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LETTER

Algal food and fuel coproduction can mitigate greenhouse gas emissions while improving land and water-use efficiency

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Keywords: integrated assessment, algal biofuels, algal food, land use change, bioenergy, carbon mitigation pathways, agriculture

Supplementary material for this article is available online

Abstract

The goals of ensuring energy, water, food, and climate security can often conflict. Microalgae (algae) are being pursued as a feedstock for both food and fuels—primarily due to algae's high areal yield and ability to grow on non-arable land, thus avoiding common bioenergy-food tradeoffs. However, algal cultivation requires significant energy inputs that may limit potential emission reductions. We examine the tradeoffs associated with producing fuel and food from algae at the energy–food–water–climate nexus. We use the GCAM integrated assessment model to demonstrate that algal food production can promote reductions in land-use change emissions through the offset of conventional agriculture. However, fuel production, either via co-production of algal food and fuel or complete biomass conversion to fuel, is necessary to ensure long-term emission reductions, due to the high energy costs of cultivation. Cultivation of salt–water algae for food products may lead to substantial freshwater savings; but, nutrients for algae cultivation will need to be sourced from waste streams to ensure sustainability. By reducing the land demand of food production, while simultaneously enhancing food and energy security, algae can further enable the development of terrestrial bioenergy technologies including those utilizing carbon capture and storage. Our results demonstrate that large-scale algae research and commercialization efforts should focus on developing both food and energy products to achieve environmental goals.

Introduction

The steady improvement in agricultural yields during the 20th century has increased food security (Evenson 2003) and limited agricultural and land-use change (LUC) greenhouse gas emissions (Burney *et al* 2010). However, future yield improvements may not be sufficient to achieve climate goals while meeting food demand (Tilman *et al* 2011). The use of terrestrial crops as feedstocks for biofuels places additional pressure on food production (Searchinger *et al* 2015) and could lead to increased LUC (Searchinger *et al* 2008, Melillo *et al* 2009, Wise *et al* 2009) and water use (Hejazi *et al* 2015). Microalgae (algae) have been proposed as an alternative source of biofuel due to productivity yields that are an order of magnitude higher than terrestrial crops (Moody *et al* 2014). However, the large energy and resource requirements (Quinn and Davis 2014) of algal cultivation constrain potential life-cycle emission reductions and increase the cost of production (Sills *et al* 2013, Beal *et al* 2015).

The use of algal biomass as a source of animal or human food offers an alternative revenue stream and additional avenues for reducing emissions and other environmental impacts. Animal feed trials have demonstrated that whole and defatted algal biomass can substitute a significant portion of both corn and soy in the diets of cattle, pigs, chicken and salmon (Drewery *et al* 2014, Ekmay *et al* 2014, Gatrell *et al* 2014, Kiron *et al* 2016) (and additional research summarized in the SI). Further nutritional research and product development will be necessary before algal food products are widely adopted in animal and human diets. However, given the variety of strains, cultivation options and processing methods, it is conceivable that algae could be produced to meet or exceed the nutritional value of conventional animal feed and human food products (Lum *et al* 2013).

Even if algal biomass were to be developed as a food product, oils extracted from the biomass could be used as an energy source (Beal *et al* 2015). In this co-production scheme, the extracted oils are upgraded to a renewable diesel fuel that would replace conventional diesel, while the residual defatted algal biomass is used as a food product to substitute for conventional agricultural crops. This approach may more optimally take advantage of the energy-rich (i.e. lipids) and nutritious (i.e. protein, carbohydrates) portions of the algal biomass. The sale of algal food products could improve commercialization potential by providing access to markets more lucrative than energy (Bryant *et al* 2012, Gerber *et al* 2016).

Large-scale production of algal food and fuel products could have significant impacts on global energy, agricultural and land markets, leading to significant changes in global resource demands and greenhouse gas emissions (Efroymson *et al* 2016). Accounting for the impacts from the offset of fossil fuels typically focuses on the direct relative reductions in carbon emissions per unit of energy consumed (Sills *et al* 2013, Quinn and Davis 2014). Assessing the impacts of offsetting conventional agriculture is more complex and includes: changes to land, water and nutrient use; temporally variable impacts on greenhouse gas emissions associated with LUC and agriculture; and, changes to food production levels.

This study evaluates these impacts under the analytical framework of an integrated assessment to show the benefits and drawbacks of three different post-cultivation uses of algal biomass grown in salt water on non-arable land:

1. the co-production of commodity food products along with diesel fuel (FD + FL) via an oil extraction and upgrading process (figure S1(A));
2. the thermochemical conversion of whole algal biomass to diesel fuel via hydrothermal liquefaction and upgrading (FL) (figure S1(B)); and,
3. the use of whole algal biomass as food (FD) (figure S1(C)).

While all pathways require significant energy and nutrient inputs, each has different resource demands and production potentials. In particular, the FL pathway features lower nutrient and energy use, stemming from the recycling of the residual non-lipid biomass. In contrast, the FD + FL and FD pathways provide nutritional products and offset conventional agricultural production, but require significant nitrogen and phosphorus inputs. While these pathways are not currently economical for the markets analyzed in this study (Beal *et al* 2015), this assessment analyzes the impacts of these pathways on global energy and agricultural markets to identify indirect impacts not typically included in a primary economic or life-cycle assessment.

Methods

This integrated evaluation of the tradeoffs for the three uses of algal biomass (FL, FD + FL, and FD) assesses each pathway's impact on several key economic and environmental indicators: food production, land use, water footprint, nutrient use, and emissions. Here we use these indicators to evaluate tradeoffs at the nexus of energy, food, water, and climate. While these indicators are a subset of identified environmental and socioeconomic indicators for industrial scale algal production (Efroymson and Dale 2015, Efroymson *et al* 2016), they represent the commonly utilized indicators in various global assessments of agriculture and bioenergy.

We use the Global Change Assessment Model (Kim *et al* 2006) (GCAM, version 4.0 R5465) to compare the direct and indirect impacts of the three different post-cultivation pathways summarized above. GCAM is a dynamic-partial equilibrium integrated assessment model capable of long term, global analysis of regional energy, agriculture and land use systems under different climate policy scenarios (e.g. CO_2 tax). For this analysis we use GCAM to evaluate food and energy production changes, nitrogen use, greenhouse gas emissions and radiative forcing (to time-integrate the impact of several greenhouse gases and LUC emissions). We extend our analysis to other resource impacts using life-cycle inventory data for phosphorus (Weidema *et al* 2013), and water footprint factors (Mekonnen and Hoekstra 2011).

Separate technologies for each algal pathway mentioned above, were implemented in GCAM based on demonstrated cultivation results (Huntley *et al* 2015) and detailed life cycle inventory data (Beal *et al* 2015). In the food producing pathways, food products are assumed to be perfectly substitutable for corn and oil crops in GCAM, based upon the results of animal feed trials (Drewery *et al* 2014, Ekmay *et al* 2014, Gatrell *et al* 2014, Kiron *et al* 2016). The fuel producing pathways model the thermochemical conversion via hydrothermal liquefaction (Jones *et al* 2014) (FL) or wet extraction (Beal *et al* 2011) (FD + FL) of algal biomass to yield lipids which are subsequently upgraded to green diesel fuel via a hydrotreatment process. This fuel is treated as a refined liquid in GCAM. Cultivation and processing requirements to generate these products (table S4) were explicitly modeled in GCAM for electricity, heat (natural gas), and nitrogen fertilizer. In this study we model the use of grid electricity, rather than dedicated low-emissions electricity sources, under the conservative assumption that electricity is a perfect commodity, and that the dedication of low-emissions electricity sources would come at an opportunity cost to using such sources for reducing the emissions intensity of grid electricity. Nutrient (N, P and CO_2) requirements for each pathway (Beal *et al* 2015, Huntley *et al* 2015) were used to calculate demands for these resources. The production of N-fertilizer also generates emissions which along with electricity and heat requirements are reported here in aggregate as algal production emissions.

The economic and environmental impacts of these post-cultivation pathways are evaluated in two illustrative production target cases. Impacts are presented in comparison to a no-algae reference case which favors conventional fossil fuels to meet global refined liquid demands. All cases include a constant terrestrial biofuel production of 5.0 EJ yr^{-1}, to account for the market impacts and land footprints of existing terrestrial biofuels estimated from current trajectories (FAO and OECD 2015) and mandates such as the United States Renewable Fuel Standard (110th Congress of the United States of America 2007). In each case, production targets are fixed and are achieved regardless of the price of algal products. This is comparable to a mandate policy, but is intended to be used here as an experimental design and control rather than serve as an evaluation of a specific policy regime.

The *energy target* case is used to compare the relative emissions and resource requirements of pursuing a fuel-only (FL) strategy versus a co-production strategy (FD + FL) for the production of renewable diesel biofuel. This case is intended to forecast aggressive industry growth that begins with 1.1 EJ yr^{-1} of output in 2025 and linearly scales to achieve an energy-production target of 27.7 EJ yr^{-1} in 2050 (figure S2). Production at this level then held constant in future years. Combined with the 5.0 EJ yr^{-1} baseline terrestrial biofuel production, total biofuel production (32.7 EJ yr^{-1}) from 2050-onward is consistent with biofuel targets for a 2 °C climate warming energy scenario (International Energy Agency 2015). When the energy target is achieved by the FD + FL pathway, food production is sufficient to nearly displace all corn and oil crops. While the implementation of these pathways in this case is ambitious, USA production levels (~10% of global production) are consistent with algal fuel production levels that have been assessed as possible, but potentially economically challenging (Venteris *et al* 2013, 2014a, 2014b). We also use a *biomass target* case to elucidate temporal scales of emissions impacts associated with the uses of biomass in the FD + FL, FL and FD pathways. Here we fix algal biomass production at 500 Mt yr^{-1} (table S1) from 2025 onward. These target cases are ambitious given the state of the algal cultivation technologies and lack of commercial success for commodity scale algal cultivation. However, such preliminary analysis of nascent technologies is critical for transparent evaluation of the opportunities and risks associated with technology deployment.

Impacts for each case are evaluated under two emissions-policy scenarios: a high carbon-intensity scenario (HI), which results in a radiative forcing of 7.5 W m^{-2} in 2100; and a low carbon intensity scenario (LI) implemented using a universal carbon price on fossil fuel and LUC emissions, which results in a reference pathway radiative forcing of 4.5 W m^{-2} (Thomson *et al* 2011). These alternative scenarios are primarily used to demonstrate the impacts of alternative global electricity mixes, which will subsequently influence production emissions due to the high electricity demand of algal cultivation. Additional detail on all assumptions, technology parameters, scenarios, modeling and validation is provided in the supplementary information.

Results and discussion

Impacts on net emissions from energy use and fuel offsets

Algae have been pursued as a source of diesel and jet-type liquid fuels due to many species' ability to produce high concentrations of lipids (Chisti 2007). The processes modeled in the fuel-generating pathways (FD + FL or FL) produces a diesel product from such lipids that displaces conventional refined liquid fossil fuels in the global energy market. The carbon for these fuels, is fixed as lipids in the algal biomass (as opposed to excretory production), and ultimately originates from the delivery of waste CO_2 as a feedstock nutrient during cultivation. Since such carbon waste streams are currently emitted into the atmosphere, current life-cycle assessment practices treat algal carbon and derived fuels as biogenic, contributing net zero emissions (Frank *et al* 2011). The substitution of a fossil carbon fuel with a biogenic carbon (algae) fuel, thus, results in a net offset of emissions (figures 1 and 2).

However, algal cultivation and processing requires substantial electricity inputs for CO_2 delivery, water pumping and circulation. This results in an emissions profile for algal production that is both large and highly sensitive to the emissions-intensity of the electricity used for production (Beal *et al* 2015), modeled here using grid electricity. Thus in a few GCAM regions representing developing economies with high emitting electricity sources, algal production

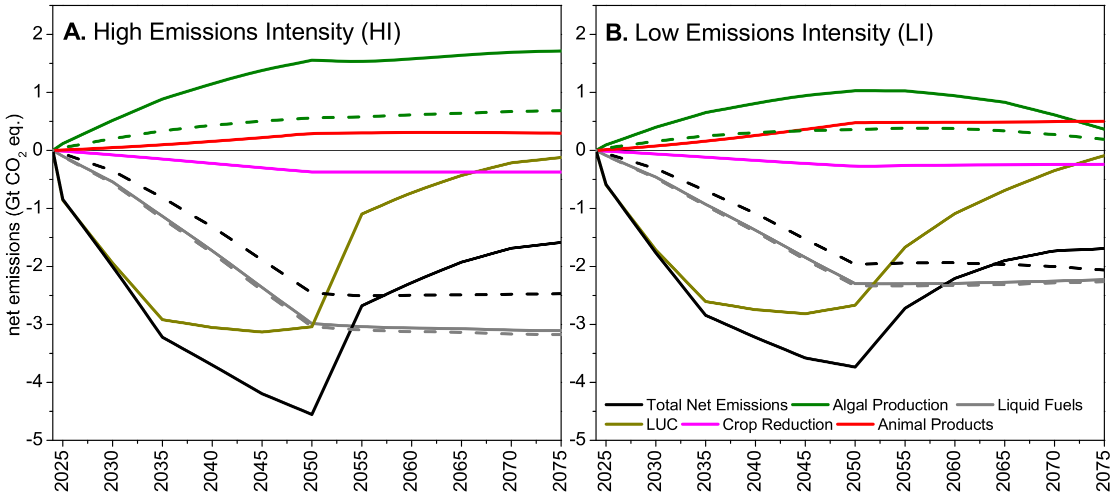

Figure 1. Emissions impacts (relative to no-algae reference pathway) of achieving a 2050-onwards energy target of 27.7 EJ with the FD + FL (solid lines) and FL (dashed lines) pathways under a high emissions intensity scenario (A) and a low emissions intensity scenario (B). Algal production grows linearly starting in 2025, achieving total biomass production of 1.7 and 3.1 Gt in 2050 onward for the FL and FD + FL pathways respectively. Due to the high energy demand the FL pathway promotes some small indirect effects in the agricultural and LUC sectors, these are omitted for clarity.

emissions exceed offset savings in the first few years. However, as regional carbon intensities decline, all regions achieve offsets that are greater than production emissions (figures 1 and 2). Furthermore, due to a proliferation of low-emission intensity sources under the LI scenario, emissions from algal production are lower than in the HI scenario. However, the net benefit of this reduction in algal production emissions is not translated to a significant net savings, as offset liquid fuels in this scenario are themselves less carbon-intensive in the LI scenario.

Reducing either the energy demand of algal production or the carbon intensity of energy used in algal production is thus critical to maximizing net emissions reductions. In particular, increases in algal productivity are necessary for improving economics in addition to lowering life-cycle production emissions (Gerber *et al* 2016). Efficiency improvements from water delivery and circulation, and carbon transport would also be beneficial (Beal *et al* 2015). However, if dedicated energy sources with zero emissions were used for cultivation and processing, productivity and efficiency improvements would become irrelevant in reducing emissions, although such improvements would still influence overall production economics. The LI scenario demonstrates this situation: as the emissions intensity of grid electricity approaches zero, the savings generated by yield improvements becomes smaller in comparison to the HI scenario (figure S7).

Even under the most optimistic scenarios for the carbon intensity of heat and electricity used to produce algal products, the primary energy demands for algal cultivation are likely to remain high leading to poor energy returns on energy invested. This may continue to challenge algae as a fuel source. Still, despite these high energy requirements, algae could play a role in mitigating emissions, especially in sectors that have more challenging carbon abatement potentials, such as agriculture.

Emissions savings from avoided land use change

For the illustrative purposes of this assessment, we assume that algal food products are perfectly substitutable for commodity corn and oil crops. With algal production levels fixed for this analysis, a surplus of food product is created causing a displacement of corn and soy production, as well as other crops due to flexibility in animal diets (figure 4). If demand for such commodities is elastic, as modeled here for animal products that consume these crops but not for human consumption of these crops, then the total crop and animal product consumption increases (figures 4 and 5(A)) due to lower crop prices resulting from the added capacity (figure S5). In addition, under the 27.7 EJ energy target with the FD + FL pathway, algal food products would nearly displace all conventional corn and oil crops (figure 4). While it is difficult to imagine such a shift, we evaluated this case to elucidate the potential tradeoffs involved with large-scale production of algal food and fuel.

Since we assume that algae have no arable land footprint, they do not compete with conventional crops for land. However, even if we assume that algae are cultivated on arable land, algae's significantly higher areal productivity, compared to conventional crops (figure S3), would lead to similarly drastic shifts in agriculture's land footprint. Subsequently the presence of algae reduces the demand for agricultural crop land, enabling increases in forest, grassland, and pasture (figure 5(B)). Even though total land savings is lower in the LI scenario, the presence of a carbon tax promotes a conversion preference for forest over

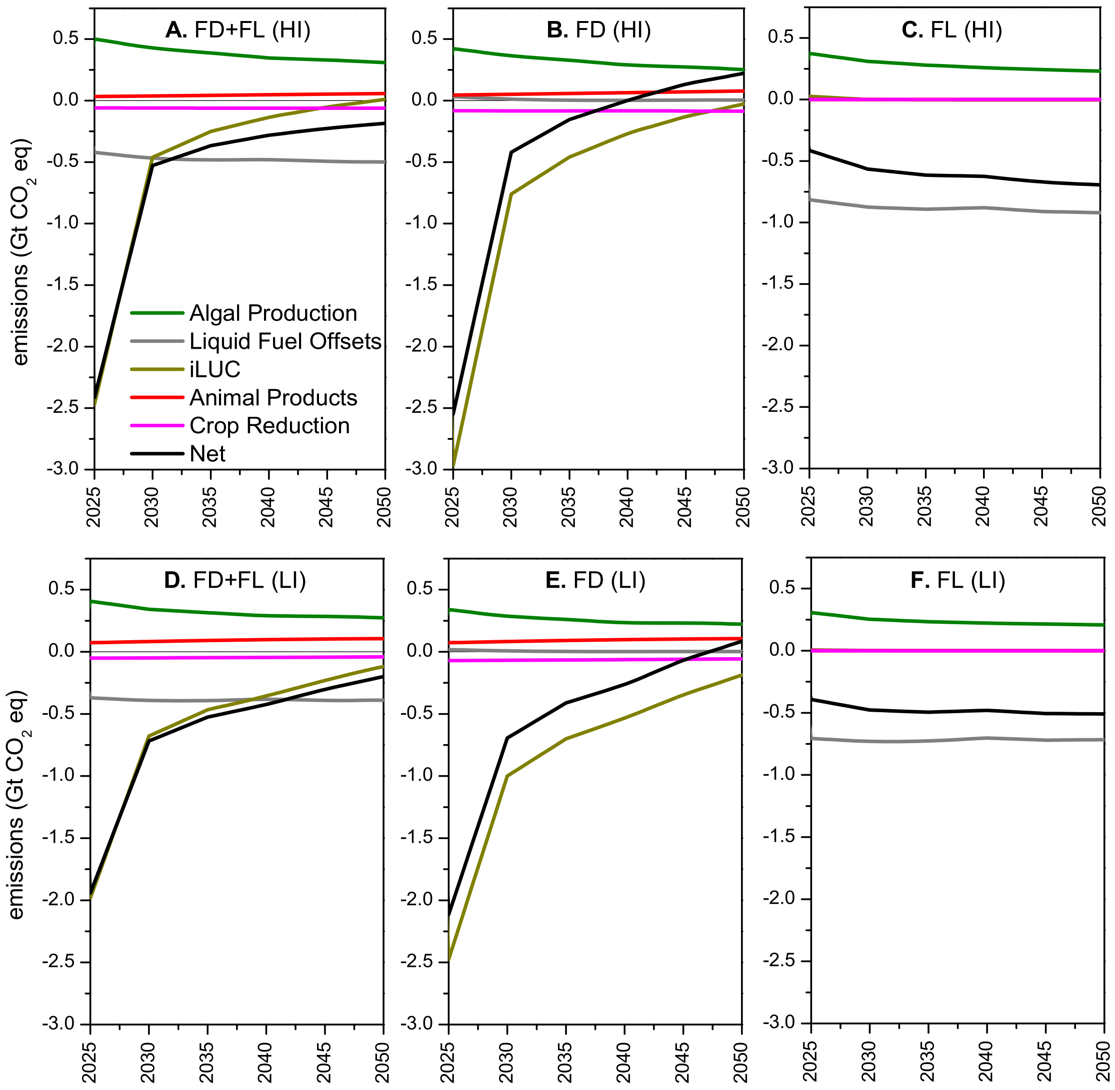

Figure 2. Emissions impacts (relative to no-algae reference pathway) for the first 25 years of constant (2025 onward) production of 500 Mt of algal biomass for the food + fuel (FD + FL, left panels), food (FD, middle panels) and fuel only (FL, right panels) pathways for the high carbon intensity (HI, top panels) and low carbon intensity (LI, bottom panels).

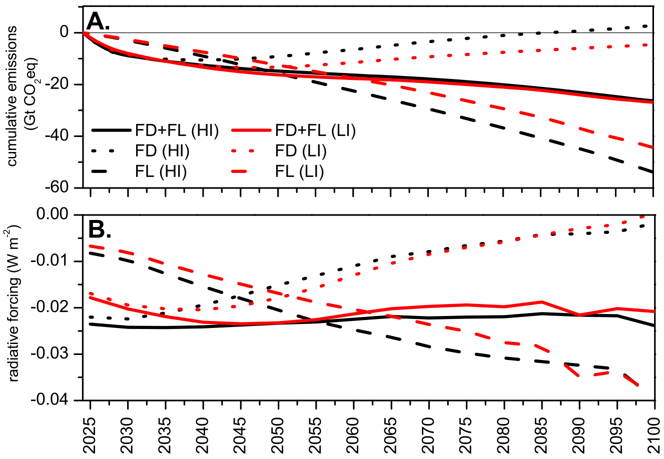

Figure 3. Long-term impact on cumulative emissions and radiative forcing (relative to no-algae reference pathway) for each pathway under high intensity (HI) (black) and low intensity (LI) (red) scenarios for the biomass target scenario (500 Mt algal biomass constant production).

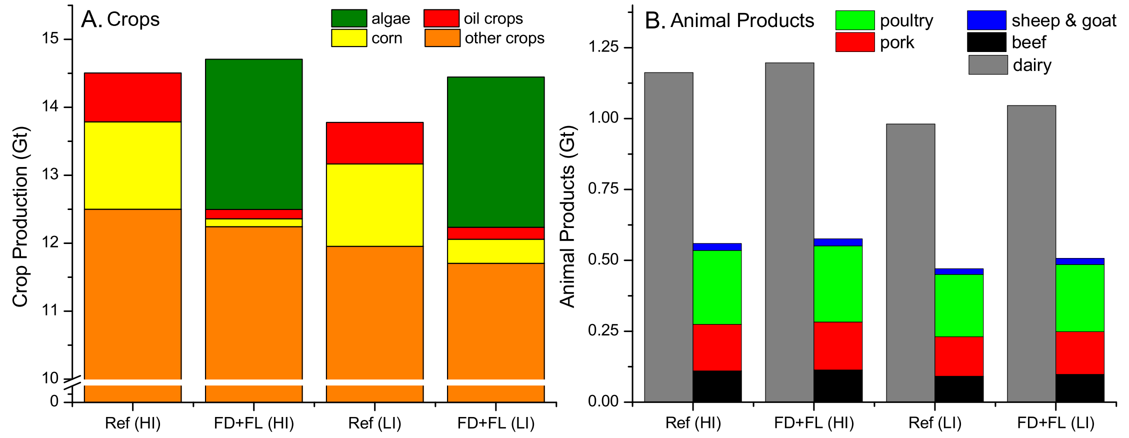

Figure 4. 2050 commodity crop (A) and animal production (B) under no-algae reference (Ref) and food and fuel (FD + FL) pathways applied to high carbon intensity (HI) and low carbon intensities (LI) scenarios for the energy target case. Due to a slight elasticity in the demand for animal products (a crop consumer) production of algal food product increases animal products and the total crop supply. The LI scenario constrains animal products due to elastic consumer demand. This leads to less demand and production of commodity crops, but algae enable a larger increase in animal product consumption and crop production than observed in the HI scenario.

pasture and grassland in comparison to the HI scenario (figure 5(B)). This shift to more pristine states occurs through reduced conversion to cropland (e.g. deforestation) and increased land reversion to pristine states (e.g. afforestation). While emissions and sequestration rates differ between these land transition processes, the aggregate emission profiles exhibit an early, large, and rapid reduction in emissions, followed by lower reductions until equilibrium land carbon density is achieved (figure 2). Land use emissions savings are thus associated with the displacement of new or current cropland, and are only realized when algal food production capacity is added. Therefore, continued algal food production is necessary to avert relapse to conventional agricultural cropland and release of emissions.

Food and energy tradeoffs in emissions savings

This integrated assessment also elucidates key tradeoffs among food, energy and climate. The first tradeoff is between emissions and food production, stemming from the responsiveness of consumption to a food surplus and changes in food prices. As modeled here, elasticity in demand for animal products results in increases in the total consumption of commodity crops (including algae) as feed and animal products. Such a rebound in crops limits the potential of algae-derived food to displace crop emissions (figure 4(D)). The increase in animal products also contributes additional emissions. In the HI scenario, the demand increase is not sufficient to offset the emission reductions from crop displacement. However, when a carbon price is applied as part of the LI scenario, animal product prices shift to a relatively inelastic part of the demand curve. Here, the algal surplus creates a greater demand for animal products, a greater demand for feed, and limits algal displacement of conventional crops (figure 5(A)). Thus, in the LI scenario, the addition of algae drives a net increase in agricultural emissions through lower crop offsets and higher animal production (figures 1 and 2). This increase in demand also limits potential reductions in water, nitrogen and phosphorus use in agriculture (figures 5(E)–(G)).

The second tradeoff results from the high energy demand of algal cultivation. When electricity from carbon-emitting sources is used, continuous production of an energy product would be necessary to maintain emission reductions. While the FD pathway delivers more food per unit of biomass (compared to the FD + FL pathway), the largest displacement of conventional agriculture, and the greatest LUC emission reductions, the high energy demand of algal cultivation eventually results in net positive emissions (figure 2). In the long term, this neutralizes the initial LUC savings (figure 3). While production emissions improve in the LI scenario (compared to the HI scenario), potential LUC and agricultural emission reductions also diminish. Alternatively, if low-carbon sources (e.g. solar) were abundant, and there was no opportunity cost associated with their use, then algae food production might become a suitable way of using renewable energy to reduce agricultural (N_2O, CH_4) and LUC emissions. The former being noted to have a highly constrained potential for reductions (Clarke *et al* 2014).

Finally, there is a temporal tradeoff between the value of upfront emission reductions and the value of ongoing reductions. While the FD + FL pathway generates large early emission reductions and sustains a net negative emissions profile, the FL pathway eventually results in a greater cumulative emissions savings (figures 2 and 3). On a biomass basis, the aggregate impact on radiative forcing suggests that the FL pathway would provide optimal use of algal biomass to maximize emission reductions. However, pursuing

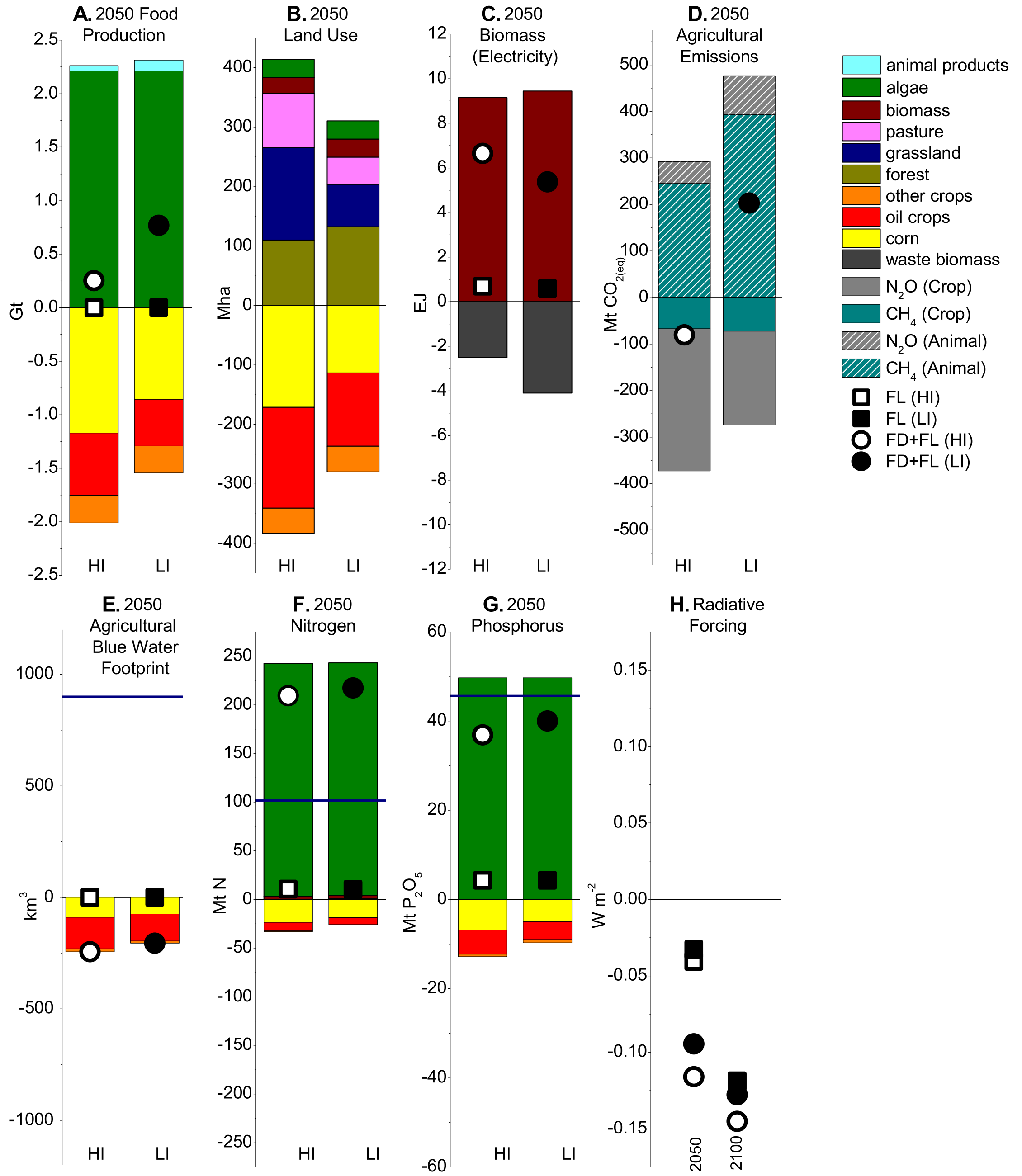

Figure 5. Impacts (relative to no-algae reference pathway) on key indicators for each scenario in the energy target case. Bars in panels (A)–(G) show changes for the FD + FL pathway represent the magnitude of current total global agricultural blue water footprint (1996–2005) (Hoekstra and Mekonnen 2012) (E), and 2014 global nitrogen (F) and 2014 phosphorus use (G) (FAO Statistics Division 2015). Panel (H) shows radiative forcing impacts.

near-term reductions (via algal food production) may be justifiable since reduction potential in the distant future is likely to be less certain. Furthermore, if the emissions intensity of the global liquid fuels sector, or substitutable sources of energy, improved at a faster rate than the emissions of global agriculture as is the case in the LI scenario, then the emissions abatement potential of food products would be greater than that of fuel.

Broader benefits of algal food production

Offsetting conventional agriculture production may have additional benefits beyond emissions reductions. By increasing aggregate global yields, the food-producing pathways (FD and FD + FL) promote a return to historical patterns of agricultural land demand while increasing food production. While our assessment demonstrates the LUC emission reductions that can occur through market mechanisms, other drivers, such as policy or advances in agricultural and energy technologies, are also likely to influence future land use patterns. For example, we observe a significant increase in the cultivation of dedicated biomass crops for electricity generation (figures 5(B), (C) and S6), in part due to the aggregate increase in global electricity demands of algal cultivation. Still, the generation of algal food products also has two larger impacts: first, by offsetting crops, it reduces the production of residual waste biomass used for electricity generation (figure S6(A)); and, second, the greater availability of land enables more dedicated biomass production (figure S6(B)). Observed here, this results in a small net increase (figures S6(C) and (D)) in biomass electricity production. Further emission reductions are likely possible through land management or bioenergy carbon with capture storage technologies, conventionally understood to be constrained by land availability (Smith *et al* 2015).

The offset of water-intensive crops with algae grown in brackish and saline waters, could also deliver substantial freshwater savings (figure 5(E)). Such global savings would be double that of the historical (1996–2005) blue water footprint in the USA and approximately 20% of the global agricultural blue-water footprint (Hoekstra and Mekonnen 2012). Despite this benefit, there is an energy cost to transporting water, and algae cultivation would, thus, be limited to coastal areas and land coinciding with access to saline aquifers (Venteris *et al* 2013). Furthermore, our water assessment assumes that dedicated biomass crops for electricity generation have a negligible blue water footprint and are only dependent on rainfall. If bioelectricity feedstocks were sourced from irrigation-dependent crops, then the blue water-demand could be substantial and severely limit the savings from replacing food crops with salt-water algae (Smith *et al* 2015). However, by reducing the land footprint of conventional agriculture, land in regions with plentiful rainfall should become more available for cultivation of energy crops with higher water demands.

Challenges of resource demands

Our modeled cultivation scheme incorporates demonstrated complete nitrogen and phosphorus assimilation (Huntley *et al* 2015), which avoids nutrient runoff and N_2O emissions associated with conventional agriculture (Ferrón *et al* 2012). Nevertheless, the food-producing pathways have high nutrient demands. For the 27.7 EJ energy target case, the FD + FL pathway requires nitrogen and phosphorus inputs that substantially exceed current global consumption of synthetic nitrogen and mineral phosphorus (figures 5(F) and (G)) (FAO Statistics Division 2015). Agricultural offsets are insufficient to reduce nutrient demand increases, in part because of eukaryotic algae's inability to fix nitrogen in contrast to leguminous crops. Still, our results highlight that agricultural nitrogen fixation is a land-inefficient way of obtaining reactive nitrogen for nutrition compared to synthetic ammonia production and algal cultivation. More concerning is the doubling in global demand for phosphorus which is conventionally sourced from mineral reserves; the stock of which, while large, is highly uncertain and its supply has been subject to large price volatility (Gilbert 2009).

Additionally, the demand for CO_2 to cultivate algae under the energy target scenario (FD + FL: 7.5 Gt CO_2, FL: 4.1 Gt CO_2) represents a significant portion of current and projected global emissions. In our model we assume that sufficient high-purity CO_2 waste streams are available for cultivation. Use of lower purity sources or those requiring longer transportation distances could increase production energy demands and emissions (Venteris *et al* 2014b, Beal *et al* 2015). While high purity streams are currently rare, technologies such as gasification and combined cycle are projected (in the GCAM reference scenarios, and elsewhere: International Energy Agency 2015) to provide high-purity CO_2 production at levels equivalent to the demand noted above.

The high resource demands, in particular that of mineral phosphorus, are unsustainable at the production levels modeled in the energy target scenario. However, various municipal and animal waste streams, if properly recycled, could support algal production at levels comparable to those modeled in the energy target case for the United States (Venteris *et al* 2014b, Canter *et al* 2015). Development of novel technologies to deliver nutrients from waste streams to algal ponds could provide additional environmental and economic benefits (Li *et al* 2015). Furthermore, high purity CO_2 could be supplied by onsite fermentation or gasification of terrestrial biomass grown on freed-up cropland. The energy derived from these processes could also be used as a low-carbon electricity source, further reducing production emissions. Ultimately, the resource challenge to large scale algal production may not be the net availability of such raw or waste-stream resources, but the siting of algal cultivation and processing facilities to economically optimize access these resources. Nutrient (N, P and CO_2) streams, suitable land (Venteris *et al* 2012), saline water (Venteris *et al* 2013), adequate growth climate (Moody *et al* 2014), and product offtake infrastructure (Venteris *et al* 2014a), may have geographically diverging resource supply curves. Given the potential of algae to integrate with current and other emerging technologies, future assessments should seek to evaluate the synergies between such technologies for retrofitting current agricultural and energy systems and designing new ones.

Conclusion

Using algae to replace conventional fuels and foods can result in several tradeoffs at the nexus of energy, food, water and climate. By shifting a portion of global food production to a high-yield crop such as algae, significant emissions savings can be realized by avoiding land use change. However continuous, non-LUC, emissions savings are insufficient to offset potential production emissions and increased meat and dairy production. Thus the co-rendering of a fuel product is necessary to generate on-going emissions savings. While cultivating marine algae for food would reduce the water footprint of global food production, the high nutrient demands raises concerns about the potential for algal production to sustainably achieve commodity-scale production levels.

The impacts of shifting a large portion of food cultivation (max 15% in the energy target scenario) from conventional agriculture to industrial scale algal cultivation are likely to extend well beyond those assessed in this study to include: human health, labor, agricultural communities, and national trade balances among others. Furthermore deployment would require public acceptance, changes in logistics, and supportive policies at national and local levels. Capital investment could be on the order of $200 billion per year in the first 25 years of the energy target scenario, using current estimates of investment requirements in the United States (Davis *et al* 2016) scaled to our forecast. For comparison, solar and wind investment in 2015 was $160 and $110 billion respectively (Frankfurt School—UNEP/BNEF 2013), but unlike algae, investments in these technologies are currently expected to provide positive returns. While not evaluated here, these impacts merit further analysis, and since they are likely to vary by region, require the use of higher resolution methodologies than that employed by this globally-focused study.

While this analysis is presented in a global context, our results provide guidance on conditions that are favorable to the algal pathways modeled here. Production should target regions where seawater, low-carbon electricity, CO_2 and waste nutrient streams are readily available, and where conventional food production is constrained by low freshwater supplies or lack of arable land. Even if these economic and environmental benefits are realized, large-scale algal cultivation will be resource intensive and will involve tradeoffs.

Future economic and ecological pressures should make such tradeoffs worthwhile. Algal fuel may be essential to reducing transportation sector emissions where there are few alternative options for aviation, shipping and heavy vehicle fuels. As a source of biofuel, algae avoid harmful impacts commonly associated with terrestrial feedstocks, such as competition with food sources and land use change. The socio-economic and ecological benefits of algal food production (FD + FL and FD pathways) also have the ability to provide value. If conventional agricultural systems are threatened by climate change (Nelson *et al* 2014) and water scarcity, or are constrained by regional land management policies (Angelsen 2010), alternative high-yield systems such as algal food products could be instrumental in ensuring food security. Algal food products should thus be considered as both a climate mitigation and adaptation technology.

Currently the best cost estimates of algal biomass production (Davis *et al* 2016) exceed that of common commodity agricultural crops, challenging the adoption of algae as both a food source and a biofuel feedstock. While further cost reductions in algae production will likely be necessary, the deficit between the prices of algal and conventional agricultural products could be further diminished if the indirect benefits identified in this study were economically realized through policy (e.g. through realization of the shadow prices of emissions, water and LUC in conventional agriculture). Regional and global policies such as energy production mandates, market-based carbon taxes, land management regimes and agricultural regulation, may drive conflicting outcomes at the energy–food–climate–water nexus. However, the algal technologies modeled here shift burdens away from land and water, minimizing potential nexus conflicts. Still, even efficient policies such as a universal carbon tax could drive an inefficient allocation of some resources, such as phosphorus to algae cultivation. Future research, commercialization and policy efforts should thus be attuned to the benefits, tradeoffs, and opportunity costs associated with algal production schemes.

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