. Schmidt, J.H., B.P. Weidema, and M. Brandão, *A framework for modelling indirect land use changes in Life Cycle Assessment.* Journal of Cleaner Production, 2015(0).
27. Cederberg, C., et al., *Including carbon emissions from deforestation in the carbon footprint of Brazilian beef.* Environmental Science & Technology, 2011. **45**(5): p. 1773-1779.
28. Bird, D.N., G. Zanchi, and N. Pena, *A method for estimating the indirect land use change from bioenergy activities based on the supply and demand of agricultural-based energy.* Biomass and Bioenergy, 2013. **59**: p. 3-15.
29. Audsley, E., et al., *How low can we go? An assessment of greenhouse gas emissions from the UK food system and the scope reduction by 2050. Report for the WWF and Food Climate Research Network.* 2010.
30. Langlois, J., et al., *Sea use impact category in life cycle assessment: characterization factors for life support functions.* The International Journal of Life Cycle Assessment, 2015. **20**(7): p. 970-981.
31. Luong, A.D., et al., *Re-evaluating Primary Biotic Resource Use for Marine Biomass Production: A New Calculation Framework.* Environmental Science & Technology, 2015. **49**(19): p. 11586-11593.
32. Cashion, T., et al., *Review and advancement of the marine biotic resource use metric in seafood LCAs: a case study of Norwegian salmon feed.* The International Journal of Life Cycle Assessment, 2016. **21**(8): p. 1106-1120.
33. Efole Ewoukem, T., et al., *Environmental impacts of farms integrating aquaculture and agriculture in Cameroon.* Journal of Cleaner Production, 2012. **28**(Supplement C): p. 208-214.
34. Pauly, D. and V. Christensen, *Primary production required to sustain global fisheries.* Nature, 1995. **374**(6519): p. 255-257.
35. Rahimnejad, S., et al., *Effects of Dietary Inclusion of Chlorella vulgaris on Growth, Blood Biochemical Parameters, and Antioxidant Enzyme Activity in Olive Flounder, Paralichthys olivaceus.* Journal of the World Aquaculture Society, 2017. **48**(1): p. 103-112.
36. García-Ortega, A., et al., *Use of biofuel by-product from the green algae Desmochloris sp. and diatom Nanofrustulum sp. meal in diets for nile tilapia Oreochromis niloticus.* 2015.
37. Ju, Z.Y., et al., *Effects of microalgae-added diets on growth performance and meat composition of tilapia (Oreochromis mossambicus).* Aquaculture Research, 2017.

38. Kissinger, K.R., A. García-Ortega, and J.T. Trushenski, *Partial fish meal replacement by soy protein concentrate, squid and algal meals in low fish-oil diets containing Schizochytrium limacinum for longfin yellowtail Seriola rivoliana.* Aquaculture, 2016. **452**: p. 37-44.
39. Kiron, V., et al., *Defatted biomass of the microalga, Desmodesmus sp., can replace fishmeal in the feeds for Atlantic salmon.* Frontiers in Marine Science, 2016. **3**: p. 67.
40. Kiron, V., et al., *Marine microalgae from biorefinery as a potential feed protein source for Atlantic salmon, common carp and whiteleg shrimp.* Aquaculture Nutrition, 2012. **18**(5): p. 521-531.
41. Libralato, S., et al., *Novel index for quantification of ecosystem effects of fishing as removal of secondary production.* Marine Ecology Progress Series, 2008. **355**: p. 107-129.
42. Huntington, T. and M.R. Hasan, *Fish as feed inputs for aquaculture–practices, sustainability and implications: a global synthesis*, in *Fish as feed inputs for aquaculture: practices, sustainability and implications*. 2009, FAO Rome. p. 1-61.
43. Farmery, A.K., et al., *Naturalness as a basis for incorporating marine biodiversity into life cycle assessment of seafood.* The International Journal of Life Cycle Assessment, 2017: p. 1-17.

Chapter 5 Conclusions and Future Research

The primary focus of this dissertation has been to systematically discuss and model limitations in assessing life cycle environmental impacts for biofuel production systems, specifically looking at methodology improvements for handling co-products in LCA in complex production systems.

Three studies are presented in this dissertation, two of which investigate the effects and limitations of system definitions, modeling assumptions, data uncertainties and specifically co-product allocation strategies. The life cycle analysis (LCA) study for algal biofuel production systems (Chapter 2) tests six co-product allocation strategies for the hydrothermal liquefaction (HTL) pathway and five allocation strategies for the lipid extraction (LE) pathway. It is found that more robust carbon intensity estimates are achievable when co-products have little contribution to the performance of the biofuel; however, when a high-value co-product is produced, e.g. the algal cake co-product, utilization outside of the production system can contribute substantially to reduced carbon intensity of the biodiesel product. Chapter 3 simulates a dry mill corn ethanol facility in California's Central Valley retrofitted to also produce ethanol from corn stover, a cellulosic feedstock. The assessment examines three facility designs, all producing corn ethanol and wet distiller's grains and solubles (WDGS) as a co-product. This assessment tracks greenhouse gas (GHG) emissions, energy consumption, criteria air pollutants, and direct water consumption. The life cycle inventories (LCIs) for corn grain, corn stover and co-product WDGS produced in California are created. Allocation scenarios are explored to assess the effect of co-product allocation methods on LCA results for both corn ethanol and stover ethanol. The stover supply scenarios (a function of harvest rate) and co-product allocation decisions contribute to the variability in results.

The assumptions made in LCAs strongly affect the results of a biofuel's environmental performance. When a new biofuel pathway is proposed with a co-product new to the market, there is no existing substitution for displacement calculations, and no market value for the co-product, e.g. the algae biomass residue from LE, algal cake. In Chapters 2 and 3, a novel approach using a feed calculator for feed market activity simulation is applied to estimate the displacement effects of the co-products algal cake and WDGS. Both studies have found the price of co-products as the underlying source of variability for environmental impact results. This conclusion reveals the fundamental uncertainty in applying the displacement approach, especially for dynamic markets like animal feed. On the other hand, it may further support a recommendation for using economic value-based allocation instead of the displacement method.

Chapter 4 introduced net primary production (NPP) as an indicator to assess ocean resource impacts from global scale algae biofuel production. The harmonization and comparison of NPP depletion from soil organic carbon and ocean organic carbon is suggested in future research. This research showed the potential importance of evaluating ocean resource depletion effects for algae fuels, but the NPP changes from the displacement of fishmeal by DDGS (co-product from corn ethanol production) is also worthy of research. The understanding of comparable land use impacts and ocean use impacts will provide a new criterion for future decision makings.

Chapter 6 Appendix

6.1 Appendix A (Chapter 2)

Table 6-1 Effects of HTL operation conditions on life cycle performance of algal renewable diesel

Temperature (°C)	Retention Time (minutes)	Primary Energy (MJ/MJ)	Fossil Energy (MJ/MJ)	GWP$_{100}$ (kg CO$_2$e/MJ)	GWP$_{20}$ (kg CO$_2$e/MJ)	Renewable Diesel (MJ/kg biomass)
250	5	2.28	1.80	0.13	0.15	5.83
	15	1.63	1.29	0.09	0.10	8.35
	30	1.51	1.20	0.09	0.10	9.05
	60	1.39	1.10	0.08	0.09	9.88
300	5	1.36	1.08	0.08	0.09	10.13
	15	0.96	0.77	0.06	0.06	14.84
	30	**0.95**	**0.76**	**0.05**	**0.06**	**15.08**
	60	0.96	0.76	0.05	0.06	14.94
350	5	1.04	0.83	0.06	0.07	13.58
	15*	**0.95**	**0.76**	**0.05**	**0.06**	**15.05**
	30	0.96	0.77	0.06	0.06	14.81
	60	0.99	0.79	0.06	0.06	14.30
400	5	1.12	0.89	0.06	0.07	12.57
	15	1.05	0.84	0.06	0.07	13.44
	30	1.09	0.87	0.06	0.07	12.85
	60	1.19	0.95	0.07	0.08	11.72

*Operation Condition at 350 C for 15 minutes is chosen to represent the optimal HTL condition in following results.

Table 6-2 LCI data used for modeling

	Rail transport	**Electricity grid mix (West)**	**Diesel mix at refinery**	**Gasoline mix**	**Tap Water**	**Urea**	**Hydrogen**	**Herbicide**	**Maize seed**	**Pesticide**	**Ammonia, liquid**	**Diammonium phosphate at N**	**Barley Grain**	**NG at boiler, agg**
Gabi 6	Processes\Transport\Railway	Processes\Energy conversion\Electricity supply\Electricity grid mix	Processes\Energy conversion\Fuel production\Refinery products	Processes\Energy conversion\Fuel production\Refinery products	Processes\Production\Material production\Water	Processes\Production\Material production\Production of materials from renewables\Fertilisers	Processes\Energy conversion\Fuel production\Refinery products	Processes\Ecoinvent\agricultural means of production\Pesticide	Processes\Ecoinvent\agricultural means of production\seed	Processes\Ecoinvent\agricultural means of production\Pesticide	Processes\Ecoinvent\chemicals\inorganics	Processes\Ecoinvent\agricultural means of production\mineral fertiliser	Processes\Ecoinvent\agricultural means of production\feed	Processes\Energy conversion\Thermal energy generation
Database	PE 2012	PE 2012	PE 2012	PE2012	PE2012	PE 2012	PE 2012	Ecoinvent 2011	Ecoinvent 2011	Ecoinvent 2011	Ecoinvent 2011	Ecoinvent 2011	Ecoinvent 2011	USLCI/PE 2012
Country	RER	US	US	US	RER	US	US	RER	CH	RER	CH	RER	CH	US
Info	Rail transport	Electricity grid mix (West)	Diesel mix at refinery	Gasoline mix (regular) at refinery	Tap Water	Urea (agrarian)	Hydrogen at refinery	herbicides, at regional storehouse	maize seed IP, at regional storehouse	pesticide unspecified, at regional storehouse	ammonia, liquid, at regional storehouse	diammonium phosphate, as N, at regional storehouse	barley IP, at feed mill	Natural gas, combusted in industrial boiler
	diesel driven, cargo	agg - LCI result	agg - LCI result	agg - LCI result	agg - LCI result	agg - LCI result	agg - LCI result	agg - LCI result	agg - LCI result	agg - LCI result	agg - LCI result	agg - LCI result	agg - LCI result	agg - LCI result
Unit	1000 kgkm	3.6 MJ	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	m3
Total Fossil Energy (MJ)	**3.53E-01**	**6.73E+00**	**5.26E+01**	**5.17E+01**	**6.22E-03**	**2.48E+01**	**1.68E+02**	**1.83E+02**	**1.34E+01**	**1.80E+02**	**4.03E+01**	**5.48E+01**	**3.38E+00**	**5.55E+01**
Total Energy (MJ)	**3.68E-01**	**9.46E+00**	**5.31E+01**	**5.68E+01**	**7.06E-03**	**2.67E+01**	**1.70E+02**	**2.22E+02**	**3.45E+01**	**2.17E+02**	**4.15E+01**	**5.77E+01**	**1.90E+01**	**5.58E+01**
CO2 (kg)	**2.46E-02**	**5.07E-01**	**5.09E-01**	**9.78E-01**	**3.48E-04**	**1.26E+00**	**2.91E+00**	**8.80E+00**	**8.40E-01**	**8.71E+00**	**1.99E+00**	**2.63E+00**	**2.09E-01**	**2.15E+00**
CH4 (kg)	**2.81E-05**	**7.93E-04**	**4.69E-03**	**4.92E-03**	**1.33E-06**	**9.66E-03**	**1.41E-02**	**2.97E-02**	**1.26E-03**	**2.86E-02**	**3.91E-03**	**5.90E-03**	**3.32E-04**	**1.14E-02**
N2O (kg)	**9.01E-07**	**8.91E-06**	**1.36E-05**	**1.42E-04**	**6.43E-09**	**9.16E-05**	**6.49E-05**	**1.91E-03**	**3.55E-03**	**1.87E-03**	**3.04E-05**	**3.96E-05**	**8.93E-04**	**7.73E-07**
GWP 100-AR5 (kg)	**2.56E-02**	**5.32E-01**	**6.44E-01**	**1.15E+00**	**3.87E-04**	**1.56E+00**	**3.32E+00**	**1.01E+01**	**1.82E+00**	**1.00E+01**	**2.10E+00**	**2.81E+00**	**4.55E-01**	**2.44E+00**
GWP 20-AR5 (kg)	**2.72E-02**	**5.76E-01**	**9.06E-01**	**1.43E+00**	**4.61E-04**	**2.10E+00**	**4.11E+00**	**1.18E+01**	**1.88E+00**	**1.16E+01**	**2.32E+00**	**3.14E+00**	**4.73E-01**	**2.97E+00**

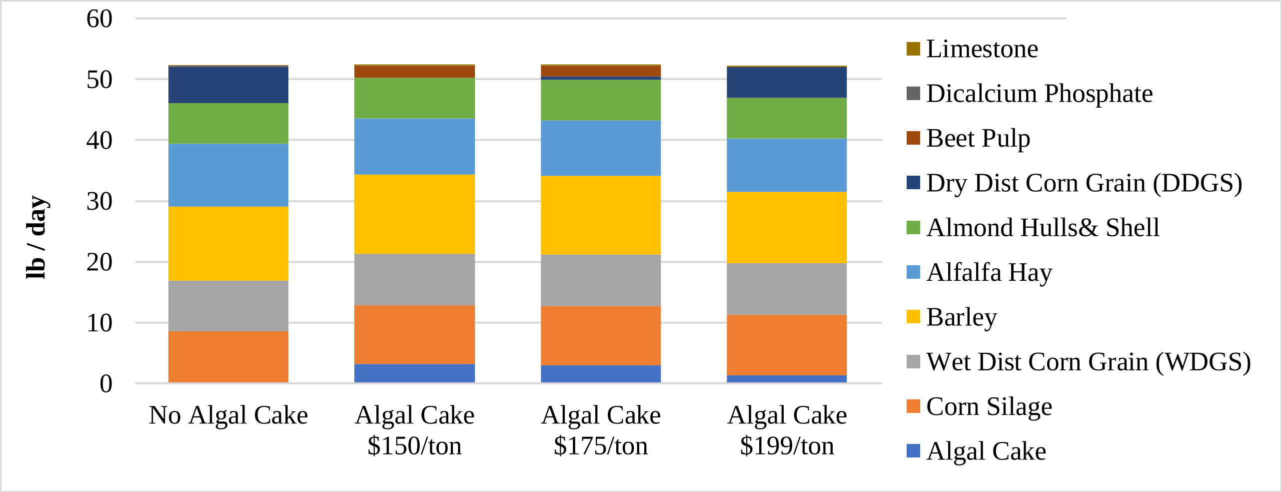

Figure 6-1 Comparison chart of feed ration compositions with algal cake addition at different prices [dry mass based]

The following assumptions and operating parameters were used in the PCDAIRY software to model algal cake displacement ratios of California dairy cattle feedstuffs:

California dairy feedstuffs lists and prices are from the California Department of Food and Agriculture's (CDFA's) California Dairy Statistics and Trends Mid-Year Review January-June 2014 Data [1] and Cost of Production 2014 Annual report by CDFA [2]. California milk price is based on averaged statewide annual CDFA data [2].

Reference:

1. *CDFA, California Dairy Statistics and Trends Mid-Year Review January-June 2014 Data, D.M. Branch, Editor. 2014: Sacramento, California, USA.*
2. *CDFA, California Dairy Review Newsletters. 2014*

6.2 Appendix B (Chapter 3)

Supplementary Material for “*Life Cycle Performance of Cellulosic Ethanol from a Retrofitted Dry Mill Corn Ethanol Plant*”

Table 6-3 All results for mixed ethanol, corn ethanol and stover ethanol with AR5

40% Harvest Rate													
		Mixed Ethanol											
		Before Allocation			Economic Allocation			GREET Displacement			California Feed Displacement		
	Unit	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case
CO_2	kg/MJ Ethanol	4.31E-02	4.31E-02	4.08E-02	3.16E-02	3.21E-02	3.05E-02	3.72E-02	3.76E-02	3.54E-02	3.86E-02	3.89E-02	3.66E-02
CH_4	kg/MJ Ethanol	1.37E-04	1.38E-04	1.21E-04	1.01E-04	1.03E-04	9.07E-05	1.33E-04	1.35E-04	1.18E-04	1.29E-04	1.30E-04	1.13E-04
N_2O	kg/MJ Ethanol	3.50E-05	3.31E-05	3.22E-05	2.56E-05	2.46E-05	2.41E-05	2.86E-05	2.71E-05	2.63E-05	2.29E-05	2.17E-05	2.11E-05
NMVOC	kg/MJ Ethanol	6.71E-05	6.36E-05	6.17E-05	4.91E-05	4.73E-05	4.62E-05	6.62E-05	6.28E-05	6.09E-05	-6.43E-05	-6.04E-05	-5.91E-05
CO	kg/MJ Ethanol	1.87E-04	1.79E-04	1.71E-04	1.37E-04	1.33E-04	1.28E-04	1.77E-04	1.69E-04	1.62E-04	1.72E-04	1.65E-04	1.57E-04
NOX	kg/MJ Ethanol	3.17E-04	3.04E-04	2.97E-04	2.32E-04	2.26E-04	2.22E-04	3.09E-04	2.96E-04	2.89E-04	2.99E-04	2.86E-04	2.80E-04
SOX	kg/MJ Ethanol	1.63E-04	1.67E-04	1.34E-04	1.20E-04	1.24E-04	1.00E-04	-4.68E-05	-3.14E-05	-5.95E-05	4.49E-05	5.51E-05	2.48E-05
PM_{10}	kg/MJ Ethanol	1.46E-05	1.39E-05	1.34E-05	1.07E-05	1.04E-05	1.00E-05	1.42E-05	1.35E-05	1.30E-05	1.11E-05	1.06E-05	1.01E-05
$PM_{2.5}$	kg/MJ Ethanol	1.44E-05	1.37E-05	1.33E-05	1.06E-05	1.02E-05	9.97E-06	1.41E-05	1.34E-05	1.30E-05	1.11E-05	1.05E-05	1.02E-05
Total Fossil Energy	MJ/MJ Ethanol	7.92E-01	7.97E-01	7.24E-01	5.80E-01	5.93E-01	5.42E-01	6.87E-01	6.98E-01	6.27E-01	6.96E-01	7.07E-01	6.35E-01
Total Energy	MJ/MJ Ethanol	8.23E-01	8.34E-01	7.75E-01	6.03E-01	6.20E-01	5.80E-01	7.04E-01	7.21E-01	6.65E-01	7.09E-01	7.26E-01	6.69E-01
GWP_{100}	**kg/MJ Ethanol**	5.62E-02	5.58E-02	5.27E-02	4.12E-02	4.15E-02	3.94E-02	4.85E-02	4.86E-02	4.56E-02	4.83E-02	4.83E-02	4.54E-02
GWP_{20}	kg/MJ Ethanol	6.39E-02	6.35E-02	5.94E-02	4.68E-02	4.72E-02	4.45E-02	5.60E-02	5.61E-02	5.22E-02	5.55E-02	5.56E-02	5.17E-02
Water	Gallon/MJ Ethanol	1.24E-02	1.26E-02	1.52E-02	9.06E-03	9.34E-03	1.13E-02	1.24E-02	1.26E-02	1.52E-02	-6.95E+00	-6.56E+00	-6.39E+00

		Corn Ethanol											
		Before Allocation			Economic Allocation			GREET Displacement			California Feed Displacement		
		Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case
CO_2	kg/MJ Ethanol	4.31E-02	4.21E-02	4.18E-02	3.16E-02	3.19E-02	3.14E-02	3.72E-02	3.70E-02	3.65E-02	3.86E-02	3.82E-02	3.77E-02
CH_4	kg/MJ Ethanol	1.37E-04	1.35E-04	1.34E-04	1.01E-04	1.02E-04	1.01E-04	1.33E-04	1.32E-04	1.31E-04	1.29E-04	1.28E-04	1.27E-04
N_2O	kg/MJ Ethanol	3.50E-05	3.34E-05	3.38E-05	2.56E-05	2.53E-05	2.54E-05	2.86E-05	2.78E-05	2.80E-05	2.29E-05	2.28E-05	2.29E-05
NMVOC	kg/MJ Ethanol	6.71E-05	6.41E-05	6.48E-05	4.91E-05	4.85E-05	4.87E-05	6.62E-05	6.34E-05	6.40E-05	-6.43E-05	-5.20E-05	-5.38E-05
CO	kg/MJ Ethanol	1.87E-04	1.80E-04	1.81E-04	1.37E-04	1.36E-04	1.36E-04	1.77E-04	1.71E-04	1.72E-04	1.72E-04	1.67E-04	1.68E-04
NOX	kg/MJ Ethanol	3.17E-04	3.04E-04	3.06E-04	2.32E-04	2.30E-04	2.30E-04	3.09E-04	2.97E-04	2.99E-04	2.99E-04	2.88E-04	2.89E-04
SOX	kg/MJ Ethanol	1.63E-04	1.63E-04	1.60E-04	1.20E-04	1.23E-04	1.20E-04	-4.68E-05	-2.31E-05	-2.97E-05	4.49E-05	5.80E-05	5.30E-05
PM_{10}	kg/MJ Ethanol	1.46E-05	1.40E-05	1.41E-05	1.07E-05	1.06E-05	1.06E-05	1.42E-05	1.36E-05	1.37E-05	1.11E-05	1.09E-05	1.08E-05
$PM_{2.5}$	kg/MJ Ethanol	1.44E-05	1.38E-05	1.39E-05	1.06E-05	1.04E-05	1.04E-05	1.41E-05	1.35E-05	1.36E-05	1.11E-05	1.08E-05	1.08E-05
Total Fossil Energy	MJ/MJ Ethanol	7.92E-01	7.78E-01	7.72E-01	5.80E-01	5.88E-01	5.81E-01	6.87E-01	6.85E-01	6.78E-01	6.96E-01	6.93E-01	6.86E-01
Total Energy	MJ/MJ Ethanol	8.23E-01	8.10E-01	8.06E-01	6.03E-01	6.12E-01	6.06E-01	7.04E-01	7.04E-01	6.98E-01	7.09E-01	7.09E-01	7.02E-01
GWP_{100}	**kg/MJ Ethanol**	5.62E-02	5.48E-02	5.45E-02	4.12E-02	4.14E-02	4.10E-02	4.85E-02	4.80E-02	4.76E-02	4.83E-02	4.78E-02	4.73E-02
GWP_{20}	kg/MJ Ethanol	6.39E-02	6.23E-02	6.20E-02	4.68E-02	4.71E-02	4.66E-02	5.60E-02	5.54E-02	5.49E-02	5.55E-02	5.49E-02	5.44E-02
Water	Gallon/MJ Ethanol	1.24E-02	1.26E-02	1.52E-02	9.06E-03	9.49E-03	1.14E-02	1.24E-02	1.26E-02	1.52E-02	-6.95E+00	-6.14E+00	-6.27E+00
		Stover Ethanol											
		Before Allocation			Economic Allocation			GREET Displacement			California Feed Displacement		
		Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case
CO_2	kg/MJ Ethanol		1.28E-01	2.48E-02		4.04E-02	1.73E-02		9.31E-02	1.78E-02		1.01E-01	1.95E-02
CH_4	kg/MJ Ethanol		3.97E-04	-9.15E-05		1.25E-04	-6.37E-05		3.75E-04	-9.61E-05		3.46E-04	-1.02E-04
N_2O	kg/MJ Ethanol		6.40E-06	6.64E-06		2.02E-06	4.62E-06		-3.15E-05	-1.02E-06		-6.51E-05	-7.81E-06
NMVOC	kg/MJ Ethanol		1.81E-05	1.25E-05		5.72E-06	8.66E-06		1.31E-05	1.14E-05		-7.61E-04	-1.45E-04
CO	kg/MJ Ethanol		1.27E-04	1.26E-05		4.02E-05	8.77E-06		6.56E-05	1.63E-07		3.86E-05	-5.28E-06

NOX	kg/MJ Ethanol		2.48E-04	1.46E-04		7.83E-05	1.02E-04		2.01E-04	1.37E-04		1.39E-04	1.24E-04
SOX	kg/MJ Ethanol		5.18E-04	-2.87E-04		1.64E-04	-1.99E-04		-7.29E-04	-5.39E-04		-1.86E-04	-4.29E-04
PM_{10}	kg/MJ Ethanol		8.34E-06	2.99E-06		2.64E-06	2.08E-06		5.77E-06	2.47E-06		-1.27E-05	-1.27E-06
$PM_{2.5}$	kg/MJ Ethanol		7.01E-06	4.69E-06		2.21E-06	3.26E-06		5.00E-06	4.28E-06		-1.29E-05	6.73E-07
Total Fossil Energy	MJ/MJ Ethanol		2.40E+00	-6.07E-02		7.57E-01	-4.22E-02		1.78E+00	-1.87E-01		1.83E+00	-1.76E-01
Total Energy	MJ/MJ Ethanol		2.83E+00	2.76E-01		8.93E-01	1.92E-01		2.12E+00	1.33E-01		2.15E+00	1.39E-01
GWP_{100}	**kg/MJ Ethanol**		1.41E-01	2.40E-02		4.44E-02	1.67E-02		9.53E-02	1.48E-02		9.37E-02	1.45E-02
GWP_{20}	kg/MJ Ethanol		1.63E-01	1.89E-02		5.15E-02	1.31E-02		1.16E-01	9.45E-03		1.13E-01	8.83E-03
Water	Gallon/MJ Ethanol		1.26E-02	1.52E-02		3.96E-03	1.05E-02		1.26E-02	1.52E-02		-4.13E+01	-8.33E+00
25% Harvest Rate													
		Mixed Ethanol											
		Before Allocation			Economic Allocation			GREET Displacement			California Feed Displacement		
		Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case
CO_2	kg/MJ Ethanol	4.31E-02	4.33E-02	4.17E-02	3.16E-02	3.22E-02	3.12E-02	3.72E-02	3.78E-02	3.63E-02	3.86E-02	3.91E-02	3.76E-02
CH_4	kg/MJ Ethanol	1.37E-04	1.39E-04	1.22E-04	1.01E-04	1.03E-04	9.14E-05	1.33E-04	1.35E-04	1.19E-04	1.29E-04	1.30E-04	1.14E-04
N_2O	kg/MJ Ethanol	3.50E-05	3.31E-05	3.22E-05	2.56E-05	2.46E-05	2.41E-05	2.86E-05	2.71E-05	2.63E-05	2.29E-05	2.17E-05	2.11E-05
NMVOC	kg/MJ Ethanol	6.71E-05	6.36E-05	6.20E-05	4.91E-05	4.73E-05	4.64E-05	6.62E-05	6.28E-05	6.12E-05	-6.43E-05	-6.03E-05	-5.89E-05
CO	kg/MJ Ethanol	1.87E-04	1.79E-04	1.72E-04	1.37E-04	1.33E-04	1.29E-04	1.77E-04	1.70E-04	1.63E-04	1.72E-04	1.65E-04	1.59E-04
NOX	kg/MJ Ethanol	3.17E-04	3.04E-04	3.00E-04	2.32E-04	2.26E-04	2.24E-04	3.09E-04	2.97E-04	2.92E-04	2.99E-04	2.87E-04	2.83E-04
SOX	kg/MJ Ethanol	1.63E-04	1.67E-04	1.34E-04	1.20E-04	1.24E-04	1.00E-04	-4.68E-05	-3.13E-05	-5.93E-05	4.49E-05	5.51E-05	2.51E-05
PM_{10}	kg/MJ Ethanol	1.46E-05	1.40E-05	1.35E-05	1.07E-05	1.04E-05	1.01E-05	1.42E-05	1.35E-05	1.31E-05	1.11E-05	1.06E-05	1.02E-05
$PM_{2.5}$	kg/MJ Ethanol	1.44E-05	1.37E-05	1.33E-05	1.06E-05	1.02E-05	9.98E-06	1.41E-05	1.34E-05	1.30E-05	1.11E-05	1.05E-05	1.02E-05
Total Fossil Energy	MJ/MJ Ethanol	7.92E-01	7.99E-01	7.33E-01	5.80E-01	5.94E-01	5.49E-01	6.87E-01	7.00E-01	6.36E-01	6.96E-01	7.09E-01	6.45E-01
Total Energy	MJ/MJ Ethanol	8.23E-01	8.35E-01	7.84E-01	6.03E-01	6.21E-01	5.87E-01	7.04E-01	7.23E-01	6.74E-01	7.09E-01	7.27E-01	6.78E-01
GWP_{100}	kg/MJ Ethanol	5.62E-02	5.60E-02	5.37E-02	4.12E-02	4.16E-02	4.02E-02	4.85E-02	4.88E-02	4.66E-02	4.83E-02	4.85E-02	4.64E-02
GWP_{20}	kg/MJ Ethanol	6.39E-02	6.37E-02	6.05E-02	4.68E-02	4.74E-02	4.53E-02	5.60E-02	5.63E-02	5.33E-02	5.55E-02	5.58E-02	5.28E-02

Water	Gallon/MJ Ethanol	1.24E-02	1.26E-02	1.52E-02	9.06E-03	9.34E-03	1.13E-02	1.24E-02	1.26E-02	1.52E-02	-6.95E+00	-6.56E+00	-6.39E+00
		Corn Ethanol											
		Before Allocation			Economic Allocation			GREET Displacement			California Feed Displacement		
		Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case
CO_2	kg/MJ Ethanol	4.31E-02	4.21E-02	4.18E-02	3.16E-02	3.19E-02	3.14E-02	3.72E-02	3.70E-02	3.65E-02	3.86E-02	3.82E-02	3.77E-02
CH_4	kg/MJ Ethanol	1.37E-04	1.35E-04	1.34E-04	1.01E-04	1.02E-04	1.01E-04	1.33E-04	1.32E-04	1.31E-04	1.29E-04	1.28E-04	1.27E-04
N_2O	kg/MJ Ethanol	3.50E-05	3.34E-05	3.38E-05	2.56E-05	2.53E-05	2.54E-05	2.86E-05	2.78E-05	2.80E-05	2.29E-05	2.28E-05	2.29E-05
NMVOC	kg/MJ Ethanol	6.71E-05	6.41E-05	6.48E-05	4.91E-05	4.85E-05	4.87E-05	6.62E-05	6.34E-05	6.40E-05	-6.43E-05	-5.20E-05	-5.38E-05
CO	kg/MJ Ethanol	1.87E-04	1.80E-04	1.81E-04	1.37E-04	1.36E-04	1.36E-04	1.77E-04	1.71E-04	1.72E-04	1.72E-04	1.67E-04	1.68E-04
NOX	kg/MJ Ethanol	3.17E-04	3.04E-04	3.06E-04	2.32E-04	2.30E-04	2.30E-04	3.09E-04	2.97E-04	2.99E-04	2.99E-04	2.88E-04	2.89E-04
SOX	kg/MJ Ethanol	1.63E-04	1.63E-04	1.60E-04	1.20E-04	1.23E-04	1.20E-04	-4.68E-05	-2.31E-05	-2.97E-05	4.49E-05	5.80E-05	5.30E-05
PM_{10}	kg/MJ Ethanol	1.46E-05	1.40E-05	1.41E-05	1.07E-05	1.06E-05	1.06E-05	1.42E-05	1.36E-05	1.37E-05	1.11E-05	1.09E-05	1.08E-05
$PM_{2.5}$	kg/MJ Ethanol	1.44E-05	1.38E-05	1.39E-05	1.06E-05	1.04E-05	1.04E-05	1.41E-05	1.35E-05	1.36E-05	1.11E-05	1.08E-05	1.08E-05
Total Fossil Energy	MJ/MJ Ethanol	7.92E-01	7.78E-01	7.72E-01	5.80E-01	5.88E-01	5.81E-01	6.87E-01	6.85E-01	6.78E-01	6.96E-01	6.93E-01	6.86E-01
Total Energy	MJ/MJ Ethanol	8.23E-01	8.10E-01	8.06E-01	6.03E-01	6.12E-01	6.06E-01	7.04E-01	7.04E-01	6.98E-01	7.09E-01	7.09E-01	7.02E-01
GWP_{100}	kg/MJ Ethanol	5.62E-02	5.48E-02	5.45E-02	4.12E-02	4.14E-02	4.10E-02	4.85E-02	4.80E-02	4.76E-02	4.83E-02	4.78E-02	4.73E-02
GWP_{20}	kg/MJ Ethanol	6.39E-02	6.23E-02	6.20E-02	4.68E-02	4.71E-02	4.66E-02	5.60E-02	5.54E-02	5.49E-02	5.55E-02	5.49E-02	5.44E-02
Water	Gallon/MJ Ethanol	1.24E-02	1.26E-02	1.52E-02	9.06E-03	9.49E-03	1.14E-02	1.24E-02	1.26E-02	1.52E-02	-6.95E+00	-6.14E+00	-6.27E+00
		Stover Ethanol											
		Before Allocation			Economic Allocation			GREET Displacement			California Feed Displacement		
		Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case
CO_2	kg/MJ Ethanol		1.44E-01	4.14E-02		4.54E-02	2.88E-02		1.09E-01	3.43E-02		1.17E-01	3.60E-02
CH_4	kg/MJ Ethanol		4.13E-04	-7.49E-05		1.31E-04	-5.21E-05		3.91E-04	-7.95E-05		3.62E-04	-8.53E-05
N_2O	kg/MJ Ethanol		6.47E-06	6.69E-06		2.04E-06	4.65E-06		-3.15E-05	-9.72E-07		-6.51E-05	-7.76E-06
NMVOC	kg/MJ Ethanol		2.18E-05	1.64E-05		6.90E-06	1.14E-05		1.68E-05	1.54E-05		-7.58E-04	-1.41E-04

CO	kg/MJ Ethanol		1.44E-04	3.08E-05		4.56E-05	2.14E-05		8.27E-05	1.83E-05		5.57E-05	1.29E-05
NOX	kg/MJ Ethanol		2.96E-04	1.95E-04		9.36E-05	1.36E-04		2.49E-04	1.86E-04		1.87E-04	1.73E-04
SOX	kg/MJ Ethanol		5.23E-04	-2.82E-04		1.65E-04	-1.96E-04		-7.25E-04	-5.34E-04		-1.81E-04	-4.24E-04
PM_{10}	kg/MJ Ethanol		1.01E-05	4.82E-06		3.19E-06	3.35E-06		7.53E-06	4.30E-06		-1.10E-05	5.62E-07
$PM_{2.5}$	kg/MJ Ethanol		7.19E-06	4.81E-06		2.27E-06	3.34E-06		5.18E-06	4.40E-06		-1.27E-05	7.92E-07
Total Fossil Energy	MJ/MJ Ethanol		2.55E+00	1.00E-01		8.07E-01	6.96E-02		1.93E+00	-2.59E-02		1.98E+00	-1.52E-02
Total Energy	MJ/MJ Ethanol		2.97E+00	4.27E-01		9.39E-01	2.97E-01		2.26E+00	2.84E-01		2.29E+00	2.90E-01
GWP_{100}	kg/MJ Ethanol		1.57E-01	4.10E-02		4.95E-02	2.86E-02		1.11E-01	3.19E-02		1.10E-01	3.16E-02
GWP_{20}	kg/MJ Ethanol		1.80E-01	3.68E-02		5.69E-02	2.56E-02		1.33E-01	2.74E-02		1.30E-01	2.68E-02
Water	Gallon/MJ Ethanol		1.26E-02	1.52E-02		3.96E-03	1.05E-02		1.26E-02	1.52E-02		-4.13E+01	-8.33E+00

Table 6-4 All results for mixed Ethanol, corn ethanol and stover ethanol with AR4

40% Harvest Rate													
		Mixed Ethanol											
		Before Allocation			**Economic Allocation**			**GREET Displacement**			**California Feed Displacement**		
		Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case
CO_2	kg/MJ Ethanol	4.31E-02	4.31E-02	4.08E-02	3.16E-02	3.21E-02	3.05E-02	3.72E-02	3.76E-02	3.54E-02	3.86E-02	3.89E-02	3.66E-02
CH_4	kg/MJ Ethanol	1.37E-04	1.38E-04	1.21E-04	1.01E-04	1.03E-04	9.07E-05	1.33E-04	1.35E-04	1.18E-04	1.29E-04	1.30E-04	1.13E-04
N_2O	kg/MJ Ethanol	3.50E-05	3.31E-05	3.22E-05	2.56E-05	2.46E-05	2.41E-05	2.86E-05	2.71E-05	2.63E-05	2.29E-05	2.17E-05	2.11E-05
NMVOC	kg/MJ Ethanol	6.71E-05	6.36E-05	6.17E-05	4.91E-05	4.73E-05	4.62E-05	6.62E-05	6.28E-05	6.09E-05	-6.43E-05	-6.04E-05	-5.91E-05
CO	kg/MJ Ethanol	1.87E-04	1.79E-04	1.71E-04	1.37E-04	1.33E-04	1.28E-04	1.77E-04	1.69E-04	1.62E-04	1.72E-04	1.65E-04	1.57E-04
NOX	kg/MJ Ethanol	3.17E-04	3.04E-04	2.97E-04	2.32E-04	2.26E-04	2.22E-04	3.09E-04	2.96E-04	2.89E-04	2.99E-04	2.86E-04	2.80E-04
SOX	kg/MJ Ethanol	1.63E-04	1.67E-04	1.34E-04	1.20E-04	1.24E-04	1.00E-04	-4.68E-05	-3.14E-05	-5.95E-05	4.49E-05	5.51E-05	2.48E-05
PM_{10}	kg/MJ Ethanol	1.46E-05	1.39E-05	1.34E-05	1.07E-05	1.04E-05	1.00E-05	1.42E-05	1.35E-05	1.30E-05	1.11E-05	1.06E-05	1.01E-05
$PM_{2.5}$	kg/MJ Ethanol	1.44E-05	1.37E-05	1.33E-05	1.06E-05	1.02E-05	9.97E-06	1.41E-05	1.34E-05	1.30E-05	1.11E-05	1.05E-05	1.02E-05
Total Fossil Energy	MJ/MJ Ethanol	7.92E-01	7.97E-01	7.24E-01	5.80E-01	5.93E-01	5.42E-01	6.87E-01	6.98E-01	6.27E-01	6.96E-01	7.07E-01	6.35E-01
Total Energy	MJ/MJ Ethanol	8.23E-01	8.34E-01	7.75E-01	6.03E-01	6.20E-01	5.80E-01	7.04E-01	7.21E-01	6.65E-01	7.09E-01	7.26E-01	6.69E-01
GWP_{100}	**kg/MJ Ethanol**	**5.69E-02**	**5.65E-02**	**5.34E-02**	**4.17E-02**	**4.20E-02**	**4.00E-02**	**4.91E-02**	**4.91E-02**	**4.62E-02**	**4.87E-02**	**4.87E-02**	**4.58E-02**
GWP_{20}	kg/MJ Ethanol	6.31E-02	6.27E-02	5.88E-02	4.62E-02	4.66E-02	4.40E-02	5.51E-02	5.51E-02	5.14E-02	5.45E-02	5.46E-02	5.09E-02
Water	Gallon/MJ Ethanol	1.24E-02	1.26E-02	1.52E-02	9.06E-03	9.34E-03	1.13E-02	1.24E-02	1.26E-02	1.52E-02	-6.95E+00	-6.56E+00	-6.39E+00
		Corn Ethanol											
		Before Allocation			Economic Allocation			GREET Displacement			California Feed Displacement		
		Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case
CO_2	kg/MJ Ethanol	4.31E-02	4.21E-02	4.18E-02	3.16E-02	3.19E-02	3.14E-02	3.72E-02	3.70E-02	3.65E-02	3.86E-02	3.82E-02	3.77E-02
CH_4	kg/MJ Ethanol	1.37E-04	1.35E-04	1.34E-04	1.01E-04	1.02E-04	1.01E-04	1.33E-04	1.32E-04	1.31E-04	1.29E-04	1.28E-04	1.27E-04
N_2O	kg/MJ Ethanol	3.50E-05	3.34E-05	3.38E-05	2.56E-05	2.53E-05	2.54E-05	2.86E-05	2.78E-05	2.80E-05	2.29E-05	2.28E-05	2.29E-05

NMVOC	kg/MJ Ethanol	6.71E-05	6.41E-05	6.48E-05	4.91E-05	4.85E-05	4.87E-05	6.62E-05	6.34E-05	6.40E-05	-6.43E-05	-5.20E-05	-5.38E-05
CO	kg/MJ Ethanol	1.87E-04	1.80E-04	1.81E-04	1.37E-04	1.36E-04	1.36E-04	1.77E-04	1.71E-04	1.72E-04	1.72E-04	1.67E-04	1.68E-04
NOX	kg/MJ Ethanol	3.17E-04	3.04E-04	3.06E-04	2.32E-04	2.30E-04	2.30E-04	3.09E-04	2.97E-04	2.99E-04	2.99E-04	2.88E-04	2.89E-04
SOX	kg/MJ Ethanol	1.63E-04	1.63E-04	1.60E-04	1.20E-04	1.23E-04	1.20E-04	-4.68E-05	-2.31E-05	-2.97E-05	4.49E-05	5.80E-05	5.30E-05
PM_{10}	kg/MJ Ethanol	1.46E-05	1.40E-05	1.41E-05	1.07E-05	1.06E-05	1.06E-05	1.42E-05	1.36E-05	1.37E-05	1.11E-05	1.09E-05	1.08E-05
$PM_{2.5}$	kg/MJ Ethanol	1.44E-05	1.38E-05	1.39E-05	1.06E-05	1.04E-05	1.04E-05	1.41E-05	1.35E-05	1.36E-05	1.11E-05	1.08E-05	1.08E-05
Total Fossil Energy	MJ/MJ Ethanol	7.92E-01	7.78E-01	7.72E-01	5.80E-01	5.88E-01	5.81E-01	6.87E-01	6.85E-01	6.78E-01	6.96E-01	6.93E-01	6.86E-01
Total Energy	MJ/MJ Ethanol	8.23E-01	8.10E-01	8.06E-01	6.03E-01	6.12E-01	6.06E-01	7.04E-01	7.04E-01	6.98E-01	7.09E-01	7.09E-01	7.02E-01
GWP_{100}	**kg/MJ Ethanol**	**5.69E-02**	**5.55E-02**	**5.52E-02**	**4.17E-02**	**4.19E-02**	**4.15E-02**	**4.91E-02**	**4.85E-02**	**4.81E-02**	**4.87E-02**	**4.82E-02**	**4.77E-02**
GWP_{20}	kg/MJ Ethanol	6.31E-02	6.15E-02	6.12E-02	4.62E-02	4.65E-02	4.60E-02	5.51E-02	5.45E-02	5.40E-02	5.45E-02	5.39E-02	5.34E-02
Water	Gallon/MJ Ethanol	1.24E-02	1.26E-02	1.52E-02	9.06E-03	9.49E-03	1.14E-02	1.24E-02	1.26E-02	1.52E-02	-6.95E+00	-6.14E+00	-6.27E+00
		Stover Ethanol											
		Before Allocation			Economic Allocation			GREET Displacement			California Feed Displacement		
		Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case
CO_2	kg/MJ Ethanol		1.28E-01	2.48E-02		4.04E-02	1.73E-02		9.31E-02	1.78E-02		1.01E-01	1.95E-02
CH_4	kg/MJ Ethanol		3.97E-04	-9.15E-05		1.25E-04	-6.37E-05		3.75E-04	-9.61E-05		3.46E-04	-1.02E-04
N_2O	kg/MJ Ethanol		6.40E-06	6.64E-06		2.02E-06	4.62E-06		-3.15E-05	-1.02E-06		-6.51E-05	-7.81E-06
NMVOC	kg/MJ Ethanol		1.81E-05	1.25E-05		5.72E-06	8.66E-06		1.31E-05	1.14E-05		-7.61E-04	-1.45E-04
CO	kg/MJ Ethanol		1.27E-04	1.26E-05		4.02E-05	8.77E-06		6.56E-05	1.63E-07		3.86E-05	-5.28E-06
NOX	kg/MJ Ethanol		2.48E-04	1.46E-04		7.83E-05	1.02E-04		2.01E-04	1.37E-04		1.39E-04	1.24E-04
SOX	kg/MJ Ethanol		5.18E-04	-2.87E-04		1.64E-04	-1.99E-04		-7.29E-04	-5.39E-04		-1.86E-04	-4.29E-04
PM_{10}	kg/MJ Ethanol		8.34E-06	2.99E-06		2.64E-06	2.08E-06		5.77E-06	2.47E-06		-1.27E-05	-1.27E-06
$PM_{2.5}$	kg/MJ Ethanol		7.01E-06	4.69E-06		2.21E-06	3.26E-06		5.00E-06	4.28E-06		-1.29E-05	6.73E-07
Total Fossil Energy	MJ/MJ Ethanol		2.40E+00	-6.07E-02		7.57E-01	-4.22E-02		1.78E+00	-1.87E-01		1.83E+00	-1.76E-01
Total Energy	MJ/MJ Ethanol		2.83E+00	2.76E-01		8.93E-01	1.92E-01		2.12E+00	1.33E-01		2.15E+00	1.39E-01

GWP_{100}	**kg/MJ Ethanol**		**1.40E-01**	**2.45E-02**		**4.41E-02**	**1.71E-02**		**9.31E-02**	**1.51E-02**		**9.05E-02**	**1.46E-02**
GWP_{20}	kg/MJ Ethanol		1.58E-01	2.02E-02		5.00E-02	1.40E-02		1.11E-01	1.06E-02		1.07E-01	9.85E-03
Water	Gallon/MJ Ethanol		1.26E-02	1.52E-02		3.96E-03	1.05E-02		1.26E-02	1.52E-02		-4.13E+01	-8.33E+00
25% Harvest Rate													
		Mixed Ethanol											
		Before Allocation			Economic Allocation			GREET Displacement			California Feed Displacement		
		Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case
CO_2	kg/MJ Ethanol	4.31E-02	4.33E-02	4.17E-02	3.16E-02	3.22E-02	3.12E-02	3.72E-02	3.78E-02	3.63E-02	3.86E-02	3.91E-02	3.76E-02
CH_4	kg/MJ Ethanol	1.37E-04	1.39E-04	1.22E-04	1.01E-04	1.03E-04	9.14E-05	1.33E-04	1.35E-04	1.19E-04	1.29E-04	1.30E-04	1.14E-04
N_2O	kg/MJ Ethanol	3.50E-05	3.31E-05	3.22E-05	2.56E-05	2.46E-05	2.41E-05	2.86E-05	2.71E-05	2.63E-05	2.29E-05	2.17E-05	2.11E-05
NMVOC	kg/MJ Ethanol	6.71E-05	6.36E-05	6.20E-05	4.91E-05	4.73E-05	4.64E-05	6.62E-05	6.28E-05	6.12E-05	-6.43E-05	-6.03E-05	-5.89E-05
CO	kg/MJ Ethanol	1.87E-04	1.79E-04	1.72E-04	1.37E-04	1.33E-04	1.29E-04	1.77E-04	1.70E-04	1.63E-04	1.72E-04	1.65E-04	1.59E-04
NOX	kg/MJ Ethanol	3.17E-04	3.04E-04	3.00E-04	2.32E-04	2.26E-04	2.24E-04	3.09E-04	2.97E-04	2.92E-04	2.99E-04	2.87E-04	2.83E-04
SOX	kg/MJ Ethanol	1.63E-04	1.67E-04	1.34E-04	1.20E-04	1.24E-04	1.00E-04	-4.68E-05	-3.13E-05	-5.93E-05	4.49E-05	5.51E-05	2.51E-05
PM_{10}	kg/MJ Ethanol	1.46E-05	1.40E-05	1.35E-05	1.07E-05	1.04E-05	1.01E-05	1.42E-05	1.35E-05	1.31E-05	1.11E-05	1.06E-05	1.02E-05
$PM_{2.5}$	kg/MJ Ethanol	1.44E-05	1.37E-05	1.33E-05	1.06E-05	1.02E-05	9.98E-06	1.41E-05	1.34E-05	1.30E-05	1.11E-05	1.05E-05	1.02E-05
Total Fossil Energy	MJ/MJ Ethanol	7.92E-01	7.99E-01	7.33E-01	5.80E-01	5.94E-01	5.49E-01	6.87E-01	7.00E-01	6.36E-01	6.96E-01	7.09E-01	6.45E-01
Total Energy	MJ/MJ Ethanol	8.23E-01	8.35E-01	7.84E-01	6.03E-01	6.21E-01	5.87E-01	7.04E-01	7.23E-01	6.74E-01	7.09E-01	7.27E-01	6.78E-01
GWP100	kg/MJ Ethanol	5.69E-02	5.67E-02	5.44E-02	4.17E-02	4.21E-02	4.07E-02	4.91E-02	4.92E-02	4.72E-02	4.87E-02	4.88E-02	4.68E-02
GWP 20	kg/MJ Ethanol	6.31E-02	6.29E-02	5.98E-02	4.62E-02	4.68E-02	4.48E-02	5.51E-02	5.53E-02	5.25E-02	5.45E-02	5.48E-02	5.19E-02
Water	Gallon/MJ Ethanol	1.24E-02	1.26E-02	1.52E-02	9.06E-03	9.34E-03	1.13E-02	1.24E-02	1.26E-02	1.52E-02	-6.95E+00	-6.56E+00	-6.39E+00
		Corn Ethanol											
		Before Allocation			Economic Allocation			GREET Displacement			California Feed Displacement		
		Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case
CO_2	kg/MJ Ethanol	4.31E-02	4.21E-02	4.18E-02	3.16E-02	3.19E-02	3.14E-02	3.72E-02	3.70E-02	3.65E-02	3.86E-02	3.82E-02	3.77E-02

CH₄	kg/MJ Ethanol	1.37E-04	1.35E-04	1.34E-04	1.01E-04	1.02E-04	1.01E-04	1.33E-04	1.32E-04	1.31E-04	1.29E-04	1.28E-04	1.27E-04
N₂O	kg/MJ Ethanol	3.50E-05	3.34E-05	3.38E-05	2.56E-05	2.53E-05	2.54E-05	2.86E-05	2.78E-05	2.80E-05	2.29E-05	2.28E-05	2.29E-05
NMVOC	kg/MJ Ethanol	6.71E-05	6.41E-05	6.48E-05	4.91E-05	4.85E-05	4.87E-05	6.62E-05	6.34E-05	6.40E-05	-6.43E-05	-5.20E-05	-5.38E-05
CO	kg/MJ Ethanol	1.87E-04	1.80E-04	1.81E-04	1.37E-04	1.36E-04	1.36E-04	1.77E-04	1.71E-04	1.72E-04	1.72E-04	1.67E-04	1.68E-04
NOX	kg/MJ Ethanol	3.17E-04	3.04E-04	3.06E-04	2.32E-04	2.30E-04	2.30E-04	3.09E-04	2.97E-04	2.99E-04	2.99E-04	2.88E-04	2.89E-04
SOX	kg/MJ Ethanol	1.63E-04	1.63E-04	1.60E-04	1.20E-04	1.23E-04	1.20E-04	-4.68E-05	-2.31E-05	-2.97E-05	4.49E-05	5.80E-05	5.30E-05
PM₁₀	kg/MJ Ethanol	1.46E-05	1.40E-05	1.41E-05	1.07E-05	1.06E-05	1.06E-05	1.42E-05	1.36E-05	1.37E-05	1.11E-05	1.09E-05	1.08E-05
PM₂.₅	kg/MJ Ethanol	1.44E-05	1.38E-05	1.39E-05	1.06E-05	1.04E-05	1.04E-05	1.41E-05	1.35E-05	1.36E-05	1.11E-05	1.08E-05	1.08E-05
Total Fossil Energy	MJ/MJ Ethanol	7.92E-01	7.78E-01	7.72E-01	5.80E-01	5.88E-01	5.81E-01	6.87E-01	6.85E-01	6.78E-01	6.96E-01	6.93E-01	6.86E-01
Total Energy	MJ/MJ Ethanol	8.23E-01	8.10E-01	8.06E-01	6.03E-01	6.12E-01	6.06E-01	7.04E-01	7.04E-01	6.98E-01	7.09E-01	7.09E-01	7.02E-01
GWP100	kg/MJ Ethanol	5.69E-02	5.55E-02	5.52E-02	4.17E-02	4.19E-02	4.15E-02	4.91E-02	4.85E-02	4.81E-02	4.87E-02	4.82E-02	4.77E-02
GWP 20	kg/MJ Ethanol	6.31E-02	6.15E-02	6.12E-02	4.62E-02	4.65E-02	4.60E-02	5.51E-02	5.45E-02	5.40E-02	5.45E-02	5.39E-02	5.34E-02
Water	Gallon/MJ Ethanol	1.24E-02	1.26E-02	1.52E-02	9.06E-03	9.49E-03	1.14E-02	1.24E-02	1.26E-02	1.52E-02	-6.95E+00	-6.14E+00	-6.27E+00
		Stover Ethanol											
		Before Allocation			Economic Allocation			GREET Displacement			California Feed Displacement		
		Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case	Baseline	Low Stover Case	High Stover Case
CO₂	kg/MJ Ethanol		1.44E-01	4.14E-02		4.54E-02	2.88E-02		1.09E-01	3.43E-02		1.17E-01	3.60E-02
CH₄	kg/MJ Ethanol		4.13E-04	-7.49E-05		1.31E-04	-5.21E-05		3.91E-04	-7.95E-05		3.62E-04	-8.53E-05
N₂O	kg/MJ Ethanol		6.47E-06	6.69E-06		2.04E-06	4.65E-06		-3.15E-05	-9.72E-07		-6.51E-05	-7.76E-06
NMVOC	kg/MJ Ethanol		2.18E-05	1.64E-05		6.90E-06	1.14E-05		1.68E-05	1.54E-05		-7.58E-04	-1.41E-04
CO	kg/MJ Ethanol		1.44E-04	3.08E-05		4.56E-05	2.14E-05		8.27E-05	1.83E-05		5.57E-05	1.29E-05
NOX	kg/MJ Ethanol		2.96E-04	1.95E-04		9.36E-05	1.36E-04		2.49E-04	1.86E-04		1.87E-04	1.73E-04
SOX	kg/MJ Ethanol		5.23E-04	-2.82E-04		1.65E-04	-1.96E-04		-7.25E-04	-5.34E-04		-1.81E-04	-4.24E-04
PM₁₀	kg/MJ Ethanol		1.01E-05	4.82E-06		3.19E-06	3.35E-06		7.53E-06	4.30E-06		-1.10E-05	5.62E-07
PM₂.₅	kg/MJ Ethanol		7.19E-06	4.81E-06		2.27E-06	3.34E-06		5.18E-06	4.40E-06		-1.27E-05	7.92E-07
Total Fossil Energy	MJ/MJ Ethanol		2.55E+00	1.00E-01		8.07E-01	6.96E-02		1.93E+00	-2.59E-02		1.98E+00	-1.52E-02

Total Energy	MJ/MJ Ethanol		2.97E+00	4.27E-01		9.39E-01	2.97E-01		2.26E+00	2.84E-01		2.29E+00	2.90E-01
GWP100	kg/MJ Ethanol		1.56E-01	4.15E-02		4.92E-02	2.89E-02		1.09E-01	3.21E-02		1.07E-01	3.16E-02
GWP 20	kg/MJ Ethanol		1.75E-01	3.79E-02		5.53E-02	2.64E-02		1.28E-01	2.83E-02		1.24E-01	2.76E-02
Water	Gallon/MJ Ethanol		1.26E-02	1.52E-02		3.96E-03	1.05E-02		1.26E-02	1.52E-02		-4.13E+01	-8.33E+00

Table 6-5 LCI of California feeds

	Alfalfa	**Cotton Seed**	**Wheat**	**Corn Silage**	**Corn Grain**	**Beet Pulp**	**WDGS (CA)**	**MidWest Corn**	**Soybean Meal-Gabi**	**DDGS-Gabi**	**Almond Hull**	Unit
CO_2	1.42E-01	9.67E-02	4.43E-01	1.35E-02	1.31E-01	1.87E-02	4.23E-02	1.34E-01	2.01E-01	8.67E-01		kg/kg
CH_4	3.18E-04	2.09E-04	8.56E-04	3.87E-05	2.46E-04	2.81E-05	1.47E-04	3.90E-04	3.57E-07	2.05E-03		kg/kg
N_2O	1.79E-05	1.61E-04	4.41E-04	4.41E-05	4.11E-04	2.25E-05	3.26E-05	2.92E-04	1.39E-07	3.41E-05		kg/kg
NMVOC	2.31E-04	4.41E-05	1.97E-04	3.41E-06	5.43E-05	9.37E-06	6.27E-05	4.50E-04	1.20E-09	2.04E-04	1.49E-02	kg/kg
CO	1.88E-04	2.52E-04	9.25E-04	1.76E-05	2.54E-04	1.91E-05	1.78E-04	1.21E-03	3.38E-04	2.60E-04	6.69E-04	kg/kg
NOx	2.45E-04	2.88E-04	2.16E-03	3.46E-05	5.13E-04	3.69E-05	2.96E-04	1.45E-03	1.39E-07	8.63E-04	2.43E-04	**kg/kg**
SO_2(SOx)	3.16E-04	8.59E-04	1.89E-03	4.46E-05	2.82E-04	7.26E-05	1.89E-04	2.32E-04	1.08E-02	1.32E-03	1.19E-02	**kg/kg**
PM10	2.58E-05	1.66E-05	6.46E-05	2.76E-06	2.79E-05	9.70E-06	1.38E-05	1.12E-04	3.06E-09	1.56E-05	3.05E-04	kg/kg
PM2.5	1.84E-05	1.19E-05	2.66E-05	3.25E-06	2.18E-05	6.09E-06	1.34E-05	8.99E-05	1.28E-09	3.09E-05	3.05E-04	kg/kg
Fossil Fuel	2.94E+00	1.86E+00	6.65E+00	3.60E-01	2.52E+00	2.20E-01	8.21E-01	2.10E+00	3.45E+00	1.50E+01	1.18E+00	MJ/kg
Total Energy	3.58E+00	2.21E+00	7.13E+00	4.18E-01	2.99E+00	3.21E-01	8.38E-01	2.14E+00	3.83E+00	1.51E+01	1.41E+00	MJ/kg
GHGs	1.51E-01	1.23E-01	5.96E-01	2.76E-02	2.59E-01	2.61E-02	5.57E-02	2.31E-01	2.01E-01	9.29E-01	9.19E-02	kg CO_2e/kg
Water	5.24E-01	3.62E-01	1.46E-02	1.56E-01	8.82E-01		9.72E-02		3.44E-03	7.01E-03		m^3/kg