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

Michael J. Walsh1*, Léda Gerber Van Doren2,3,4, Deborah L. Sills5, Ian Archibald6, Colin M. Beal4,7, Xin Gen Lei8, Mark E. Huntley4,9, Zackary Johnson10, Charles H. Greene2

Affiliations:

1Center for Integration of Science & Industry, Bentley University, Waltham MA, 02452, USA.
2Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, NY, 14853, USA.
3Department of Chemical and Biomolecular Engineering, Cornell University, Ithaca, NY, 14853, USA.
4College of Agriculture, Forestry & Natural Resource Management, University of Hawai‘i Hilo
5Department of Civil and Environmental Engineering, Bucknell University, Lewisburg PA, 17837, USA.
6Cinglas Ltd., Chester, United Kingdom.
7B&D Engineering and Consulting LLC, 7419 State Hwy 789, Lander, WY, 82520, USA.
8Department of Animal Science, Cornell University, Ithaca, NY, 14853, USA.
9Department of Biological & Environmental Engineering, Cornell University, Ithaca, NY, 14853, USA.
10Duke University Marine Laboratory, Nichols School of the Environment, Duke University, Beaufort, NC, 28516, USA.

*Corresponding author: michael.jay.walsh@outlook.com
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Abbreviations

| Abbreviation | Description |
|--------------|-------------|
| GCAM | Global Change Assessment Model |
| FL  | Pathway designation: biodiesel fuel and agricultural substitute from microalgae |
| FD  | Pathway designation: use of whole algal biomass for food |
| FD+FL | Pathway designation: biodiesel fuel only from microalgae |
| LCA | Life cycle assessment |
| LEA | Lipid-extracted algal biomass, (partial lipid removal) |
| LUC | Land use change |
| MAGICC | Model for the Assessment of Greenhouse-gas Induced Climate Change |
| PBR | Photobioreactor |
| PED | Price elasticity of demand |

1 Overview

We use integrated assessment to evaluate direct and indirect environmental impacts of algal fuel and food (human and animal) production. We explore three pathways for algae harvested from a hybrid photobioreactor (PBR) and open pond cultivation system demonstrated at large scale (S1): (1) a food and fuel (FD+FL, Figure S 1A) pathway where neutral algal lipids are extracted and upgraded to renewable diesel fuel, while the residual, lipid-extracted algae (LEA) is used as a food substitute; (2) a fuel only pathway (FL, Figure S 1B) that produces renewable diesel fuel and utilizes residual biomass for internal process energy and nutrient recycling; and, (3) a food only pathway (FD, Figure S 1C) where the whole algal biomass is utilized as a food product. These pathways were evaluated because they demonstrate important environmental tradeoffs corresponding to production resource demands and impacts of the generated energy and food products.

We assess the impacts for the FD+FL and FL pathways assuming that algae production increases linearly from 1.1 EJ y⁻¹ of production in 2025 to achieve and energy-production target of 27.7 EJ y⁻¹ in 2050 (Figure S 2) based upon the IEA 2DS Scenario (S2). We also compare the benefits and tradeoffs of the three alternative post-cultivation pathways (FL, FD, and FD+FL) on constant production of a fixed amount of algal biomass (500 Mt) (Table S 1). Algal production pathways were compared to a no-algae pathway that assumed the continuation of conventional agriculture and liquid fuels.

We employ the Global Change Assessment Model (GCAM) (S3–S5) a 32-region dynamic integrated assessment model, to compare and evaluate these technology platforms across the energy and agricultural sectors. Our analysis focuses on determining net impacts on greenhouse gas emissions, including emissions due to land use change (LUC) stemming from the second order impacts of the substitution of key global crops with algal food products. We also extend our analysis to explore other life cycle environmental impacts (e.g., demand of nutrients and water).

2 Substitutability of algal biomass for food

Large scale cultivation of algae for animal or human consumption has been considered since the 1950’s (S6, S7), and has long been viewed as a potential solution to historically projected yield limitations in terrestrial agriculture (S8). Costs have typically limited production of algal food products outside of niche markets (S9). However, recent volatility in food prices (e.g. FAO Food Price Index) and heightened interest in the health-promoting foods (including animal products) could lead to more favorable economic conditions for algal food products. The economic value of which is determined by its nutritional composition (i.e. protein content) in comparison to other food products (S10–S12).
The nutritional composition of algal food product (whole or LEA) varies depending on algal species, cultivation conditions and post-cultivation processing. Given the wide array of species, algae could provide a high degree of flexibility and potential for targeted nutritional applications (S13, S14). For example, the nutritional composition of LEA Desmodesmus sp. grown under high-nitrogen conditions (S1) is protein-rich compared to corn and soybeans (Table S2).

LEA products have been tested in several types animals used for the production of meat, dairy and eggs. LEA from Staurosira sp., a diatom, substituted up to 7.5% of a corn and soybean meal diet for egg laying hens (S15) and broiler chickens (S16). Subsequent LEA feed trials using a low-ash, green algae, Desmodesmus sp., demonstrated tolerance for 10% to 25% substitutions of conventional feed (corn and soybean meal) in growing salmon, pigs, broiler chicks, and layer hens (S17–S19). Collectively, these studies noted that supplementation with amino acids or hydrolytic enzymes was useful to mitigate observed intolerances in the LEA-inclusive diets, suggesting that higher levels of substitution may be attainable with supplementation (S14). This could also be achieved through optimized or targeted use of algal biomass. For example, Chlorella sp. LEA was shown to effectively substitute at isonitrogenous levels for cotton seed meal as the protein supplement to straw in steer straw-diets (S20). Another cattle study, targeting carbohydrate replacement with LEA, demonstrated that carbohydrate-rich LEA (see Table S2) could substitute for corn up to 45% of the diet (S21). While this final study utilized LEA from heterotrophically grown algae, it provides an additional example of the diverse application of algae as feed.

Research on human consumption of algal products is more limited, although examples of human consumption of whole algal biomass exist, albeit at small scales, such as in niche markets or demonstration products (S22). In addition, the high concentration of omega-3 fatty acids and biologically active metabolites in algal biomass (S13) has spurred an interest in using algal products for targeted nutritional applications (S23). Incorporation of algal flour into conventional food products has been challenged mostly due to aesthetic and taste problems (S24). Despite this early product evaluation, numerous patents for algal food products exist (e.g. (S25)), demonstrating commercial interest.

Given the diverse nutritional applications of algae, it is difficult to predict how they would complement or offset existing agricultural products. While corn was directly substituted in some of the trials (S15–S17, S20, S21) noted above, defatted oil crop meal products (e.g. soybean meal, cottonseed meal) rather than the commodity crop equivalent were substituted. However, this may ignore some of the benefits (e.g. higher protein and oil content of some LEA over soybean meal (Table S2)). Given the range of nutritional composition of both LEA and whole algal biomass (see Table S2 and (S11–S13)), we assume for simplicity that algal food product (LEA or whole) will be cultivated to be perfectly substitutable on a mass basis for corn and oil crop1 commodities. Furthermore, we assume that substitution of these crops occurs based upon the regional shares (or regional ratios) of production of these crops. By substituting a blend of grain and proteinaceous crops, we are able evaluate the replacement of a representative cross section of global agriculture and the markets that would be likely targets for large-scale algal cultivation at scales equivalent to biofuel targets.

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1 Oil crops include soy, rapeseed, linseed, sunflower seed, safflower seed, and sesame seed.
3 Algal product pathway descriptions

3.1 Algal biomass cultivation

The cultivation model, based upon large-scale experiments in which the green alga *Desmodesmus* sp. was grown in a hybrid cultivation system under high nitrogen-loading described by Huntley et al. (S1), utilizes photobioreactors (PBRs) in a first growth stage combined with open, race-way style ponds, for a second growth stage. Algae are harvested after in-pond gravity settling, and then dewatered with a belt filter press (S26). Harvested algal biomass can either be sold as whole algal biomass as modeled in the FD pathway (Figure S 1C) or converted to generate liquid fuels, as modeled in the FD+FL (Figure S 1A) and the FL (Figure S 1B) pathways. Table S 3 lists general productivity and operational parameters for cultivation and transformation processes.

3.1.1 Carbon dioxide requirements for cultivation

Our cultivation model utilizes high purity (94%) carbon dioxide gas as a feedstock for algal growth, and accounts for CO₂ losses from outgassing and respiration as well as the energy required for CO₂ delivery based upon (S26). While this feedstock carbon is sourced from waste streams, the delivered CO₂ is treated as atmospheric or biogenic CO₂ since this stream would have ultimately been emitted into the atmosphere. Therefore, its impact on the increase of greenhouse gases in the atmosphere is allocated to the upstream process producing the waste CO₂ stream, and not to the algae fuel or food products. Respired CO₂ is thus also of biogenic and atmospheric origin and does not contribute to net emissions. This approach represents widely accepted practices in CO₂ life-cycle accounting methodologies (S27, S28) and emulates how carbon in terrestrial crops is accounted for.

High purity CO₂ sources (e.g. hydrogen production, fermentation) are currently limited. If less pure waste streams were used (e.g. flue gas: ~10% CO₂), energy inputs for delivery increase considerably, and reduce life cycle emissions savings (S26). Thus, the large-scale algal cultivation modeled here will require more common sources of high purity CO₂ or efficient delivery of flue gas to maintain the emissions profile associated with production. While high purity CO₂ sources are currently rare, future forecasts of energy production (e.g. (S2, S29, S30)) as well as the GCAM framework predict wide scale deployment of gasification, combined cycle and other technologies that produce high purity CO₂ streams. Depending on carbon mitigation polices some of these technologies will be coupled with carbon capture and sequestration (CCS) and some not (S31). Our model runs in GCAM suggests that 8 (LI) to 18 (HI) Gt CO₂ are emitted via non-sequestering combined cycle or coal liquefaction technologies.

While CCS has been slow to emerge and is challenged by the energy requirements for capture and purification (S32), the utilization of CO₂ (CCU) creates new market incentives. Recent demands for high purity CO₂ for applications such as enhanced oil recovery has demonstrated a potential market for captured CO₂ that could reduce costs and spur technological progress for high purity streams (S33). While co-location may challenge implementation, algae and high-purity carbon sources should be viewed as synergistic technologies. Furthermore, lower constraints on land from algal food product cultivation could enable an increase in production of bioenergy crops. In such a scenario, large scale, co-located combustion, fermentation or gasification of bioenergy crops or managed biomass waste could provide access to CO₂ over a range of purities (S34). Given the potential, but uncertain development of high purity CO₂-emitting technologies, we assume for our illustrative scenarios that feedstock CO₂ supplies are sufficient and have an energy penalty equivalent to the high-purity stream modeled in (S26).
3.2 FD+FL Conversion: Co-production of algal diesel and food product via wet extraction

Conventionally, extraction of lipids from algal biomass was modeled using solvent (e.g. hexane) (S35), but this approach requires energy-intensive drying of the biomass. Novel wet extraction processes, such as the approach adopted for this study, are less energy intensive (S36), but have not seen widespread commercial application. Following harvest and dewatering with belt filter press, the algal biomass undergoes a wet oil extraction process (S26, S37) in the FD+FL Pathway (Figure S 1A). The process has a 75% efficiency, leaving a residual amount of oil (typically nutritionally desirable polar lipids such as omega-3 fatty acids) associated with the LEA biomass. The crude oil extract is upgraded using a hydrotreatment step to hydrogenation-derived renewable diesel, which is assumed to be substitutable (e.g. drop-in) for conventional fossil diesel. An efficiency of 85% is assumed for this process, taking the higher range of the experimental values for hydrotreatment of algal oil (S38). Process energy demands for extraction, are based upon the implementation of this technology in (S26).

3.3 FL Conversion: Production of algal biodiesel via hydrothermal liquefaction combined with catalytic hydrothermal gasification

In the FL pathway (Figure S 1B), harvested algal biomass undergoes hydrothermal liquefaction (HTL), a high pressure and high temperature process that converts whole biomass to biocrude oil, resulting in biocrude yields (in unit of percent biomass) that are higher than the lipid fraction of the cell (S38). This oil phase is subsequently upgraded to a renewable diesel via hydrotreatment as described above for the FD+FL pathway. HTL also produces an aqueous phase, that is processed using catalytic hydrothermal gasification (CHG) to produce syngas which is used to deliver process heat and electricity via a combined heat and power engine (S39, S40). The CHG process delivers purified water and solid salts containing nutrients that can be recycled and sent back to the cultivation ponds.

3.4 Algal food product post-processing

For simplicity, the food products obtained from the FD and FD+FL pathways are assumed to be identical. Practically this may mean that an algal species with a nutritional profile equivalent to LEA is cultivated in the FD pathway. In the FD and FD+FL pathways, further processing of whole algae or LEA, such as pelletizing or complete drying, is not accounted for. The final use of algal food product (either whole algal biomass or LEA) is highly uncertain since neither products nor consumers and offtake pathways are currently defined. If sold as an animal feed the biomass may have to be dried, pelletized, and shipped to an animal production facility. While such processes may increase energy inputs this may be similar to the extrusion and pelleting of conventional feed and food products. We thus do not account for any further processing after dewatering (FD) or wet extraction (FD+FL).

3.5 Pathway inventories

Simplified life cycle inventories (Table S 4) for the FD+FL, FL, and FD pathways were developed based on the state of the art processes described in (S26). We assume that heat and electricity inputs for cultivation and extraction decline by 2% per year from 2025-2050 due to increases in algal productivity (discussed in Section 4.1). This improvement stems from the efficiency gained by converting a more concentrated production stream and covers: water delivery, culture circulation, nutrient delivery, carbon delivery, harvesting, dewatering, and extraction (wet extraction and HTL). We assume that the energy requirements do not improve for the hydrotreatment upgrading of algal lipids to attain renewable diesel. The impact of this yield improvement factor is discussed in Section 5.2.
4 Scenario Generation: Cultivation & production forecasting

In the energy target case, we separately evaluate the global scale up of the FD+FL and FL pathways to achieve an energy production target of 27.7 EJ of biofuel in 2050. This production value was selected to bring total 2050 biofuels production to 32.7 EJ, a target identified by the IEA 2DS scenario forecast of renewable liquid fuels (S2), and assumes a constant baseline terrestrial biofuels supply of 5.0 EJ y\(^{-1}\). Algal fuel production begins in 2025 at 1.1 EJ and scales linearly until 2050 (Figure S2) after which production is assumed to be constant through 2100.

In the algal biomass target case, production of 500 Mt of algal biomass begins in 2025 and is held constant in future years. The algal biomass is processed using the FD+FL, FL or FD pathways to generate food and fuel products (Table S1). The 5.0 EJ annual terrestrial biofuel production target is also assumed in this case. Although this case is less descriptive of real world technology adoption, it is used to demonstrate: (1) the tradeoffs in terms of environmental impacts associated with the post-cultivation pathways given a constant biomass production; and, (2) the temporal behavior of LUC associated with a fixed amount of algal food production.

The biofuel production forecast of 5.0 EJ y\(^{-1}\) from 2025 onward, was based upon forecasts of production in 2025 using the renewable fuel standard for the USA (S41), and OECD projections for the rest of the world (S42). 3.28 EJ of conventional EtOH was produced using regional feedstocks such as corn, sugarcane, wheat, and cassava; 1.68 EJ of conventional biodiesel was produced using soy, rapeseed, jatropha, and palm oil; a small amount (19 PJ) of cellulosic EtOH was produced from a mixture of switchgrass and woody biomass in the USA, Japan and EU27 regions; Fischer-Tropsch biodiesel production was set to 0. By keeping terrestrial biofuels fixed, we can attribute most LUC directly to the offsetting of conventional agriculture. However, we allow market-driven (unfixed) electricity generation from terrestrial biomass. The impacts of this are discussed below in Section 5.1.

4.1 Algal yield projections

We assume that commercial production in 2025 begins with a yield of 22 g m\(^{-2}\) d\(^{-1}\) (ash free dry weight) algal biomass, based upon demonstrated large-scale cultivation results (S1). Table S3 contains cultivation and biorefinery operational parameters (similar to those in (S26)) that are used to determine net algal yields and product output shown in Figure S3. In all cases a 2% compounding increase in productivity is assumed per year until 2050 and productivity is then held constant at 36.1 g m\(^{-2}\) d\(^{-1}\). This improvement factor based upon historical agricultural yield improvements which averaged 2% a year from 1961-2005 (S43). The algal productivity values lies within a number of previously evaluated yield factors (S44). The impact of the productivity factor and a comparison to no improvement is addressed in Section 5.2.1. Productivity factors and improvement, are assumed to be achieved globally. Practically, this might mean that within a given region, cultivation would be located where yields are maximized at these values.

4.2 Regional algal cultivation projections

Although this study focuses on global impacts, we employ an integrated assessment model, GCAM, that determines market changes in 32 regions. Subsequently, global algal production forecasts were disaggregated to be descriptive of future global algal production. Regional shares (Table S5) of global algal production were calculated by weighting regional total land stocks with scores (ranging from 0 to 5) derived from the authors’ evaluation of the potential for algal production in each region, influenced by productivity estimates (S45) as well as considerations of insolation, temperature, energy demands, and historic algal production. For example, score-weights of 5 were allocated to most regions near the equator. Score-weights of 4 were allocated to subtropical regions and the USA which resulted in
production levels consistent with those evaluated in national assessments described below (Section 4.3). Countries such as China (2) and Japan (2) which have historical aquaculture industries are unlikely to see large scale deployment, but may still have limited areas where productivity levels are high. A score of (1) was given to regions which may experience limited production. Although algal cultivation in Canada has been discussed (S46), this region as well as other low productivity regions (Russia, East Asia, and non-EU European countries) were scored at 0 (no production).

The scores of African regions and Australia NZ were reduced to ensure that supply in these regions did not exceed demand. In GCAM, final energy products such as those produced by the algal pathways modeled here are non-tradable (S4). In such cases, production levels in these regions would have been curtailed to meet demand, subsequently curtailing global aggregate production. While final energy products are not tradable, offset energy resources and food product commodities (corn and oil crops) are tradable and create global impacts. Although it might be of interest to explore different regional allocation schemes, this is unlikely to significantly change our results.

Current (2015) regional shares of corn and oil crops in diets are used to determine regional allocations of algal food product to corn and oil crops markets. This is consistent with the practice in each model where current regional commodity crop diet allocations are maintained. This has the result of offsetting more corn than oil crops by a 2:1 factor. We acknowledge that this might not represent the optimum substitution given the nutritional profile of some algal food products. Furthermore, the impacts of corn and oil crops can vary drastically, as oil crops tend to be more land intensive, while corn is more water and nutrient intensive. Despite these uncertainties, the selection of these two widely cultivated crops and assumption of general substitution enables an illustrative analysis of the impact of algae food products on global agricultural markets.

4.3 Corroboration of industry growth potential in the United States

Our production peak volume in the United States (Table S5) is approximate to the 21 billion gallons a year (79.5 BLY) target of conventional and advanced biofuel production, mandated by the Renewable Fuel Standard of the Energy Independence and Security Act of 2007 (S47). Several recent studies (S48–S54) use this target to evaluate the resource (e.g. water, fertilizer, land) demands of algal fuels in the United States. These studies demonstrated that meeting the 21 BGY target would push against specific resource limits that while possible, may involve significant economic tradeoffs. Furthermore, these studies explored several cultivation and processing models to produce fuel that are generally less resource intensive than the FD+FL pathway. Alternatively, while these studies utilize current technological assumptions and do not focus on a target date for achieving these goals, we forecast technological progress, through yield improvements, in route to nearing the 21 BGY target in 2050. At that point, improvements in yield are likely to drive down land requirements, but nutrient availability is likely to remain a challenge. Additionally, co-location of algae production facilities with sources of CO₂, salt water and nutrients, will further challenge growth potential. Such resource availability is likely to vary widely across the world, but developing markets offer a greater opportunity for designing integrated systems from scratch.

5 Integrated Assessment Methods

GCAM was used to evaluate the impacts of each algal pathway technology described in Section 3, with inventory data shown in Table S3. Analysis was performed from 2025 to 2100 on 5 year intervals. GCAM is widely used in integrated assessment analysis and has been used extensively to evaluate the impact of terrestrial biofuels on land use change (S55–S59). A recent detailed summary of the version employed for this study (GCAM 4.0 R5465) is provided in the supplementary section of (S60). As a
partial equilibrium model, GCAM seeks an optimum price for supply-demand equilibrium across various products and sectors for a global (32-region) economy. GCAM is dynamic in space and time, allowing for the examination of technology improvement, regional variability and identification of key market drivers. GCAM is integrated with the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) (S61) for assessment of climate impacts.

Our analysis compares the impacts of each algal pathway to a no-algae reference scenario. We specifically focus on indicators for agricultural and energy production, LUC, and emissions. MAGICC output was used for long-term assessment of global radiative forcing as our simulations resulted in significant changes in CO$_2$, CH$_4$ and N$_2$O. Since the emissions profile of algae is highly dependent on the source of energy inputs (S26), we evaluate the emissions profile of algal pathways under two different scenarios: (1) a high emissions intensity (HI) scenario that results in a net radiative forcing change of 7.5 W m$^{-2}$ for the reference no-algae pathway; and, (2) a low emissions intensity (LI) scenario where radiative forcing in the reference no-algae pathway is limited to 4.5 W m$^{-2}$ similar to the RCP 4.5 pathway (S62).

The HI reference scenario is identical to the GCAM 4.0 reference scenario, but has fixed (5.0 EJ yr$^{-1}$) terrestrial biofuel production as described above. The LI references scenario also includes the fixed biofuel production levels, but a lower global carbon intensity is achieved using a specified carbon tax (Table S6). The tax was applied universally to emissions from both fossil fuel combustion and land use change. This had the impact, in comparison to a tax solely on fossil-fuel combustion, of favoring forestation over the use of land for the cultivation of bioenergy feedstocks as was observed in Wise et al. (S58). While the pursuit of bioenergy for carbon capture and sequestration is limited by land (S63) that would be made free by algal production, exploring the carbon benefits of such scenarios was outside the scope of this study.

We assume that algal production has no arable-land footprint, because production will likely be sited on non-arable (Figure S4A) or low-value arable land and will not compete with conventional crops. This is consistent with how technologies, such as solar and wind are modeled in GCAM. Even if algae were cultivated on competitive arable land, the higher yields of food product (Figure S3) would still lead to a net offset of conventional agriculture and reduction in land use.

5.1 Economic framework
Algal diesel fuel is assumed to be perfectly fungible (e.g. a drop-in fuel) with refined liquid transportation fuels (Figure S4B). As described in Section 2, we also assume that algal food product is perfectly substitutable for corn and oil crop commodities (Figure S4D) at the regional distributions listed in Table S5. In this study, no assumptions about algal production costs are made, and instead a fixed output is used with the aim of evaluating impacts of specified levels of algal production. This approach is similar to that used by previous integrated assessments evaluating the impacts of biofuel technologies (S59, S64, S65) and is comparable to a global mandate. Such a mandate should not be interpreted as an optimal policy application, but instead we use this approach to compare the alternative pathways under the control objectives of a consistent energy target, and a consistent level of algal biomass production.

Since algal output is fixed and unresponsive to market changes, algal food product is delivered to and consumed by these commodity markets at and regardless of the equilibrium market price. The highest priced energy and food products are subsequently displaced by the fixed production of algal fuel and food. While our experimental design utilizes a mandate, this arrangement could also be interpreted with algal production becoming price competitive with these products without the inefficiency associated with a mandate. While this understanding is highly optimistic given the high resource demand of algal production it would posit that: (1) technological progress will continue to reduce the cost of algal products
in relation to conventional food and energy sources, similar to cost reductions observed in other industries (e.g. solar and genetic sequencing among others); (2) the value, delivered by the improved environmental consequences of algal production assessed here, will be realized via a regulatory mechanism (e.g. carbon and water pricing); or, most likely, (3) some combination of both the these mechanisms could promote price parity.

On the demand side, price elasticity of demand (PED) is explicitly modeled in GCAM. In the default implementation, consumer demand for commodity crops is assumed to be perfectly inelastic (PED =0). While this may not reflect actual consumer behavior, it avoids a situation where increases in food prices from land use changes or emissions prices would cause a reduction in crop consumption. A detailed evaluation of this behavior in integrated assessment models is found in (S65). Alternatively, the default implementation of GCAM assumes animal product (meat and dairy) consumption is slightly responsive (PED\textsubscript{USA} = -0.09, PED\textsubscript{Rest of World} = -0.25 (S4)) to price, which itself is influenced by the price of crops and thus responsive to land prices, emissions taxes and commodity crop supply. Subsequently the demand curve for food crop consumption is an aggregate of the human and animal crop demand and is slightly elastic. Because of this elasticity, adding algal food product to a substitutable commodity crop market will create an overall net increase in the quantity of commodity product (Figure S 5), lower market prices, and offset the conventional commodity production by the amount of algal food product added to the market minus the amount equal to the net increase in commodity consumption. While the increase in production is relatively small, due to the low PED of animal product consumption, this effect illustrates for comparative analysis, potential indirect impacts enabled by additional food production.

GCAM assumes that consumer diets are fixed and that portions of the diet are not switched among crops, resulting in a constant share for each crop in consumer demand. However, animal feed in GCAM allows for some switching among crops using a logit methodology (S4, S5). This causes small reductions in production of other crops due to the surplus provided by algal food and feed products (Fig. 5-main text).

In the high intensity scenario, production of algal food products nearly completely offsets global corn and oil crop production. Furthermore, production of algal corn substitute exceeds non-energy consumption of corn. This would imply that excess algal food product (~6% of total production) is subsequently allocated to meet the terrestrial biofuel (corn ethanol) demand, and offset corn cultivation and land use. This scenario is conceivable given that the fermentation of algal biomass for ethanol production is a potential alternative use of the residual biomass (S26). While this result is a consequence of the large production scales forecasted here, it is useful to highlight that these systems will be more dynamic than that modeled, with terrestrial biofuel production being responsive to the presence of algal biofuels and food products.

Additional shifts occur in downstream markets as conventional agricultural crops are substituted (Figure S 4). In particular, the offsetting of conventional agriculture by algae drives down the demand for land, leading to less land conversion (e.g. deforestation) and increased restoration to natural states (e.g. afforestation). In some markets, however, production changes are influenced by more than one market driver. For example, a small increase in the production of dedicated terrestrial bioenergy crops is influenced by the reduction in residual biomass (Figure S 4H, Figure S 6A, Fig. 5C-main text), greater availability of land for dedicated biomass crops (Figure S 4I, Figure S 6B, Fig. 5 B&C-main text) and algae’s greater demand for electricity, (Figure S 4B). The last driver is exclusively observable in the increased biomass consumption of the FL pathway (Figure S 6A-C).

While nitrogen demand increases significantly (Fig. 5F-main text) due to the high-fertilizer requirement of algal production (Figure S 4C), it has negligible impact on other crops due to the relatively low cost and ease of synthetic nitrogen production. This may not be the case for phosphorus fertilizer, a limited
mineral resource. While the global supply of phosphorus is likely sufficient to sustain demand for the indefinite future (S66), algae’s demand for phosphorus fertilizer is sizable (Fig. 1G-main text) and may impact agricultural markets due to supply and supply chain constraints. Market impacts of phosphorus demand are not explicitly modeled in this study due to limitations of GCAM, uncertainty in global supplies (S67), as well as an acknowledgement that this high demand will need to be met with non-mineral, alternative, phosphorus sources such as waste streams (S53, S68).

5.2 Emissions accounting
Since GCAM is a sector-based model, emissions are attributed to the sectors that generate emissions such as electricity production. This contrasts with conventional life cycle assessment where emissions are aggregated and attributed directly to the product. The sector-based approach makes full attribution challenging due to the presence of trade and second order impacts. Fortunately, the required GCAM-model inputs for algae production (electricity, natural gas and nitrogen fertilizer) are distinct from the output (corn, oil crops, and refined liquids). While there is some sector crossover (i.e. a small change in the amount of liquids fuels used for electricity production) and shifts within a given sector (i.e. changing modes of transportation) these second order impacts were small. We thus aggregated emissions in GCAM to six categories: animal products, crops, fertilizer, refined liquids, other energy, LUC. Changes in fertilizer and other energy were further aggregated to algal production. 100-year global warming potential (GWP) factors (S69) were used to convert methane (GWP: 34) and nitrous oxide (GWP: 298) in these categories to calculate carbon dioxide equivalences for Figs. 1-3 in the main text and Figure S7.

5.2.1 Emissions sensitivity to production conditions
The emissions intensity of the electricity source, along with productivity, are highly sensitive variables in the production of algae (Figure S7). However, as electricity sources improve, as shown in the low-intensity scenario, yield improvements become less influential. While this suggests that yield improvements may not be as important for reducing life cycle emissions when less carbon intensive electricity sources are used, the importance of yield improvements should not be discounted. Compared to no improvement, an annual 2% improvement in yield will have profound impacts on reducing the cost of production and land footprint.

Algal productivity is one of several production parameters that will influence overall process energy demands, the production emissions profile and ultimately the net emissions profile. These parameters include productivity, biomass composition, CO₂ delivery, water delivery and circulation, and conversion efficiency. All of these parameters have the potential to vary depending on production location, co-location with resource providing services, and state of the technology involved in cultivation and processing. Evaluation these factors is beyond the resolution of this study, but the sensitivity of production energy demands to these parameters has been evaluated elsewhere (S26, S70).

5.2.2 Other climate impacts not considered (I): Emissions from construction and land development
We do not include emissions associated with algae facility construction, which have been shown to be negligible for the full life cycle environmental performance (S26). We also do not include in our analysis any impacts such as emissions from the development of land for algal cultivation. This is consistent with how other technologies, such as solar and wind, are modeled, each of which are assumed to occupy non-arable lands.

However, despite their unsuitability for agriculture, marginal land used for algae cultivation may contain significant above ground and below ground carbon stocks. Pond excavation, and land coverage will likely release vegetative carbon and potentially soil carbon. To estimate the upper limit of emissions from land
development we assume a carbon loss of 2.22 kg C m\(^{-2}\). This value represents the difference in carbon stored in grassland and developed land using the average land carbon density values of the two eco-regions in the United States currently targeted for algal cultivation: Mississippi Alluvial and Southeast USA Coastal Plains (S71), and Warm Deserts (S72).

The estimated emissions from land development are small (<5%) in comparison to the net cumulative (2025-2050) emissions for all pathways (Table S 7). In particular, for the food producing pathways, emissions from land occupation savings were significantly less than the emissions savings associated with the land use change associated with offset agriculture. While emissions from land development are uncertain, these estimates likely represent an extreme upper bound as land development could be managed in a way to minimize vegetative and soil carbon loss.

5.2.3 Other climate impacts not considered (II): Albedo from land development and increased forestation

Land development for algal cultivation may also change surface albedo and subsequently global radiative forcing. Algal ponds have a low albedo of around 0.15 (S73). Albedo values for cropland vary between 0.15 and 0.20, whereas albedo values for degraded and desert land approach 0.40 (S69). The transformation of degraded land, here assumed to have a similar albedo to cropland, is thus likely to have a slightly negative effect on global albedo. However, our land requirements for algal cultivation in 2050 – 30.6 Mha in the energy target case for the FD+FL pathway – are relatively small fractions of global land, suggesting only a minor impact on albedo.

The conversion of cropland to forest will also reduce albedo which may counteract greenhouse gas forcing (S74, S75). However, the net change in forest (FD+FL-HI energy target: +110 Mha; and, FD+FL-LI energy target: +132 Mha), modeled here, is relatively small compared to the illustrative scenarios demonstrated in studies (S74, S75). Furthermore, both these studies indicated that tropical afforestation would deliver the greatest net cooling impact once albedo effects are accounted for. Since algal production will occur in tropical regions, it is conceivable that forestation will be favored in these regions.

5.3 Projection of phosphorus and water use

Estimates of water and phosphorus use are not integrated with GCAM 4.0 and were determined by applying life cycle inventory coefficients to GCAM production values. Phosphorus use inventory data was obtained from ecoinvent version 3.1 (S76) and regionalized where possible. Inventory data was applied to algae production, corn and oil crops. Other major crops such as wheat, rice and sugar were also included in the inventory, but due to the small production changes in these crops, their inclusion had little influence on the overall net impacts.

Water impacts are reported as blue water footprint, which describes the removal of water from fresh surface and groundwater sources as a result of irrigation (S77). To calculate total blue water footprint we apply country water footprint factors (S77) to GCAM production data that was disaggregated using 2014 FAOSTAT national production values and individual crop shares for the oil crops and other grains categories (S78). We do not attribute any water impact to the cultivation of dedicated bioenergy crops for electricity, as these crops (e.g. switchgrass) which generally have no irrigation demand. Estimates, generated from life cycle inventory data (S76) of water impacts from increased electricity and animal production, and decreased liquid fossil fuel use were found to be small and are excluded from this crop-focused analysis.
6 Corroboration of LUC estimates

The system dynamics model, BioLUC (S79), was used to corroborate LUC estimates from GCAM. While BioLUC is not a full-economy model, it uses agricultural demand forecasts, population growth and empirical econometric observations of global land use patterns (S80) to project the development of crop land from pristine land (forests & grassland). This approach provides a high-level analysis of LUC, based upon socioeconomic factors such as yields and population pressure. It is an alternative to the low-level economic-equilibrium approach used in GCAM, as it econometrically incorporates other drivers (e.g. policy) of LUC, rather than being based solely on supply-demand economics (S81).

In BioLUC, agricultural demand (for food or bioenergy) drives the creation of cropland from a latent land pool. In the default implementation, population pressure drives the conversion of Near Pristine Land (forest, grassland) to the latent land pool using a regression relating the population density and the fraction of deforested land as described by Köthke et al. (S80). However, this is insufficient if regional aggregate food yields are drastically changing, as promoted with algae food production. To account for the large changes in aggregate regional yield driven by algae, we incorporated into BioLUC a 4-variable regression, also demonstrated by Köthke et al. (S80), which predicts the fraction of deforested land as a function of: population pressure; yield; land suitability; and, forest share of total area. The latter two parameters are assumed to be constant over time and vary only by region. The former are calculated from population projections and aggregate crop yields which both vary by time and region. Aggregated crop yields and regression coefficients were recalculated using a combination of cereal and oil crop yields, but did not differ significantly from those published by Köthke et al. (S80).

All other default parameters for BioLUC were retained. While some parameters (e.g. population, nutritional demand, etc.) differed between GCAM and BioLUC, they were based on similar data sources (e.g. (S78)) and did not vary greatly. No attempts were made to harmonize these values. Like GCAM, aggregate consumer demand of crops is modeled as inelastic, but animal demand behaves slightly elastic, as it is responsive to product availability. Furthermore, unlike GCAM, animal diets in BioLUC are fixed and require an immutable proportion of commodity crops inputs (corn, oil crop, wheat, sugar, rice). Thus, as corn and oil crops are substituted by algal food, freed up land can be used for increased production of the other feed crops to enable increased animal production. While the increase in other crops is minor, the difference between this approach and GCAM’s highlights the importance of understanding how algal food products substitute for other products.

Validation was conducted for the energy target case from 2025-2050 due to limits of BioLUC’s base data. However, this was sufficient as most algal-driven land use change occurs during this period. Using default BioLUC parameters, we incorporated baseline demand for terrestrial energy crops and input regional algal food offsets of corn and oil crops. With the large-scale substitution of conventional crops with algal food, average crop yields increased significantly (Table S8), with four regions increasing to levels that lie outside the range of values used in the regression of Köthke et al. (S80). Still, 15 of 19 BioLUC regions were within the range of values used in the initial econometric regression. Subsequently, we assume that the model remains reasonably descriptive for our purposes, under these higher yields.

BioLUC divides arable lands into 4 categories: near pristine land (NPL), a combination of forest and natural grassland; crop land that is actively being used or left fallow, and includes managed pastures: latent land which includes unmanaged pastures, permanent meadows (natural grassland excluded); and abandoned land. NPL was disaggregated into forest and grassland based upon historical values for regional shares of each land type. Because of inconsistencies between GCAM and BioLUC’s land types (most notably the treatment of grassland), validation was performed on three aggregated land categories.
In response to algal food production, cropland reductions, forest increases, and other land increases were highly consistent between BioLUC and GCAM from 2025 to 2050 (Figure S 8). Application of various sources of vegetative coverage carbon density data (S76, S82, S83) to the LUC results obtained from BioLUC also generated similar LUC emissions results to that of GCAM, (data not shown). Comparison of the low carbon intensity scenario (run in GCAM) to BioLUC results highlights how policy (e.g. a universal carbon tax that constrains LUC) can influence model behavior. Further information on the use of various data sources and models in assessment of land use change and associated emissions is discussed elsewhere (S64, S65, S81, S84).
7 Figures

A. FD+FL Pathway

B. FL Pathway

C. FD Pathway

Figure S1. Simplified process diagrams for: (A) the food and fuel (FD+FL); (B) the fuel only (FL) pathways; and, (C) the food only (FD). Process inputs are only shown at the start of the process for simplicity.
Figure S 2. Production forecast for the energy target case showing algal food product generated with the FD+FL pathway. Production is assumed to remain constant after 2050. Energy output is identical between the FD+FL and FL pathways, but algal biomass production, land occupation, and cultivation sites differ substantially between the two pathways. 2050-2100 biomass production levels are 1.7 and 3.1 Gt for the FL and FD+FL pathways respectively. GCAM analysis is performed at 5-year intervals (black circles).
Figure S 3. Projected energy (A) and food product (B) annual yields for algae and conventional agriculture crops. Algal yields were calculated assuming a 2025 starting algal biomass yield of 22 g m$^{-2}$ d$^{-1}$ and an annual compounding growth rate of 2% per year. Net annual output yield was determined using the parameters in Table S 3. Conventional agriculture yields represent global averaged that were calculated using global production and land occupation values for each crop from the GCAM analysis of the no-algae reference case, high intensity scenario. Energy yields were calculated using energy transformation values from (S4).
Figure S 4. Production changes (pentagon arrows) and drivers (line arrows) for the FD+FL pathway. Size of pentagon arrows is intended to be generally descriptive of the magnitude of changes in demand for each product and is not precisely scaled to results. Sectors represented by white markers are not included in GCAM analysis due to uncertainties and model limitations. (A) Algae is assumed to be cultivated on non-arable land; (B) algal fuel product offsets conventional refined petroleum liquids, but algal cultivation and processing requires inputs of electricity and natural gas; (C) algal demands high fertilizer production, with nitrogen itself requiring; (D) generation of an algal food product offsets conventional agricultural production of substitutable crops, and increases animal production; (E) this reduces crop land and fertilizer requirements and (F) frees arable land for conversion to grassland, forest or pasture; (G) more pasture also enables more animal production; (H) while the decline in substitutable crop production also causes a decline in residual biomass, this is offset by additional biomass production driven by (I) higher land availability and electricity demand.
Figure S 5. Supply and demand curves for terrestrial crops showing the impact of the addition of economically competitive algal food product to substitutable crop markets (e.g. corn, oil crops) starting at an initial price ($P_0$) and production quantity ($Q_0$). The addition of competitive, low cost, algal food product causes the supply curve to shift rightward. Due to market elasticity, prices are lowered ($P_1$) and total quantity consumed increases ($Q_1$). Conventional crop production is subsequently reduced ($Q_1(crop)$). Crop demand curve is slightly elastic due to an elasticity in the demand for animal products, a crop consumer. Human consumption of crops is assumed to be perfectly inelastic.
Figure S 6. (A-C) Impact of food and fuel (FD+FL) and fuel only (FL) pathways on the production of terrestrial biomass for electricity in the energy target case, showing both high carbon intensity (HI) and low carbon intensity scenarios (LI). (D) Total agricultural biomass for energy. Changes in municipal solid waste (MSW) biomass for energy production were negligible and are not included here. Energy values represent total energy content of biomass. Actual generated electricity energy values are lower due to efficiency losses, which are large for older, yet extant, power plants.
Figure S7. Impact of yield improvement on production-sector (electricity, gas and fertilizer) emissions for (A) FD+FL, (B) FL and (C) FD pathways for the biomass target case in both the high emissions intensity (HI) and low emissions intensity (LI) scenarios. Production emissions in the LI scenario go negative due to electricity generation from bioenergy carbon capture and storage technologies.
Figure S 8. Model calculations of land use change from application of the FD+FL pathway to the energy target case using BioLUC (red), GCAM-low intensity (LI) (black) and GCAM-high intensity (HI) (green).
8 Tables

**Table S 1.** Output values for the 500 Mt algal biomass target case. Production is assumed to begin in 2025 and remain constant. Algal biomass cultivation and land occupation (non-arable) are consistent across all pathways (FD+FL - food and fuel; FD – food only; FL – fuel only).

|                      | FD+FL | FD  | FL  |
|----------------------|-------|-----|-----|
| Algal Biomass (Mt)   | 500   | 500 | 500 |
| Fuel Output (EJ)     | 4.54  | 0   | 8.20|
| Food Output (Mt)     | 362   | 500 | 0   |

**Table S 2.** Nutritional composition of LEA and selected food products. Due to their prevalence, soybeans are used as an example of oil crops. Compositional balance is mostly water and nutrients, except in the case of LEA which is reported as dry weight. *Energy values calculated using (S85)

|                      | Corn | Soybeans | Soybean Meal | Protein rich LEA (*Desmodesmus sp.*) | Carbohydrate-rich LEA (heterotrophic) |
|----------------------|------|----------|--------------|--------------------------------------|--------------------------------------|
| Ash (minerals)       | 3%   | 5%       | 6%           | 4%                                   | 6%                                   |
| Protein              | 9%   | 36%      | 49%          | 54%                                  | 10%                                  |
| Lipid                | 5%   | 20%      | 2%           | 13%                                  | 7%                                   |
| Carbohydrate         | 74%  | 30%      | 36%          | 29%                                  | 77%                                  |
| Energy (kcal/kg)     | 3650 | 4460     | 3370         | *4490                                | *4110                                |
| Reference            | (S86) | (S86)   | (S86)        | (S1)                                 | (S21)                                |
Table S 3. Production parameters and fuel product yields for algal platforms based upon (S26). *Algal oil energy content estimated using lipid composition data from (S38) and is assumed to be the same for lipids extracted in the FD+FL pathway and the biocrude produced in the FL pathway.

| Parameter                                    | Units                                      | Value   |
|----------------------------------------------|--------------------------------------------|---------|
| 2025 Algal Biomass Yield                     | g m$^{-2}$ d$^{-1}$ (ash-free dry weight)  | 22.0    |
| Productivity Improvement Rate                | y$^{-1}$                                   | 2%      |
| Facility Uptime (days)                       | days                                      | 330     |
| Facility Cultivation Footprint Fraction      | ha *cultivated* ha$^{-1}$ *occupied*      | 0.9     |
| Biomass Recovery Efficiency                  | kg *harvested* kg$^{-1}$ *cultivated*      | 92.0%   |
| FD+FL Oil Yield                              | kg *algal lipids* kg$^{-1}$ *algal biomass*| 27.7%   |
| FD+FL Food Yield                             | kg *algal food product* kg$^{-1}$ *algal biomass* | 72.3% |
| FL Oil Yield                                 | kg *algal lipids* kg$^{-1}$ *algal biomass* | 50.0%   |
| Algal Oil Energy Content*                    | MJ *algal lipids* kg$^{-1}$ *algal lipids* | 38.6    |
| Diesel Hydrogenation Upgrading Efficiency    | MJ *renewable diesel* MJ *algal lipids*  | 85.0%   |
| 2025 FD+FL Algal Food Yield                 | T ha$^{-1}$ yr$^{-1}$                      | 44.1    |
| 2025 FD Algal Food Yield                     | T ha$^{-1}$ yr$^{-1}$                      | 60.9    |
| 2025 FD+FL Biodiesel Yield                   | L ha$^{-1}$ yr$^{-1}$                      | 14,300  |
| 2025 FL Biodiesel Yield                      | L ha$^{-1}$ yr$^{-1}$                      | 25,900  |
| 2025 FD+FL Biodiesel Yield                   | gal ha$^{-1}$ yr$^{-1}$                    | 3,790   |
| 2025 FL Biodiesel Yield                      | gal ha$^{-1}$ yr$^{-1}$                    | 6,840   |
### Table S 4. Algal pathway inventories. *Improves with yield.

| Technology parameters                  | FD+FL (GJ⁻¹ Diesel) | FL (GJ⁻¹ Diesel) | FD (T⁻¹ Food) |
|----------------------------------------|----------------------|------------------|---------------|
| Nitrogen fertilizer (kg N)             | 8.63                 | 0.37             | 78.3          |
| Phosphorus fertilizer (kg P₂O₅)       | 1.79                 | 0.15             | 16.2          |
| CO₂ fertilizer (t CO₂)                 | 0.27                 | 0.15             | 2.45          |
| Electricity, cultivation & extraction (GJ)* |          |                  |               |
| 2025 (Starting)                        | 0.648                | 0.313            | 4.84          |
| 2030                                   | 0.586                | 0.283            | 4.38          |
| 2035                                   | 0.530                | 0.256            | 3.96          |
| 2040                                   | 0.479                | 0.231            | 3.58          |
| 2045                                   | 0.433                | 0.209            | 3.23          |
| 2050-2100                              | 0.391                | 0.189            | 2.92          |
| Electricity, hydrotreatment (GJ)       | 0.022                | 0.022            | 0             |
| Heat, extraction (GJ)*                 |                      |                  |               |
| 2025 (Starting)                        | 0.037                | 0                | 0             |
| 2030                                   | 0.033                | 0                | 0             |
| 2035                                   | 0.030                | 0                | 0             |
| 2040                                   | 0.027                | 0                | 0             |
| 2045                                   | 0.025                | 0                | 0             |
| 2050-2100                              | 0.022                | 0                | 0             |
| Heat, hydrotreatment (GJ)              | 0.023                | 0.023            | 0             |
| Biomass harvested (dry kg)             | 110.2                | 61.0             | 1000          |
| Algal Food Output Total (dry kg)       | 79.7                 | 0                | 1000          |
| % allocated to Corn                    | Regional (Table S 5) | 0                | Regional (Table S 5) |
| % allocated Oil Crops                  | Regional (Table S 5) | 0                | Regional (Table S 5) |
| Region                | Land Area (Mha) | Global Algae Share (%) | 2050 Production Values (energy target case) | Algal food product disposition (both cases) |
|----------------------|-----------------|------------------------|--------------------------------------------|---------------------------------------------|
|                      |                 |                        | FL and FD+FL (EJ) | FL Land (Mha) | FD+FL Land (Mha) | FD+FL Food Product (MT) | Corn (%) | Soy (%) |
| USA                  | 916             | 4                      | 10.6            | 2.94         | 1.79            | 3.24                  | 235      | 78      | 22      |
| Africa Eastern       | 516             | 3.5                    | 5.2             | 1.45         | 0.89            | 1.60                  | 116      | 63      | 37      |
| Africa Northern      | 600             | 4.5                    | 7.8             | 2.17         | 1.32            | 2.39                  | 173      | 84      | 16      |
| Africa Southern      | 558             | 2                      | 3.2             | 0.90         | 0.55            | 0.99                  | 72       | 56      | 44      |
| Africa Western       | 1,131           | 3                      | 9.8             | 2.73         | 1.66            | 3.01                  | 217      | 25      | 75      |
| Australia NZ         | 795             | 4.6                    | 1.28            | 0.78         | 1.41            | 102                   | 13       | 87      |
| Brazil               | 836             | 5.12                   | 3.36            | 2.05         | 3.70            | 268                   | 39       | 61      |
| Canada               | 909             | 0                      | 0.0             | 0.00         | 0.00            | 0.00                  | 0        | 0       | 0       |
| Cent Am & Caribbean  | 72              | 5.1                    | 1.0             | 0.29         | 0.18            | 0.32                  | 23       | 71      | 29      |
| Central Asia         | 566             | 0                      | 1.5             | 0.00         | 0.00            | 0.00                  | 0        | 0       | 0       |
| China                | 943             | 2.55                   | 1.51            | 0.92         | 1.67            | 121                   | 26       | 74      |
| EU-12                | 106             | 1                      | 0.3             | 0.08         | 0.05            | 0.09                  | 7        | 79      | 21      |
| EU-15                | 355             | 1.0                    | 1.0             | 0.29         | 0.17            | 0.31                  | 23       | 26      | 74      |
| Europe Eastern       | 82              | 1                      | 0.2             | 0.07         | 0.04            | 0.07                  | 5        | 15      | 85      |
| Europe Non EU        | 113             | 1                      | 0.3             | 0.09         | 0.06            | 0.10                  | 7        | 21      | 79      |
| Eur. Free Trade Assn.| 51              | 0                      | 0.0             | 0.00         | 0.00            | 0.00                  | 0        | 0       | 0       |
| India                | 297             | 5                      | 4.3             | 1.19         | 0.73            | 1.32                  | 95       | 5       | 95      |
| Indonesia            | 181             | 5                      | 2.6             | 0.73         | 0.44            | 0.80                  | 58       | 26      | 74      |
| Japan                | 36              | 2                      | 0.2             | 0.06         | 0.04            | 0.06                  | 5        | 81      | 19      |
| Mexico               | 194             | 5                      | 2.8             | 0.78         | 0.48            | 0.86                  | 62       | 24      | 76      |
| Middle East          | 547             | 5.79                   | 2.20            | 1.34         | 2.42            | 175                   | 87       | 13      |
| Pakistan             | 77              | 5                      | 1.1             | 0.31         | 0.19            | 0.34                  | 25       | 28      | 72      |
| Russia               | 1,638           | 0                      | 0.0             | 0.00         | 0.00            | 0.00                  | 0        | 0       | 0       |
| South Africa         | 121             | 5                      | 1.8             | 0.49         | 0.30            | 0.54                  | 39       | 3       | 97      |
| S. America Northern  | 132             | 5                      | 1.9             | 0.53         | 0.32            | 0.58                  | 42       | 78      | 22      |
| S. America Southern  | 393             | 4                      | 4.6             | 1.26         | 0.77            | 1.39                  | 101      | 67      | 33      |
| South Asia           | 103             | 5                      | 1.5             | 0.41         | 0.25            | 0.46                  | 33       | 60      | 40      |
| South Korea          | 10              | 1                      | 0.0             | 0.01         | 0.00            | 0.01                  | 1        | 60      | 40      |
| Southeast Asia       | 318             | 5                      | 4.6             | 1.28         | 0.78            | 1.41                  | 102      | 26      | 74      |
| Taiwan               | 0               | 0                      | 0.0             | 0.00         | 0.00            | 0.00                  | 0        | 0       | 0       |
| Argentina            | 274             | 4                      | 3.2             | 0.88         | 0.54            | 0.97                  | 70       | 78      | 22      |
| Colombia             | 111             | 5                      | 1.6             | 0.45         | 0.27            | 0.49                  | 36       | 63      | 37      |

**Global** 12,981 100 27.73 16.91 30.57 2,211
Table S 6. Carbon tax used to generate low emissions intensity (LI) scenario in GCAM.

| Year | Tax (1975$/tonC) |
|------|------------------|
| 2020 | 22.72            |
| 2025 | 29.00            |
| 2030 | 37.01            |
| 2035 | 47.23            |
| 2040 | 60.28            |
| 2045 | 76.94            |
| 2050 | 98.20            |
| 2055 | 125.33           |
| 2060 | 159.95           |
| 2065 | 204.14           |
| 2070 | 260.54           |
| 2075 | 332.53           |
| 2080 | 354.29           |
| 2085 | 389.40           |
| 2090 | 413.49           |
| 2095 | 450.43           |
| 2100 | 487.37           |
Table S 7. Land occupation and cumulative land development emissions for algal production in comparison to pathway indirect land use change (iLUC) and net cumulative emissions for high carbon intensity (HI) and low carbon intensity (LI) scenarios.

| Target Case | Pathway | Full Land Occupation (Mha) | Estimated Maximum Land Development Emissions (Gt CO₂) | Cumulative iLUC Emissions (2025-2050, HI) | Net Cumulative Emissions (2025-2050, HI) | Cumulative iLUC Emissions (2025-2050, LI) | Net Cumulative Emissions (2025-2050, LI) |
|-------------|---------|-----------------------------|------------------------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|
| Energy      | FD+FL   | 30.6                        | 2.49                                                 | -66.94                                 | -81.79                                 | -59.24                                 | -70.06                                 |
|             | FL      | 16.9                        | 1.38                                                 | 0.25                                   | -29.41                                 | 0.06                                   | -24.19                                 |
| Biomass     | FD+FL   | 7.7                         | 0.67                                                 | -11.87                                 | -14.80                                 | -14.95                                 | -16.27                                 |
|             | FD      | 7.7                         | 0.67                                                 | -17.06                                 | -9.17                                  | -20.89                                 | -13.27                                 |
|             | FL      | 7.7                         | 0.67                                                 | 0.02                                   | -15.70                                 | 0.02                                   | -12.50                                 |
Table S 8. Average regional food yields (T ha\(^{-1}\)) for BioLUC regions in the energy target scenario. Food products used to calculate yields included corn, oil crops, wheat, rice and algae, with algae contributing no land food print in yield calculation. Values that lie outside those used in the original regression (S80) are in boldface.

| BioLUC Region | 2015 | 2050 FD+FL | % Change |
|---------------|------|------------|----------|
| BRAZIL        | 3.4  | **16.9**   | 404%     |
| C_C_Amer      | 3.1  | **16.0**   | 419%     |
| CAN           | 2.8  | 3.5        | 26%      |
| CHIHKG        | 3.9  | 4.4        | 11%      |
| E_Asia        | 2.4  | 3.4        | 42%      |
| EU27          | 4.4  | 5.9        | 34%      |
| INDIA         | 1.7  | 3.2        | 87%      |
| JAPAN         | 7.7  | 7.7        | 0%       |
| Mala_Indo     | 3.4  | 6.4        | 90%      |
| MEAS_Nafr     | 1.7  | 7.1        | 319%     |
| Oceania       | 1.6  | 5.9        | 280%     |
| Oth_CEE_CIS   | 2.3  | 2.7        | 17%      |
| R_Europe      | 4.0  | 3.9        | -1%      |
| R_S_Asia      | 2.5  | 4.1        | 67%      |
| R_SE_Asia     | 3.4  | 4.5        | 33%      |
| Russia        | 2.4  | 4.2        | 74%      |
| S_o_Amer      | 3.2  | **17.4**   | 447%     |
| S_S_AFR       | 1.1  | 3.9        | 245%     |
| USA           | 5.1  | **11.1**   | 117%     |
Table S 9. Correspondence of land categories between BioLUC and GCAM.

| GCAM Category     | Corresponding BioLUC Category | Aggregated Category (Figure S 8) |
|-------------------|-------------------------------|----------------------------------|
| biomass           | Crops                         | Crops                            |
| crops             | Crops                         | Crops                            |
| forest (managed)  | Near Pristine Land            | Forest                           |
| forest (unmanaged)| Near Pristine Land            | Forest                           |
| grass             | Near Pristine Land, Latent Land| Other                            |
| otherarable       | Latent Land, Abandoned Land   | Other                            |
| pasture (grazed)  | Crops                         | Crops                            |
| pasture (other)   | Latent Land                   | Other                            |
| shrubs            | Near Pristine Land            | Other                            |

9 References

S1. M. Huntley et al., Demonstrated Large-Scale Production of Marine Microalgae for Fuels and Feed. Algal Res. 10, 249–265 (2015).

S2. International Energy Agency, “Energy Technology Perspectives 2015: Mobilising Innovation to Accelerate Climate Action” (Paris France, 2015), (available at http://www.iea.org/).

S3. S. H. Kim et al., The ObjECTS Framework for Integrated Assessment: Hybrid Modeling of Transportation. Energy J. 27, 63–91 (2006).

S4. P. Kyle et al., “GCAM 3.0 Agriculture and Land Use: Data Sources and Methods” (2011).

S5. M. Wise, K. Calvin, GCAM 3.0 Agriculture and Land Use Modeling: Technical Description of Modeling Approach (2011) (available at https://wiki.umd.edu/gcam/images/8/87/GCAM3AGTechDescript12_5_11.pdf).

S6. G. F. Combs, Algae (Chlorella) as a Source of Nutrients for the Chick. Science. 116, 453–454 (1952).

S7. J. M. Hundley, R. B. Ing, R. W. Krauss, Algae as Sources of Lysine and Threonine in Supplementing Wheat and Bread Diets. Science. 124, 536–537 (1956).

S8. W. Belasco, Algae Burgers for a Hungry World? The Rise and Fall of Chlorella Cuisine. Technol. Cult. (1997), doi:10.2307/3106856.

S9. J. Sheehan, T. Dunahay, J. Benemann, P. Roessler, “A Look Back at the U.S. Department of Energy’s Aquatic Species Program: Biodiesel from Algae; Close-Out Report” (Golden, CO, 1998), doi:10.2172/15003040.

S10. P. J. le B. Williams, L. M. L. Laurens, Microalgal as biodiesel & biomass feedstocks: Review & analysis of the biochemistry, energetics & economics. Energy Environ. Sci. 3, 554 (2010).

S11. H. L. Bryant et al., The value of post-extracted algae residue. Algal Res. 1, 185–193 (2012).

S12. A. Maisashvili et al., The values of whole algae and lipid extracted algae meal for aquaculture. Algal Res. 9, 133–142 (2015).
S13. A. P. Batista, L. Gouveia, N. M. Bandarra, J. M. Franco, A. Raymundo, Comparison of microalgal biomass profiles as novel functional ingredient for food products. *Algal Res.* **2**, 164–173 (2013).

S14. S. Gatrell, K. Lum, J. Kim, X. G. Lei, Nonruminant nutrition symposium: Potential of defatted microalgae from the biofuel industry as an ingredient to replace corn and soybean meal in swine and poultry diets. *J. Anim. Sci.* **92**, 1306–1314 (2014).

S15. X. Leng, K.-N. Hsu, R. E. Austic, X. G. Lei, Effect of dietary defatted diatom biomass on egg production and quality of laying hens. *J. Anim. Sci. Biotechnol.* **5**, 3 (2014).

S16. R. E. Austic, A. Mustafa, B. Jung, S. Gatrell, X. G. Lei, Potential and limitation of a new defatted diatom microalgal biomass in replacing soybean meal and corn in diets for broiler chickens. *J. Agric. Food Chem.* **61**, 7341–8 (2013).

S17. R. Ekmay, S. Gatrell, K. Lum, J. Kim, X. G. Lei, Nutritional and metabolic impacts of a defatted green marine microalgal (Desmodesmus sp.) biomass in diets for weanling pigs and broiler chickens. *J. Agric. Food Chem.* **62**, 9783–9791 (2014).

S18. R. D. Ekmay, K. Chou, A. Magnuson, X. G. Lei, Continual feeding of two types of microalgal biomass affected protein digestion and metabolism in laying hens. *J. Anim. Sci.* **93**, 287–97 (2015).

S19. V. Kiron *et al.*, Defatted biomass of the microalga, Desmodesmus sp., can replace fishmeal in the feeds for Atlantic salmon. *Front. Mar. Sci.* **3** (2016), doi:10.3389/fmars.2016.00067.

S20. M. L. Drewery, J. E. Sawyer, W. E. Pinchak, T. a Wickersham, Effect of increasing amounts of postextraction algal residue on straw utilization in steers. *J. Anim. Sci.* **92**, 4642–4649 (2014).

S21. M. L. Van Emon, D. D. Loy, S. L. Hansen, Determining the preference, in vitro digestibility, in situ disappearance, and grower period performance of steers fed a novel algae meal derived from heterotrophic microalgae. *J. Anim. Sci.* **93**, 3121–3129 (2015).

S22. C. Enzing, M. Ploeg, M. Barbosa, L. Sijtsma, *Microalgae-based products for the food and feed sector: an outlook for Europe* (2014; ftp://ftp.jrc.es/pub/EURdoc/EURdoc/JRC85709.pdf).

S23. S. K. Gatrell, J. Kim, T. J. Derksen, E. V O’Neil, X. G. Lei, Creating ω-3 Fatty-Acid-Enriched Chicken Using Defatted Green Microalgal Biomass. *J. Agric. Food Chem.* **63**, 9315–22 (2015).

S24. E. W. Becker, Micro-algae as a source of protein. *Biotechnol. Adv.* **25**, 207–210 (2007).

S25. G. Brooks *et al.*, Novel microalgal food compositions (2012), (available at https://www.google.com/patents/US20120128851).

S26. C. M. Beal *et al.*, Algal biofuel production for fuels and feed in a 100-ha facility: A comprehensive techno-economic analysis and life cycle assessment. *Algal Res.* **10**, 266–279 (2015).

S27. E. Frank, J. Han, I. Palou-Rivera, a. Elgowainy, M. Q. Wang, Life-Cycle Analysis of Algal Lipid Fuels with the GREET Model. *Cent. Transp. ...* (2011), doi:ANL/ESD/11-5.
S28. R. Davis et al., Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion Process Design and Economics for the Production of Algal Biomass: Algal Biomass P (2016).

S29. International Energy Agency, *World Energy Outlook 2014* (2014).

S30. International Energy Agency, “2014 Energy Technology Perspectives: Harnessing Electricity’s Potential” (2014).

S31. T. Bruckner et al., “Chapter 7. Energy Systems” (2014), (available at https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_full.pdf).

S32. V. Maddali, G. A. Tularam, P. Glynn, Economic and Time-Sensitive Issues Surrounding CCS: A Policy Analysis. *Environ. Sci. Technol.* (2015), doi:10.1021/acs.est.5b00839.

S33. M. M. F. Hasan, F. Boukouvala, E. L. First, C. A. Floudas, Nationwide, regional, and statewide CO2 Capture, Utilization, and Sequestration supply chain network optimization. *Ind. Eng. Chem. Res.* 53, 7489–7506 (2014).

S34. J. Gale et al., “Chapter 2. Sources of CO2” (2005), (available at http://www.ipcc-wg3.de/publications/special-reports/files-images/SRCCS-Chapter2.pdf).

S35. R. Davis, C. Kinchin, J. Markham, E. C. D. Tan, L. M. L. Laurens, Process Design and Economics for the Conversion of Algal Biomass to Biofuels: Algal Biomass Fractionation to Lipid- and Carbohydrate-Derived Fuel Products (2014).

S36. D. L. Sills et al., Quantitative uncertainty analysis of Life Cycle Assessment for algal biofuel production. *Environ. Sci. Technol.* 47, 687–94 (2013).

S37. C. M. Beal, R. E. Hebner, M. E. Webber, R. S. Ruoff, A. F. Seibert, The Energy Return on Investment for Algal Biocrude: Results for a Research Production Facility. *BioEnergy Res.* 5, 341–362 (2011).

S38. S. B. Jones et al., *Process design and economics for the conversion of algal biomass to hydrocarbons: whole algae hydrothermal liquefaction and upgrading* (Pacific Northwest National Laboratory, 2014).

S39. S. Jones, P. Meyer, L. Snowden-Swan, Process design and economics for the conversion of lignocellulosic biomass to hydrocarbon fuels: fast pyrolysis and hydrotreating bio-oil pathway, NREL/TP–5100–61178 (2013).

S40. D. C. Elliott et al., *Catalytic hydrothermal gasification of lignin-rich biorefinery residues and algae* (Pacific Northwest National Laboratory Richland, WA, 2009).

S41. U. EPA, “Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis” (Washington, D.C., 2010), (available at http://www.epa.gov/oms/renewablefuels/420r10006.pdf).

S42. *OECD-FAO Agricultural Outlook 2015-2024* (2015).
S43. J. A. Burney, S. J. Davis, D. B. Lobell, Greenhouse gas mitigation by agricultural intensification. *Proc. Natl. Acad. Sci. U. S. A.* 107, 12052–7 (2010).

S44. J. C. Quinn, R. Davis, The potentials and challenges of algae based biofuels: A review of the techno-economic, life cycle, and resource assessment modeling. *Bioresour. Technol.* (2014), doi:10.1016/j.biortech.2014.10.075.

S45. J. W. Moody, C. M. McGinty, J. C. Quinn, Global evaluation of biofuel potential from microalgae. *Proc. Natl. Acad. Sci. U. S. A.* 111, 8691–6 (2014).

S46. M. A. Scaife, A. Merkx-Jacques, D. L. Woodhall, R. E. Armenta, Algal biofuels in Canada: Status and potential. *Renew. Sustain. Energy Rev.* 44, 620–642 (2015).

S47. 110th Congress of the United States of America, *Energy Independence and Security Act of 2007* (USA, 2007).

S48. M. S. Wigmosta, A. M. Coleman, R. J. Skaggs, M. H. Huesemann, L. J. Lane, *Water Resour. Res.*, in press, doi:10.1029/2010WR009966.

S49. E. R. Venteris, R. L. Skaggs, A. M. Coleman, M. S. Wigmosta, An assessment of land availability and price in the coterminous United States for conversion to algal biofuel production. *Biomass and Bioenergy* 47, 483–497 (2012).

S50. R. Davis, D. Fishman, E. Frank, M. Wigmosta, “Renewable Diesel from Algal Lipids: An Integrated Baseline for Cost, Emissions, and Resource Potential from a Harmonized Model” (2012), (available at http://www.algaebiomass.org/wp-content/uploads/2012/11/NREL_AlgalDieselResourcePotential.pdf).

S51. E. R. Venteris, R. L. Skaggs, A. M. Coleman, M. S. Wigmosta, A GIS cost model to assess the availability of freshwater, seawater, and saline groundwater for algal biofuel production in the United States. *Environ. Sci. Technol.* 47, 4840–9 (2013).

S52. R. E. Davis et al., Integrated evaluation of cost, emissions, and resource potential for algal biofuels at the national scale. *Environ. Sci. Technol.* 48, 6035–42 (2014).

S53. E. R. Venteris, R. L. Skaggs, M. S. Wigmosta, A. M. Coleman, A national-scale comparison of resource and nutrient demands for algae-based biofuel production by lipid extraction and hydrothermal liquefaction. *Biomass and Bioenergy* 64, 276–290 (2014).

S54. E. R. Venteris, R. C. McBride, A. M. Coleman, R. L. Skaggs, M. S. Wigmosta, Siting algae cultivation facilities for biofuel production in the united states: Trade-offs between growth rate, site constructability, water availability, and infrastructure. *Environ. Sci. Technol.* 48, 3559–3566 (2014).

S55. M. Wise et al., An approach to computing marginal land use change carbon intensities for bioenergy in policy applications. *Econ. Model.* 47, 307–318 (2015).

S56. A. M. Thomson et al., Climate mitigation and the future of tropical landscapes. *Proc. Natl. Acad. Sci. U. S. A.* 107, 19633–8 (2010).
S57. K. Calvin et al., Trade-offs of different land and bioenergy policies on the path to achieving climate targets. *Clim. Change.* 123, 691–704 (2013).

S58. M. Wise et al., Implications of Limiting CO2 Concentrations for Land Use and Energy. *Science.* 324, 1183–1186 (2009).

S59. M. Wise, J. Dooley, P. Luckow, K. Calvin, P. Kyle, Agriculture, land use, energy and carbon emission impacts of global biofuel mandates to mid-century. *Appl. Energy.* 114, 763–773 (2014).

S60. A. A. Fawcett et al., Can Paris pledges avert severe climate change? *Science* (2015), doi:10.1126/science.aad5761.

S61. M. Hulme, S. C. B. Raper, T. M. L. Wigley, An integrated framework to address climate change (ESCAPE) and further developments of the global and regional climate modules (MAGICC). *Energy Policy.* 23, 347–355 (1995).

S62. A. M. Thomson et al., RCP4.5: a pathway for stabilization of radiative forcing by 2100. *Clim. Change.* 109, 77–94 (2011).

S63. P. Smith et al., Biophysical and economic limits to negative CO2 emissions. *Nat. Clim. Chang.* (2015), doi:10.1038/nclimage2870.

S64. R. J. Plevin, J. Beckman, A. a. Golub, J. Witcover, M. O’Hare, Carbon Accounting and Economic Model Uncertainty of Emissions from Biofuels-Induced Land Use Change. *Environ. Sci. Technol.*, 150213094002002 (2015).

S65. T. Searchinger, R. Edwards, D. Mulligan, R. Heimlich, R. Plevin, Do biofuel policies seek to cut emissions by cutting food? *Science.* 347, 1420–1422 (2015).

S66. U.S. Geological Survey, “Mineral Commodity Summaries 2015” (2015), doi:http://dx.doi.org/10.3133/70140094.

S67. N. Gilbert, Environment: The disappearing nutrient. *Nature.* 461, 716–8 (2009).

S68. C. E. Canter, P. Blowers, R. M. Handler, D. R. Shonnard, Implications of widespread algal biofuels production on macronutrient fertilizer supplies: Nutrient demand and evaluation of potential alternate nutrient sources. *Appl. Energy.* 143, 71–80 (2015).

S69. T. F. Stocker et al., Climate change 2013: The physical science basis. *Intergov. Panel Clim. Chang. Work. Gr. I Contrib. to IPCC Fifth Assess. Rep. (AR5)(Cambridge Univ Press. New York)* (2013).

S70. L. N. H. Gerber, J. W. Tester, C. M. Beal, M. Huntley, D. Sills, Target cultivation and financing parameters for sustainable production of fuel and feed from microalgae. *Environ. Sci. Technol.*, acs.est.5b05381 (2016).

S71. Z. Zhu, B. C. Reed, Baseline and projected future carbon storage and greenhouse-gas fluxes in ecosystems of the eastern United States (US Geological Survey, 2014).

S72. S. Liu et al., in Baseline and Projected Future Carbon Storage and Greenhouse-Gas Fluxes in
Ecosystems of the Western United States, Z. Zhu, B. C. Reed, Eds. (US Geological Survey, 2012), pp. 45–63.

S73. K. Wagener, Mass cultures of marine algae for energy farming in coastal deserts. *Int. J. Biometeorol.* **27**, 227–233 (1983).

S74. V. K. Arora, A. Montenegro, Small temperature benefits provided by realistic afforestation efforts. *Nat. Geosci.* **4**, 514–518 (2011).

S75. A. D. Jones, K. V. Calvin, W. D. Collins, J. Edmonds, Accounting for radiative forcing from albedo change in future global land-use scenarios. *Clim. Change.* **131**, 691–703 (2015).

S76. ecoinvent (2013), (available at http://www.ecoinvent.org/).

S77. M. M. Mekonnen, A. Y. Hoekstra, The green, blue and grey water footprint of crops and derived crop products. *Hydrol. Earth Syst. Sci.* **15**, 1577–1600 (2011).

S78. FAO Statistics Division, “FAOSTAT” (2015), (available at http://faostat3.fao.org/home/E).

S79. E. Warner et al., Modeling biofuel expansion effects on land use change dynamics. *Environ. Res. Lett.* **8**, 015003 (2013).

S80. M. Köthke, B. Leischner, P. Elsasser, Uniform global deforestation patterns — An empirical analysis. *For. Policy Econ.* **28**, 23–37 (2013).

S81. E. Warner, Y. Zhang, D. Inman, G. Heath, Challenges in the estimation of greenhouse gas emissions from biofuel-induced global land-use change. *Biofuels, Bioprod. Biorefining.* **8**, 114–125 (2014).

S82. E. J. Lindquist et al., Global forest land-use change 1990-2005. *FAO For. Pap.* (2012).

S83. N. L. Harris et al., Baseline map of carbon emissions from deforestation in tropical regions. *Science.* **336**, 1573–6 (2012).

S84. L. Panichelli, E. Gnansounou, Impact of agricultural-based biofuel production on greenhouse gas emissions from land-use change : Key modelling choices. *Renew. Sustain. Energy Rev.* **42**, 344–360 (2015).

S85. Council Directive of 24 September 1990 on nutrition labelling for foodstuffs (90/496/EEC) (Luxembourg: European Commission, 1990; http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1990L0496:20081211:EN:PDF), vol. L276.

S86. USDA, “National Nutrient Database for Standard Reference” (2014), (available at http://www.ars.usda.gov/Services/docs.htm?docid=8964).