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Land use change implications for large-scale cultivation of algae feedstocks in the United States Gulf Coast

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A B S T R A C T

Algae is considered a promising future feedstock for biofuels. Although several studies have been conducted to assess the environmental impact of algae-based fuels, land use change is one area that is commonly overlooked in previous life cycle assessment studies. However, land use change can impact the life cycle greenhouse gas (GHG) emissions of algal biofuels when large tracts of land are converted to algal raceway cultivation systems. This study assesses the impacts of land use change through a variety of means. The Intergovernmental Panel on Climate Change (IPCC) Tier 1 methodology was utilized to assess potential emissions resulting from the conversion of potential algae facility sites in the U.S. Gulf Coast, consisting of grassland, cropland, and forestland in several management conditions. These emission values over a 20-year time horizon were combined with guidance on promising sites for algae raceway development to provide an estimate of industry-wide GHG emissions impacts due to direct land use change (LUC). Direct LUC impacts appear to be important, with average GHG emissions of between 4 and 8 g CO_{2eq}/MJ for grassland and cropland conversion, which is roughly 6.3% and 12.5% of the total GHG emission over the entire algae renewable diesel life cycle without considering the LUC. Emissions due to direct LUC could be even larger if previously forested lands are cleared, averaging 24.7 g CO_{2eq}/MJ across a range of potential algae sites. This article details the methods, assumptions and initial LCA results for these land use change scenarios when considering the algae biofuels life cycle. Results from this LCA can help decision-makers recognize the importance of facility siting in overall environmental performance, and select locations of algae cultivation facilities to minimize direct LUC emissions.

1. Introduction

Algae-based alternative fuels are viewed as a promising bioenergy pathway for many reasons, including high biomass growth rates, tolerance to brackish water, and the ability to be sited on marginal lands (Chisti, 2007; Mata et al., 2010). Questions persist, however, about the environmental and economic benefits of this immature industry (ANL et al., 2012). Life cycle assessment (LCA) studies have been conducted to determine the greenhouse gas emissions of the entire supply chain of algae-based fuels, and many different modeling assumptions have been used to characterize algae cultivation, harvesting, and downstream processing. One area of the fuel life cycle commonly overlooked in algae systems is the concept of land use change (LUC). Changes in land use patterns can lead to release of CO_2 into the atmosphere from the decomposition or burning of above and belowground biomass, and from changes to the carbon content of soils in the system.

Among many algae cultivation configurations, there are two most particular common types of configurations for algae cultivation: the open pond (OP) system and horizontal tubular photo bioreactors (PBRs). Pulz (2001) conducted a comprehensive comparison of pros and cons of OP system and PBRs. Several scientific studies following Pulz's research are in general agreement that although PBRs may have higher lipid production, the OP algae cultivation system is preferable to PBR cultivation system in terms of energy consumption and GHG emissions, and is less expensive than PBRs because of the lower costs to build and operate (Chisti, 2007; Resurreccion et al., 2012). The preferable OP system infrastructure requires a large area of land for pond construction, with an estimation of 30 million acres of land requirement to meet US oil demand (Hannon et al., 2010). Therefore, a thorough investigation

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of the environmental impacts associated with algae biofuels should include an assessment of the consequence of the anticipated LUC activities that will take place over the life of the algae cultivation system.

Land use change in other biomass feedstocks has been shown to be an important component of the life cycle fuel greenhouse gas (GHG) emissions of biofuels (Georgianna and Mayfield, 2012; Kim et al., 2009; Searchinger et al., 2008). This is the case whether the change in emissions is directly due to switching use of land (e.g., switching crops) (Clarens et al., 2011) or indirectly due to consequential changes in land use outside of the biofuel system from market forces linked to the biofuel production (Fritsche et al., 2010). One notable example of indirect land use change would be diversion of corn from food and animal feed to fuel ethanol production, which then may stimulate natural land types to converted to corn production (Haag and Mill, 1987). Although studies have been conducted to indicate the high variability of environmental impacts during cultivation of algae feedstocks (Carlsson et al., 2007; Chisti, 2007; Handler et al., 2012), little thought has been given to the emissions from converting land to algal cultivation (Brentner et al., 2011; Frank et al., 2011), or it has been assumed emissions are negligible compared to other life cycle stages (Clarens et al., 2011; Stephenson et al., 2010). Lardon et al. (2009) estimated that land use of algae biodiesel is low compared to other biofuels, which roughly 1/6 to rapeseed biodiesel and 1/10 to soybean derived diesel. The author concluded that this considerably low land use impact was a result of the high algae biomass yield, algae oil content, and oil production rate compared to other biomass feedstocks. This comparison of land use for different biofuels systems in Lardon et al. (2009) is also an example of how traditional life cycle assessment has typically dealt with land use as primarily an issue of land occupation, thereby removing that land from other productive uses. Recent land use change studies attempt to evaluate the impact of land transformations and hold the new products being grown on the land accountable for those impacts.

A recent comprehensive government report authored by members of U.S. national laboratory research teams, including Argonne National Laboratory, Pacific Northwest National Laboratory, and the National Renewable Energy Laboratory, attempted to standardize assumptions regarding the current performance baseline in algae biofuels production to present an accurate picture of the environmental, economic, and resource implications of large scale algae production in the U.S. Gulf Coast (ANL et al., 2012). In this study, the unit operations involved in producing renewable diesel (RD) from algae included open pond cultivation, dissolved air flotation harvesting, centrifugation for dewatering, solvent oil extraction followed by hydrotreatment to renewable diesel, without considering impacts due to land use change. Greenhouse gas emissions for the baseline scenario were 63.9 g CO_{2eq}/MJ RD, but emissions could vary by more than 5 g CO_{2eq}/MJ RD depending on the growing seasons and in different regions.

In spite of the progress in understanding GHG emissions from algae-biofuel production systems, research on the environmental impacts of LUC emissions from algae cultivation remains lacking in the literature. The study reported here utilized methodology adopted by the Intergovernmental Panel on Climate Change (IPCC) to evaluate several scenarios (IPCC, 2006a) to quantify the range of potential GHG emissions due to direct LUC in algal cultivation systems. IPCC Tier 1 methodology was used to assess potential emissions resulting from conversion of U.S. Gulf Coast grassland, cropland and forestland in several management conditions. This assessment was enabled by the prior national laboratory (ANL et al., 2012) comprehensive report that evaluated promising sites for algae raceway development in the Gulf Coast region of the USA, and provided a detailed, geographically specific example of what a large scale algae industry might look like. The objective of this study was to provide a more comprehensive view of the life cycle GHG emissions that can be expected from large scale algae cultivation by quantifying direct LUC emissions (hereafter referred to simply as LUC), and also provide guidance to stakeholders and planners when selecting promising sites for algae cultivation.

2. Methods

In the national laboratory report (ANL et al., 2012) to harmonize environmental, economic, and resource assumptions surrounding algae production, the resource assessment team at Pacific Northwest National Laboratory conducted a nationwide review for algae facility locations that had favorable characteristics like sunlight, slope, freshwater availability, and proximity to other relevant supporting infrastructure for oil and fuel distribution. They identified 4492 sites, across the Gulf Coast and Georgia, as the most promising areas. Among the data gathered by PNNL was the predominant current land use classification, and the potential facility locations were classified as either 'cropland', grassland', 'forestland', or 'marginal/barren' as a primary approximation for site characterization. Barren land has been defined by the IPCC as being land that is no longer being managed for useful purposes (IPCC, 2006b), but definitions of what constitutes marginal lands are often context-specific, as the term usually relates to the relative productivity of comparable lands.

In this study, the LUC impact on GHG emissions was analyzed across the range of potential locations that were deemed suitable for algae cultivation. Although each of the identified sites are large (485 ha) and likely contain several land use classes, sites were only classified according to primary land use classification. Fig. 1 shows the potential locations of these sites, which are mostly located in the Gulf Coast area.

2.1. Goal and scope definition

The goal of this study is to weigh the importance of land use change considerations in large-scale algae cultivation. The direct LUC emissions of algae feedstock cultivation will be summarized for conversions of grassland, cropland, and forestland, respectively. Scenarios will encompass particular combinations of location and prior land use type, in order to compare the potential LUC emissions resulting from different lands in different climate, regions, under different current management conditions. The functional unit for this analysis is defined as 1 MJ of algae-based renewable diesel.

2.2. Life cycle inventory analysis

The IPCC has issued guidelines on the methods that should be used to evaluate national greenhouse gas inventories for a variety of sectors, including land use change. IPCC guidelines are published for different tiers of accuracy, based on the availability of national or regional-scale data or more in-depth modeling assessments of biomass and soil carbon changes (IPCC, 2006b). Tier 1 include simple methods with default values. Tier 2 are similar approaches but with country specific emission factors and other related data. Tier 3 are carried out with more sophisticate approaches and models, while compatible with the lower tiers. As an initial estimate, Tier 1 guidelines are used here, with the default IPCC values for biomass and soil carbon based upon different soil types, climate regions, and management practice of the areas in question.

IPCC Tier 1 guidance provides the estimates of soil organic carbon stocks based on 30 cm depth while limited data are available at Tier 2 for greater depth (IPCC, 2006c). Design of algae