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Determination of the life cycle climate change impacts of land use and albedo change in algal biofuel production

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ABSTRACT

Geographic factors including land use change (LUC) impacts could significantly affect the sustainability of algal biofuels. Life cycle assessments (LCAs) of algal biofuels must evolve in their methodology in order to more accurately reflect the spatial and temporal heterogeneity of environmental impacts, which includes impacts arising from direct LUC. In this study, LCA methods were developed to integrate climate change impacts of direct LUC associated with cultivation of microalgae in open ponds and the effects of temporal and geographic variables on algal growth. The climate change impacts of LUC include the impacts of changing the surface albedo of an area, changing the carbon flux on the land, and removing the original biomass from the transformed land. Two LCA cases were analyzed for algal biofuel feedstocks production in climatically similar regions: the Everglades ecoregion and the Tamaulipas-Texas Semi-Arid Plain ecoregion. The relative contributions of foreground fuel production processes and LUC to the life cycle climate change impacts of renewable gasoline from microalgae were compared. Site-specific GIS data was collected to model algal production on potentially available land for the two case studies. The LUC impacts arising from albedo change and carbon flux change contributed significantly to the life cycle climate change impacts and differed between the two climatically similar regions. The baseline life cycle climate change impacts of algal renewable gasoline production with LUC impacts in the Everglades are 33.8% higher than those of conventional gasoline, while production in the Tamaulipas-Texas Semi-Arid Plain leads to 8.97% lower life cycle climate change impacts. The inclusion of LUC impacts increased the mean result and the range of the Monte Carlo simulations for both ecoregions. This methodology can help assess the geographically specific sustainability of algal biofuels on a life cycle basis and can guide siting decisions for algal biofuel feedstock production.

1. Introduction

Life cycle assessments (LCAs) enable scientists to compare the environmental impacts of biofuels to those of petroleum fuels and to identify production aspects that can be optimized to lower environmental impacts. An LCA for biofuels can produce more complete and location-specific results with the inclusion of spatially explicit data [1,2], such as climatic variables that affect feedstock production and land use change (LUC) impacts [3–5].

LUC impacts have been shown to play a significant role in the results of LCAs of crop-derived biofuels [6,7]. Notably, Searchinger et al. demonstrated in 2008 that the production of corn ethanol and switchgrass-derived biofuels creates substantially greater life cycle greenhouse gas (LC-GHG) emissions than the production of conventional gasoline when indirect LUC impacts are considered [3]. Indirect LUC impacts arise from displacement of cropland into new cultivation areas when cropland is allocated to biofuel production. Unlike in most crop-based biofuel feedstock production systems, where food production on cropland is displaced, indirect LUC impacts may be minimized or avoided for algal biofuel feedstock production, which does not require arable land. Nonetheless, direct LUC impacts are still incurred; these include changes incurred during the initial transformation of a land area and during its occupation by the system investigated [8,9]. Three major direct LUC impacts that can be included into an algal biofuel LCA model are:

1. Removal of the original carbon stored in vegetation on the land during implementation of algal cultivation (a land transformation

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impact);
2. Change in the surface albedo of an area, for which a decrease in albedo induces a radiative forcing by affecting the shortwave radiation budget, thus contributing to climate change (a land occupation impact); and
3. Change in the fluxes of greenhouse gases during algal production compared to the original carbon cycling on the occupied land (a land occupation impact).

Although some LCAs of biofuels produced from algae have incorporated the calculated land area required for production of the functional unit as a separate impact category [10–13], none have examined the geographically-specific life cycle climate change impacts from direct LUC impacts.

A prominent study of the direct LUC impacts of crop-based biofuels by Fargione et al. (2008) determined the "carbon debt" incurred by converting existing land cover types to soy, palm, and corn cropland for biodiesel and ethanol production [7]. The land cover types that were considered for conversion to biofuel feedstock cultivation in this analysis were Amazonian rainforest, Brazilian woody cerrado, grassy cerrado, southeast Asian rainforest and peatland, US central grassland, US abandoned cropland, and US marginal cropland [7]. The Fargione et al. study considered the annual net primary productivity (NPP) of the original land cover in its calculations of "carbon debt" as well [7]. This approach has been used in multiple biofuel LCAs [14,15]. The Stratton et al. (2010) report assessed direct LUC impacts for multiple bio-jet fuel feedstocks (albeit not algae) primarily by using the data published by Fargione et al. (2008) [7,15]. The LUC impacts determined in the Stratton et al. report were subsequently incorporated into other LCAs, including a study by Caiazzo et al. (2014) which added albedo change impacts to LCA studies of numerous crop-based biofuels [16,17].

The approach used by Fargione et al. for direct LUC impacts can be improved with geographic datasets that have become available since its publication. When geographic datasets are available, they are preferable to single values pulled from multiple literature sources for their ability to adapt biofuel LCAs to various geographic contexts. For example, the above-ground biomass carbon values used by Fargione et al. for the Amazonian rainforest were averaged from two studies [18,19], one of which lists the measured above-ground biomass from 44 sites collected from 36 studies with varying methodologies published between 1957 and 1997 [18]. Through this method, the temporal and geographic sensitivity of these values is diminished and the source of the data and the data collection methodology are occasionally unclear. More recently, published biofuel LCAs, including LCAs that do not incorporate LUC impacts, have also begun to include more geographically specific data [1,2,5], such as GIS datasets for existing biomass on land and land cover types, and satellite data measured uniformly on a known temporal basis and with known precision and methodology over large geographic areas. Other LUC studies have developed methods that do not rely on the Fargione et al. data in order to include spatial heterogeneity. Elliott et al. (2014) presented a spatial modeling methodology to determine the LC-GHG emissions of specific crop-based biofuels arising from LUC that uses some similar datasets to those used in this analysis [5]. Many of these methods stem from the Argonne Carbon Calculator for Land Use Change from Biofuels Production (CCLUB), which is designed to determine the LC-GHG emissions from LUC impacts of producing ethanol from switchgrass, corn, miscanthus, and corn stover [20]. However, the impacts of albedo change and change in carbon flux were not included in this model.

The LUC impacts of algae require an adapted approach from the methodology for LUC impacts of crop-based biofuels. Microalgal feedstocks have a different harvesting schedule and can potentially be continuously harvested throughout a growing season, whereas most crops are harvested once per growing season. In addition to a difference in harvesting frequency, the surface of cultivation areas is different between crop-based and algal biofuel feedstocks, which subsequently affects their relative albedo change impacts. The surface of plant biomass defines the surface albedo of crops, while a water medium with suspended matter defines the surface albedo of open algal ponds. Microalgae may need non-fresh water and nutrient sources to lower the environmental impacts of production [11,13,17,21–27], which would require collocation with water and resource recovery facilities (WRRFs, also known as wastewater treatment plants or WWTPs) and implementation on the available land around these plants. The direct LUC impacts of algal biofuel feedstocks production will depend on the original conditions on the land adjacent to municipal WRRFs. The climate change impact associated with changing an area of land to algal ponds depends on the prior land cover, which can be determined for each site. Additionally, it is possible that the conversion of the same land cover type to algal ponds in different geographic regions would lead to different LUC impacts, due to differences in algal productivity and thus carbon fixation. A spatially explicit biofuel LCA must appropriately account for regional differences in factors that affect feedstock growth [2].

The objectives of this study are to develop a geographically specific algal biofuel LCA model that includes direct LUC impacts and to investigate the extent to which these LUC impacts contribute to the overall life cycle climate change impacts of renewable gasoline produced from wastewater algae. Two regional case studies were chosen due to their similarities in climate for algae production and due to their differences in land conditions (Table 1). The areas represent two EPA-designated Level II ecoregions: the Everglades and the Tamaulipas-Texas Semi-Arid Plain (Tamaulipas). With these two regions, the impact of direct LUC due to land conditions can be compared while controlling for algal productivity, which is dependent on temperature, solar radiation, and nutrient concentrations in wastewater.

2. Methods

An LCA model was developed in Python code for the determination of the life cycle climate change impacts of renewable gasoline produced through hydrothermal liquefaction (HTL) of microalgae cultivated in wastewater effluent (Fig. 1). Python codes were also developed and used for sensitivity analyses and Monte Carlo analyses. The LCA model determines the life cycle climate change impacts of 1 GJ of algal renewable gasoline based on 102 variable input parameters with minimum, baseline, and maximum values that are linked by equations to the functional unit. The parameters in Table 2 were the same for both case studies and are not geographically specific. The sources of these values are described in their respective Methods sections below.

Geographic data was collected for potentially available land within a 5-km radius of municipal water and resource recovery facilities (WRRFs) in two Level II ecoregions: the Everglades and the Tamaulipas-Texas Semi-Arid Plain (Tamaulipas). The Everglades ecoregion is at the southern tip of the state of Florida, and the Tamaulipas ecoregion is located in southwest Texas (Fig. 2). These regions have similar average temperatures and solar radiation, but they differ in their current net primary productivity (NPP), albedo, and above-ground biomass

Table 1
Comparison of existing land characteristics near wastewater treatment plants in the Everglades and the Tamaulipas-Texas Semi-Arid Plain ecoregions.

Characteristics	Everglades	Tamaulipas-Texas Semi-Arid Plain
Average monthly temperature range (°C)	18.81–28.37	12.60–30.14
Average monthly solar radiation range (kWh m^{-2} day^{-1})	3.959–5.994	3.974–6.089
Average above-ground biomass (kg m^{-2})	2.646	0.353
Average annual net primary productivity (kg m^{-2} $year^{-1}$)	3.191	0.425
Average monthly albedo range	0.1339–0.1467	0.1512–0.1633