A Geographical Assessment of Vegetation Carbon Stocks and Greenhouse Gas Emissions on Potential Microalgae-based Biofuel Facilities in the United States

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Abstract

The microalgae biofuels life cycle assessments (LCA) present in the literature have excluded the effects of direct land use change (DLUC) from facility construction under the assumption that DLUC effects are negligible. This study seeks to model the Greenhouse Gas (GHG) emissions of microalgae biofuels including DLUC by quantifying the CO₂ equivalence of carbon released to the atmosphere through the construction of microalgae facilities. The locations and types of biomass and Soil Organic Carbon that are disturbed through microalgae cultivation facility construction are quantified using geographical models of microalgae productivity potential including consideration of land availability. The results of this study demonstrate that previous LCA of microalgae to biofuel processes have overestimated GHG benefits of microalgae-based biofuels production by failing to include the effect of DLUC. Previous estimations of microalgae biofuel production potential have correspondingly overestimated the volume of biofuels that can be produced in compliance with U.S. environmental goals.

Keywords: Microalgae facilities. Carbon stocks. Direct Land Use Change. Greenhouse gas emissions.

1. Introduction

The cultivation of microalgae-based biofuel feedstocks have various advantages compared to conventional biofuels feedstocks including higher solar efficiency, high production rates, and utilization of low quality land (Wijffels & Barbosa, 2010). However, the conversion of undeveloped or low-quality land to microalgae cultivation has the potential to be a disadvantage

relative to conventional biofuels due to the environmental cost associated with land use change. For conventional biofuels, direct land use changes (DLUC) are a relatively minor component of the biofuels' life cycle greenhouse gas (GHG) emissions because conventional biofuels are often cultivated on preexisting dedicated croplands (Kendall & Chang, 2009). For example, the DLUC effects of switching from feed corn cultivation to ethanol corn cultivation are very small. In comparison, microalgae cultivation facilities are typically assumed to require the conversion of marginal agricultural, range, or undisturbed land, for which DLUC must be quantified to understand the impact on the life cycle emissions of the biofuel product.

A variety of research efforts have quantified the productivity potential and life cycle environmental impacts of microalgae biofuels. The results of these assessments are found to be highly sensitive to the siting of the modeled facility. Researchers have subsequently considered geographically-specific inputs to these LCAs including meteorological data, land types and availability, carbon dioxide (CO₂) accessibility, and more. The results of these efforts have been an evaluation of the localized life cycle impacts of microalgae-based biofuel facilities in the U.S. (Batan et al., 2013; Brentner et al., 2011; Frank et al., 2011; Quinn et al., 2013; Quinn & Davis, 2015; Sills et al., 2013; Vasudevan et al., 2012; Venteris et al., 2013; Wigmosta et al., 2011; Woertz et al., 2014). Sustainability results currently in the literature show algal based systems to have great potential. Combining land and CO₂ availability microalgae has the capability to produce 44 billion gallon per year in the U.S. (Quinn et al., 2013). The water footprint of microalgae biofuels when optimally sited is comparable to that of other biofuels 80-291 m³.GJ⁻¹ (Batan et al., 2013; Dominguez-Faus et al., 2009; King & Webber, 2008; Mekonnen & Hoekstra, 2011; Wu et al., 2009; Yang et al., 2011). The environmental impact of algal systems as assessed through net energy ratios and net GHG emissions of microalgae of well-developed

facilities are favorable relative to petroleum-derived and biofuels ranging between -0.74-0.93 MJ consumed·(MJ produced)⁻¹; and between -95.7 to 534 gCO₂eq.MJ⁻¹ (Adesanya et al., 2014; Azadi et al., 2014; Batan et al., 2010; Brentner et al., 2011; Campbell et al., 2011; Collet et al., 2014; Frank et al., 2013; Grierson et al., 2013; Handler et al., 2014; Liu et al., 2013; Passell et al., 2013; Ponnusamy et al., 2014; Quinn et al., 2014; Shirvani et al., 2011; Sills et al., 2013; Soh et al., 2014; Vasudevan et al., 2012; Woertz et al., 2014). None of the cited studies have taken into consideration the DLUC associated with the construction of the biofuel facilities. Canter et al. (2014) investigated the emissions associated with the actual construction of the facility but do not consider emissions associated with the disruption of the soil. Ignoring DLUC in these analyses represents a discrepancy in boundary assumptions between microalgae life cycle assessments (LCAs) and the state of the art for conventional biofuels.

In general, DLUC has been shown to be a significant contributor to world-wide GHG emissions through the transport of CO₂ to the atmosphere from carbon stocks stored in soil and above ground biomass (AGB). Currently approximately 30% of anthropogenic carbon emissions are generated by deforestation and forest degradation (Goetz et al., 2009). Although DLUC is considered negligible in evaluating the environmental impacts of many 1st generation biofuels, for some particularly land-disruptive applications, DLUC has been demonstrated to have a significant effect on lifecycle emissions. For an example, gasoline and diesel produced from Canadian oil sand crude is estimated to result in 18% to 21% higher GHG emissions than U.S. conventional crudes, with the differences due primarily to DLUC (Cai et al., 2015). Recent remote sensing research has resulted in the development of datasets that can broadly represent the AGB and soil organic carbon (SOC) for not only forested, but also for the shrubland, and scrubland that are expected to be utilized for microalgae-based biofuel production facilities

(Kellndorfer et al., 2012; Quinn et al., 2013). There is a need to integrate available carbon stock data with microalgae based LCA to have a more holistic understanding of the environmental impact associated with biofuels derived from microalgae.

This study integrates AGB and SOC datasets with microalgae biofuels LCAs into a geographical assessment of the effect of DLUC on the life cycle GHG emissions of microalgae biofuels. The results and quantified sensitivities of this assessment allow insight into the relative importance of DLUC in assessing the sustainability of microalgae based biofuels facilities. Geographically resolved results can be used to quantitatively exclude environmentally-disadvantageous lands from consideration for microalgae biofuels cultivation. These methods and results represent the next level of fidelity in the critical assessment of microalgae biofuels on the metrics of environmental impact and will support long-term investment planning.

2. Materials and Methods

To evaluate the life cycle GHG emissions from microalgae-based biofuel facilities, inclusive of DLUC, carbon fluxes from microalgae cultivation and industrial processes must be taken into account (Batan et al., 2010), along with the carbon associated with disturbed AGB and Soil SOC release due to facility construction activities. The modeling workflow, illustrated in Figure 1, integrates the equivalent CO₂ emissions from these disturbances by applying the Intergovernmental Panel on Climate Change (IPCC) method simulated spatially across the U.S. By adding the effects of DLUC to the results of microalgae biofuels LCAs in literature, we can develop a more comprehensive assessment of the net GHG emissions of potential microalgae-based biofuel facilities in the U.S.

2.1 Spatial Inputs to Life Cycle Assessment and Direct Land Use Change Modeling

The AGB dataset is derived from the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) for biogeochemical dynamics, National Aeronautics and Space Administration (NASA) (Kelldorfer et al., 2012). The AGB, which is comprised of the dried matter of living organisms above ground (Mitchard, 2013), was utilized to obtain the land cover carbon, which is measured as tonnes of dried matter per hectare. The AGB maps of the U.S. and the potential microalgae-based biofuel facilities areas processed in our research is included in the supplementary material for three scenarios described below.

The potential locations for microalgae-based biofuel facilities and their lipid productivities are derived from previous research on siting of microalgae biofuels facilities as reported in Quinn et al. (2013). Only facilities of more than 400 contiguous hectares are considered. Three scenarios of land use constraints, each with progressively lower restrictions on siting, for locating microalgae biofuels facilities are considered wherein the facilities are only located on 1) barren land with slope of less than 1%, 2) barren land with slope of less than 2%, and 3) forest or pasture or barren areas with slopes of less than 5% (see supplementary material). The projection used for this geographical assessment is the North America Albers Equal Area Conic and the datum is the North American 1983.

To take into account the carbon disturbance in the soil due to the potential change in the land use, the total SOC estimated by the U.S. Department of Agriculture (USDA) in the total soil profile at 30 meters resolution has been incorporated in the carbon stocks balance of this assessment. These SOC maps are included in the supplementary information. By utilizing minimum microalgae facilities sizes of 400 Ha, the carbon stocks liberated by facility

construction can be well represented using AGB and SOC datasets at resolutions of 240 m and 30 m, respectively.

2.3 Spatial Analysis of Direct Land Use Change and Related Emissions

With these inputs, we use geographical information systems (GIS) tools to synthesize the spatial GHG emissions and environmental impacts of microalgae-based biofuels production across the US. This assessment incorporates the methods of the *Good Practice Guidance for Land use, Land-use Change and Forestry* of the Intergovernmental Panel on Climate Change (IPCC, 2014). Map-algebra was applied to calculate the carbon stocks from the attribute values of the AGB and the microalgae-based biofuel facilities:

$$L_{OL} = A_d * B_w * (1 - f_{BL}) * CF + SOC \quad (1)$$

L_{OL} represents the annual losses of carbon (tonnes of carbon per year); A_d is the vegetation areas affected by disturbance (hectares per year); B_w is the average biomass stock of ground cover areas (tonnes of dried matter per hectare); f_{BL} is the fraction of biomass left to decay in the environment (transferred to dead organic matter); and CF is the carbon fraction of dry matter (tonnes of carbon per ton of dried matter) (IPCC, 2014). The variable f_{BL} was assumed to be zero in this research as would be characteristic of an industrial facility, and CF is assumed to be 50% as recommended by the IPCC. SOC is derived from the USDA database as detailed in section 2.1. The value of A_d was obtained from the geographical assessment of microalgae biofuel potential included in the supplementary information.

The computed losses of carbon (L_{OL}) are converted to the equivalent CO₂ emissions by the ratio of molecular weights of CO₂ (MW_{CO_2}) and carbon (MW_C) (Mitchard, 2013). The CO₂eq produced due to land disturbance is amortized over the microalgae facilities' lifetime (T), which

is estimated to be 10 years, providing an annual equivalent CO₂ balance for the disturbed areas (tonnes of equivalent CO₂ per year) (IPCC, 2014):

$$CO_{2eq} = \frac{L_{OL} * \left(\frac{MW_{CO_2}}{MW_C} \right) - C_{FFG}}{T} \quad (2)$$

For comparison to an undisturbed condition, the CO₂ equivalent balance must take into account the annual increase in carbon stocks associated with accumulating AGB:

$$C_{FFG} = T * G_W * (1 + R) * CF \quad (3)$$

Where C_{FFG} is the annual increase in carbon stocks due to biomass increment (tonnes of carbon per year); T is the lifetime in years of the microalgae facilities, assumed to be 10 years in our research; G_W is the average annual AGB increment (tonnes of dried matter per hectare per year), 0.4 for barren areas and 0.8 for forest or pastures areas as derived from the IPCC guidelines; and R is the “root-to-shoot” ratio (ratios of belowground to aboveground biomass), 2.83 was assigned for barren areas and 0.48 for forest-pastures-barren areas as per IPCC guidelines.

2.4 Total GHG emissions

The results from the life cycle modeling, AGB and SOC, are combined for a total greenhouse impact quantified through the metric of CO_{2eq}. The GHG emissions due to DLUC are normalized by the functional unit of energy produced from microalgae-based biofuels. The energy production as a function of US geography is obtained from previous work pertaining to barren land areas in the U.S. (Quinn et al., 2013).

3. Results and Discussion

The results of this research are presented in three forms. First, this study quantifies the carbon that is disturbed through construction of microalgae-based biofuel facilities including both AGB and SOC. Second, by considering life cycle emissions to include both fuel production and DLUC emissions, we find that in many of the locations that are proposed for siting of algae based biofuel facilities, the environmental benefits of microalgae based feedstock are negated due to liberation of carbon stocks. We present examples at a state level and highlight microalgae cultivation locations that should be excluded from potential production studies due to DLUC emissions. Finally, by considering a variety of LCAs from the literature, we find that the liberation of carbon stocks is not a negligible component of microalgae biofuels LCAs. Inclusion of carbon stocks in LCA reduces the net GHG benefit of microalgae by between 3-85% for the most cited microalgae biofuels LCAs.

3.1 AGB and SOC disturbed by microalgae-based biofuel facilities

Using the metrics of AGB and SOC, the modeling results demonstrate that the barren land areas that have been selected in some of the previous microalgae cultivation research by Quinn et al. (2013) are consistent with low values of AGB and SOC. Studies by Venteris et al. (2013) and Wigmosta et al. (2011) that consider forested, or pasture lands as suitable for microalgae production will disturb AGB and SOC at higher rates per unit of land area. Using the methods of this study for the baseline scenarios, 1 tonne per hectare of AGB and SOC corresponds to 0.18 AGB plus 0.37 SOC for a total of 0.55 tonnes of CO₂eq per year, per hectare, equivalent to 5% of the life cycle GHG emissions savings associated with microalgae production over the 10 year life of the facility. We use these values of 1 tonne per hectare of AGB and SOC as the limits under which DLUC can be considered negligible.

When considering the construction of microalgae cultivation facilities (>400 Ha facility size) on barren lands with slopes of less than 2% as in Quinn et al. (2013), 95.4 % of these facilities are located at sites with less than one tonnes AGB per hectare. The mean AGB across the US under this land use scenario is 4.9 tonnes per hectare, the maximum is 1,500 tonnes per hectare. Considering SOC under the same land use limitations, 78% of the proposed microalgae cultivation land area has less than 1 one tonnes per hectare of SOC. Under this land use scenario, the mean SOC at the proposed microalgae cultivation facilities is 8.6 tonnes per hectare. If forested, pasture, and barren lands are considered available to build potential microalgae-based biofuel facilities, then only 64.1% of this land area has AGB of less than 1 tonne of biomass per hectare, and 88% of these areas have SOC of less than 1 tonne per hectare.

In summary, the majority of the land area available for microalgae cultivation under the land use scenarios proposed in previous research (Barren) has negligible quantities of SOC and AGB. Under the baseline land use limitation scenario (>400 ha facility size, US-wide cultivation on barren lands with slopes of less than 2%), between 5% and 22% of area under microalgae cultivation has greater than negligible GHG emissions due to DLUC. The fraction of the cultivation area with non-negligible DLUC GHG emissions increases under less-restrictive land use limitation scenarios as the SOC and AGB increase (see supplementary information).

3.2 Carbon stocks limit the locations available for sustainable microalgae-based biofuel cultivation

By ignoring the contribution of disturbed carbon stocks and DLUC in microalgae-based biofuel LCAs, previous researchers have overestimated microalgae productivity potential that can be realized with environmental benefits. In this section, we combine the area-specific DLUC-associated GHG emissions with an area-specific lipid productivity model derived from

Quinn et al. (2013), to present results in the form of energy-specific GHG emissions (in units of $\text{gCO}_2\text{eq MJ}^{-1}$).

From the results of this geographical assessment, we find that previously selected barren land areas for algae-facilities have DLUC-associated, functional unit-specific, GHG emissions ranging from 3 to $802 \text{ gCO}_2\text{eq MJ}^{-1}$. **Figure S6** presents the distribution of DLUC-associated GHG emissions as a cumulative distribution of land area in the US. More than 99% of the proposed cultivation areas under the baseline land use restriction scenario have DLUC-associated GHG emissions of less than or equal to $100 \text{ gCO}_2\text{eq MJ}^{-1}$. **Figure 2** presents the functional unit-specific, GHG emissions of the 13 LCA studies that posit net GHG *benefits* for microalgae cultivation as reviewed by Quinn and Davis (2015). The GHG emissions benefits from each study can therefore be compared to the fraction of US microalgae cultivation area (under the baseline land limitation scenario) to determine the fraction of the US microalgae cultivation area where the GHG benefits of microalgae biofuels production including DLUC are less than zero. For example, consider the LCA results documented in Frank et al. (2013), wherein microalgae cultivation and fuels production was found to have a net GHG emissions benefit of $20 \text{ gCO}_2\text{eq MJ}^{-1}$, without consideration of DLUC. Moving vertically along the $20 \text{ gCO}_2\text{eq MJ}^{-1}$ line to the intercept with the cumulative distribution function, we can find that on 83% of the proposed microalgae cultivation area, DLUC GHG emissions are less than the GHG emissions benefits of microalgae biofuels production. Consequently, on 17% of the proposed microalgae cultivation area, the GHG emissions benefits of microalgae biofuels production are completely negated by DLUC.

Using the methods of this study, we can make similar evaluations on a state-by-state level with the understanding that microalgae facility siting will perhaps be localized to states with

particularly amenable climate and geography. For each case considered here, we restrict microalgae production facilities to be sited on >400 Ha sites, on barren land with slope of less than 2%. **Figure S7** presents the DLUC-associated GHG emissions from microalgae production in Arizona, where the median GHG emissions due to DLUC is 9 gCO₂eq MJ⁻¹, and **Figure S8** shows that Florida has a median DLUC-associated GHG emissions of 17 gCO₂eq MJ⁻¹. The distribution of GHG emissions for these states compared to literature are presented in **Figure 3**.

These results can be used to assess the tradeoff between microalgae productivity potential and DLUC-inclusive GHG emissions. Many studies of microalgae productivity potential have selected locations for production facilities where the disturbance of AGB and SOC can negate the GHG benefit from algae biofuels production (Davis et al., 2014; Venteris et al., 2013; Wigmosta et al., 2011). For example, although Venteris et al. (2013) highlighted the state of Florida as an ideal place for microalgae-based biofuel technology their models neglected the impacts of DLUC on land availability. This lead to their recommendation to allow microalgae cultivation on forested and rangelands, which would have even higher DLUC environmental impacts than presented here (see the supplemental material for other land restriction scenarios). By neglecting DLUC, previous microalgae productivity potential studies have overestimated the amount of microalgae that can be produced while maintaining a net GHG benefit.

3.3 Including DLUC reduces GHG benefit of microalgae biofuel

By neglecting the contribution of disturbed carbon stocks to microalgae-based biofuel life cycle GHGs, previous research has also underestimated the life cycle GHG emissions of microalgae-based biofuels that can be achieved at scale. In order to understand the effect of DLUC on the net GHGs of microalgae biofuels, we can compare the distribution of DLUC-

specific GHG emissions to the GHG emissions of the microalgae biofuels production process in the context of the US Renewable Fuel Standards policy.

The US Renewable Fuel Standard requires that Advanced Biofuels achieve a 50% life cycle GHG emissions reduction relative to the life cycle GHG emissions of conventional diesel (50% of $92 \text{ gCO}_2\text{eq MJ}^{-1}$ equals $46 \text{ gCO}_2\text{eq MJ}^{-1}$) (EPA., 2016). To allow a direct comparison to the well-to-pump results that are presented in the microalgae biofuels literature, we can subtract the pump-to-wheels GHG emissions associated with biodiesel of $73.6 \text{ gCO}_2\text{eq.MJ}^{-1}$. This calculation suggests that any microalgae biofuels facility that is sited such that its DLUC-inclusive well-to-pump GHG emissions are greater than $-27.6 \text{ gCO}_2\text{eq.MJ}^{-1}$, will be ineligible for Low Carbon Fuel Standard credits and its corresponding economic benefits. This comparison is presented in **Figure 4**. In this case, all of the LCAs from literature that do not meet the RFS Advanced Biofuels criteria (without DLUC) are removed from consideration. Again, we can compare the scale of the GHG emissions savings from microalgae biofuels production to the GHG emissions produced due to DLUC. For example, were Florida's barren land to be developed without consideration of its carbon stocks (leading to a statistically average DLUC contribution of $17 \text{ gCO}_2\text{eq.MJ}^{-1}$), then the net DLUC-inclusive GHG emissions of the studies of Quinn et al. (2014) and Campbell et al. (2011) would both not be able to meet the requirements of the US Renewable Fuel Standard Advanced Biofuels as their net GHG emissions benefits are less than $27.6 \text{ gCO}_2\text{eq.MJ}^{-1} + 17 \text{ gCO}_2\text{eq.MJ}^{-1} = 44.6 \text{ gCO}_2\text{eq.MJ}^{-1}$.

4. Conclusions

The GHG emissions from DLUC have been demonstrated to be a significant determinant of microalgae biofuels GHG emissions and the selection of geographical locations for the

sustainable production of microalgae-based biofuels. DLUC should be considered in future microalgae-based biofuels LCA and scalability assessments.

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Figure Captions:

Figure 1. System boundaries and analysis flowchart for calculation of GHG emissions ($\text{gCO}_2\text{eq.MJ}^{-1}$) due to DLUC based on GIS model of microalgae-based biofuel facilities in the U.S.

Figure 2. Cumulative distribution of potential US microalgae-based biofuels facilities' DLUC-inclusive GHG emissions ($\text{gCO}_2\text{eq.MJ}^{-1}$) and well-to-pump (excluding DLUC) GHG emissions benefits associated with microalgae biofuels production as represented in literature. The modeled algal biofuel scenario is based on a land restriction of barren and slop of $<2\%$.

Figure 3. The functional unit-specific, well-to-pump GHG emissions (excluding DLUC) of the 13 LCA studies that suggest net GHG benefits for microalgae cultivation can be compared to the cumulative distribution of GHG emissions due to DLUC for the U.S, and the states of Arizona and Florida.

Figure 4. The functional unit-specific, well-to-pump GHG emissions (excluding DLUC) of the 8 LCA studies with net GHG benefits that meet the RFS Advanced Biofuels Criteria (without DLUC) for microalgae cultivation can be compared to the cumulative distribution of GHG emissions due to DLUC for the U.S, and the states of Arizona and Florida. The limit of $-27.6 \text{ gCO}_2\text{eq.MJ}^{-1}$ represents the well-to-pump equivalent limit that allows microalgae based biofuels to receive Low Carbon Fuel Standard credits.

Figure 1

Figure 2

Figure 3

Figure 4