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Environmental Life Cycle Comparison of Algae to Other Bioenergy Feedstocks

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Algae are an attractive source of biomass energy since they do not compete with food crops and have higher energy yields per area than terrestrial crops. In spite of these advantages, algae cultivation has not yet been compared with conventional crops from a life cycle perspective. In this work, the impacts associated with algae production were determined using a stochastic life cycle model and compared with switchgrass, canola, and corn farming. The results indicate that these conventional crops have lower environmental impacts than algae in energy use, greenhouse gas emissions, and water regardless of cultivation location. Only in total land use and eutrophication potential do algae perform favorably. The large environmental footprint of algae cultivation is driven predominantly by upstream impacts, such as the demand for CO_2 and fertilizer. To reduce these impacts, flue gas and, to a greater extent, wastewater could be used to offset most of the environmental burdens associated with algae. To demonstrate the benefits of algae production coupled with wastewater treatment, the model was expanded to include three different municipal wastewater effluents as sources of nitrogen and phosphorus. Each provided a significant reduction in the burdens of algae cultivation, and the use of source-separated urine was found to make algae more environmentally beneficial than the terrestrial crops.

Introduction

The promise of sustainable energy production from algae has generated tremendous interest in recent years (*1*, *2*). Petroleum shortages and the climate implications of combusting proven reserves have driven research and business ventures into algae-based fuels (*3*). This attention stems from several of algae's seemingly desirable characteristics that set it apart from other biomass sources. The first of these is that algae tend to produce more biomass than terrestrial plants per unit area, and unlike terrestrial plants, they can be cultivated on otherwise marginal land using freshwater or saltwater (*4*). A fast-growing aquatic alternative to conventional crops is appealing since most developed nations consume more energy than they could offset using slow-growing terrestrial crops (*5*). A second characteristic is that algae do not compete directly with food crops (*3*). The United States ethanol boom of 2008 was one of many factors that contributed to a spike in corn prices worldwide, raising complex ethical issues that could be avoided by production of separate crops for food and fuel (*6*, *7*). The third characteristic is that algae, by virtue of their fast growth rates and aquatic habitat, could be cultivated in systems designed for simultaneous biomass production, uptake of anthropogenic CO_2, and removal of certain water pollutants (*8*, *9*). Although both algae and terrestrial photosynthetic organisms tend to grow faster in the presence of slightly elevated CO_2 and nutrient levels, these nutrients are more easily delivered to algae than to terrestrial plants.

There has been steady interest in algae-to-energy systems over the past several decades. Between 1980 and the mid-1990s, research was largely focused on identifying strains exhibiting high lipid content with the objective of using algae-extracted lipids to make liquid fuels (*3*). More recent efforts have investigated the use of genetic modifications to enhance lipid production or induce lipid excretion (*10*). Complementing these efforts have been a host of studies investigating algae growth rates in the presence of flue gas, optimal growth and lipid yields under different light fluxes (*11*), reactor configurations (*12*), or nutrient loads (*9*). Previous pilot-scale operations have demonstrated that monoculture systems can be prone to contamination, indicating that cultivation of mixed native communities may result in more robust operation despite the potential decrease in lipid content (*13*). Finally, economic analyses have shown that photobioreactors are unlikely to scale efficiently and that unlined ponds may be the most reasonable configuration for algae cultivation at large scale (*8*). Despite this tremendous increase in understanding, important questions remain, many of them focused on (1) algae cultivation methods and (2) chemical conversion of algae biomass into fuels.

The inefficiencies associated with biomass production and subsequent conversion to biofuel have been individually investigated to varying extents in recent work (*14*, *15*). Conventional practice relies on chemical (e.g., lipids to biodiesel via esterification), biochemical (e.g., corn to ethanol via fermentation), or thermochemical (e.g., switchgrass to syngas via pyrolysis) conversion processes. Some analyses suggest that biomass energy is more efficiently leveraged via electricity production, even for transportation applications (*16*). Additional work has highlighted the significant energy and water demand associated with ethanol production from commodity crops, most notably corn (*17*). Farrell et al. (2006) demonstrated that current corn ethanol technologies are net energy positive but have greenhouse gas emissions on par with petroleum fuels (*18*). Although water demand during algae cultivation has not been directly addressed in the preliminary algae LCA analyses published to date (*19*, *20*), it seems likely that cultivation in open ponds and significant fertilizer requirements may make algae-derived energy as water intensive as terrestrial crops. Taken together, these analyses seem to suggest that the environmental burdens of producing energy from biomass could be greater than those associated with petroleum-based fuels. In light of these results, full-cost accounting via life cycle assessment (LCA) has become critical for optimizing biomass-to-fuel production systems. Specific questions of interest include which crops are best suited for conversion into energy carriers, which locations are best suited to growing a particular energy crop, and which process modifications can minimize overall environmental burdens.

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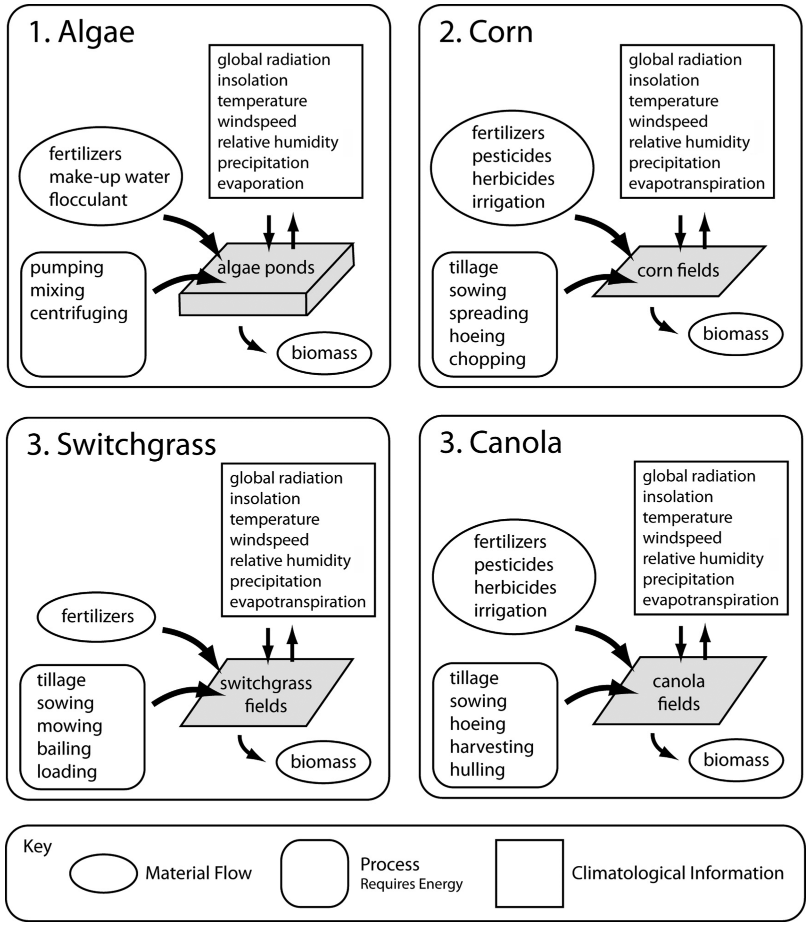

FIGURE 1. Schematic of systems considered in this work. Model scope includes all upstream processing of biomass material. Conversion to liquid or solid fuel is intentionally excluded.

With respect to algae, the life cycle burdens of the cultivation processes in particular have not been reported. While some aspects of the fuel production system have been studied (*21*), several questions remain largely unanswered. For example, the influence of regional climate, water availability, nutrient supply, and harvesting technology has not been conclusively quantified. The work of Kadam has explored the use of flue gas as a carbon source for producing algae near power plants (*20*). This work effectively identified some of the limiting factors associated with algae production, such as fertilizers, but it only touched on these and did not include the effects of regional yields nor did it compare algae with conventional bioenergy crops. Work by Lardon et al. summarizes the life cycle implications of algae-to-fuel conversions without detailing the cultivation burdens (*21*). The purpose of this paper is to combine data from previously published pilot-scale demonstration projects, climactic records, and other sources into a stochastic life cycle model of algae cultivation processes (*8, 22*). The resulting environmental burdens are compared with switchgrass, corn, and canola, since these are leading contenders for production of next-generation biofuels. For all crops, the entire plant was used to facilitate comparison on a total energy basis. Biofuel conversion processes were excluded from the scope of this analysis because they have been explored in other papers. Moreover, it is expected that they should not impact the research question driving this work, namely, which biofeedstock produces the most biomass energy with the lowest environmental burden?

Life Cycle Model. The scope of this analysis includes those processes required for cultivation of biomass (Figure 1). A cradle-to-gate boundary was applied which includes all products and processes upstream of delivered dry biomass. The decision to exclude additional processing steps was based on uncertainties surrounding (1) conversion of algae into liquid fuels (*23*), (2) methods to produce liquid fuels from cellulosic material in general (*24*), and (3) the benefits of creating liquid fuels versus bioelectricity (*16*). The functional unit was chosen as 317 GJ of biomass-derived energy, an amount on the same order as the primary energy consumption of either one American, two Japanese, or three Polish citizens in 1 year (*25*).

The LCA model was built in spreadsheet format using the Crystal Ball predictive modeling suite. This software allows a user to run Monte Carlo analyses for complex systems by defining statistical distributions for input parameters (*26*). The program then automates sampling from the various input distributions and generates distributions of selected output parameters. The output from this LCA model are five impact areas of interest (with units): energy consumption (MJ), water use (m^3), greenhouse gas emissions (GHG) (kg CO_2 equiv), eutrophication potential (kg PO_4^- equiv), and land use (ha). A complete description of the modeling process can be found in the Supporting Information.

Model Inputs. The biomass production model was based on several data sources including 30 years of meteorological data (*27, 28*). Insolation and radiation use efficiencies were taken from the literature and used to compute biomass yield estimates as a function of photosynthetically active radiation. Biomass energy content for each crop was computed using a range of higher heating values (HHV) taken from the literature and fit to a triangular distribution. Likeliest values were 18.3 and 24.0 GJ/Mg for switchgrass and algae, respectively. Because both corn and canola are comprised of stover and grain/seed, it was necessary to take a mass-weighted average of HHVs over the entire crop. The resulting

TABLE 1. Five Life Cycle Burdens for Production of One Functional Unit of Energy (317 GJ) Algae, Corn, Canola, and Switchgrass in Virginia[a]

	land (ha)	energy (MJ) $\times 10^4$	GHG (kg CO_2 equiv) $\times 10^4$	water (m^3) $\times 10^4$	eutrophication (kg PO_4^- equiv)
algae	0.4 ± 0.05	30 ± 6.6	1.8 ± 0.58	12 ± 2.4	3.3 ± 0.86
corn	1.3 ± 0.3	3.8 ± 0.35	-2.6 ± 0.09	0.82 ± 0.19	26 ± 5.4
canola	2.0 ± 0.2	7.0 ± 0.83	-1.6 ± 0.10	1.0 ± 0.14	28 ± 5.8
switchgrass	1.7 ± 0.4	2.9 ± 0.27	-2.4 ± 0.18	0.57 ± 0.21	6.1 ± 1.7

[a] The standard deviation of each value is also presented (±). Additional information about the distributions is provided in the Supporting Information.

likeliest values for the whole crop were 16.4 and 20.0 GJ/Mg for corn and canola, respectively. The model was run for three locations: Virginia, Iowa, and California, in the United States. These were selected because they represent climactically distinct yet highly bioproductive regions. Annual yield estimates were computed for each crop in each location. Results were compared with external reports where possible and found to be consistent (see Supporting Information).

Life Cycle Inventory Data. Life cycle inventory data for corn grain, switchgrass silage, canola seed, fertilizers, electricity, and flocculants were obtained from the Ecoinvent database (*29*). The straw produced from corn and canola cultivation was also included in the energy estimates to capture maximal biomass productivity per land area (*30*). The model was developed to capture the impacts from growing corn kernels along with agricultural residues including stover, stalks, cobs, husks, and leaves. The effects on the model of using only the corn kernel are discussed in the Supporting Information. In all instances, data from the United States was sought; however, European Union data was used where United States data was unavailable. Transportation burdens were expected to account for only a small fraction of each crop's overall footprint; however, it was expected that crops with higher energy densities per unit weight would accrue lower transportation burdens for the same functional unit. Transportation of dry biomass from the production facility to an end user was thus modeled using a fixed distance of 100 km traveled via truck freight.

Algae Production Processes. Algae production was modeled in open ponds using a raceway configuration, a well-documented approach wherein slow-moving paddle wheels are used to aerate and circulate the algae growth medium (*8*, *22*). Other growth configurations have been proposed, most notably so-called "photobioreactors"; however, ponds appear to be the most promising option at present (*8*). It was assumed that fertilizers and flocculants were added as water is pumped into or out of the ponds so that no additional mixing is required. Harvesting was assumed to proceed via a combination of flocculation and centrifugation (*31*), consistent with pilot-scale demonstrations and conventional practice for the dewatering of biosolids during municipal wastewater treatment (*32*). CO_2 was bubbled into the ponds via an automated control system whereby the CO_2 was added to the medium to maintain dissolved gas levels and pH at a constant level.

The manufacture of algae pond infrastructure (e.g., paddle wheels, centrifuges, pumps, etc.) was estimated and found to be negligible relative to the other life cycle stages modeled here as discussed in the Supporting Information. For consistency, the manufacture of agricultural equipment was also not included in evaluation of corn, canola, or switchgrass. The energy to operate this machinery, mostly as diesel fuel or electricity, was included.

Wastewater Treatment (WWT) Offsets. A major focus of this work was to explore life cycle synergies between algae cultivation and wastewater treatment processes, and so three types of wastewater effluents were evaluated for their usefulness as nutrient sources. These include effluents from conventional activated sludge (CAS) and biological nitrogen removal (BNR) wastewater treatment plants (WWTPs), as well as source-separated urine (SSU). Offset WWT burdens were quantified using published life cycle impact data (*33*). It was assumed that treated wastewater effluents would be required to meet stringent Tier 4 standards under Virginia's Pollution Discharge Elimination System (VPDES). Effluent concentrations of total nitrogen (N) and total phosphorus (P) would have to be less than 3.0 and 0.1 mg/L, respectively (*34*).

Results and Discussion

Comparison among Crops. Energy production from algae, corn, canola, and switchgrass were compared on the basis of five life cycle impact categories. The terrestrial crops were found to have significantly lower energy use, greenhouse gas emissions, and water use than algae (Table 1). Energy production for all four crops is net positive, i.e., more energy is generated than consumed during biomass production. Algae cultivation emits more GHG than it sequesters, whereas use of corn, canola, or switchgrass results in net CO_2 uptake. The net emissions for all biofuels would be positive if the biomass is burned, but this result suggests that algae requires more fossil-based carbon to produce the same amount of bioenergy. The results for terrestrial crops, which have previously been investigated in a number of other life cycle studies, are consistent with published values. For example, to produce the functional unit used in this study, corn has been found to consume between 2.4×10^4 and 3.9×10^4 MJ (*35*) while switchgrass has been found to consume between 2.9×10^4 and 4.0×10^4 (*36*).

Land use is one impact in which algae offers a clear and appreciable improvement over corn, canola, and switchgrass. Algae cultivation uses land roughly 3.3 times more efficiently than corn, 4.3 times more efficiently than switchgrass, and 5 times more efficiently than canola. If corn were harvested only for the kernel, as is common practice, this disparity would be even larger since more land, roughly 100% more, would be needed to grow the same amount of biomass. Although the improvement offered by algae is less dramatic than has been suggested previously (*37*), the results suggest that algae cultivation will be less limited by land availability than conventional crops. The land use estimates indicate that algae cultivation on roughly 13% of the United States' land area could meet the nation's total annual energy consumption. In contrast, use of corn would require 41% of the total land area, while switchgrass and canola would require 56% and 66%, respectively. The land use changes implicit in large-scale bioenergy deployment are expected to have important implications for climate change and other impacts. These so-called 'indirect' changes are associated with conversion of arable land into production and were not included here. The focus of this work is to provide a comparative tool for already cultivated arable land, although future decisions to deploy bioenergy should consider the large-scale implications of land use changes.

It should also be mentioned that algae production processes are still in their infancy such that the system

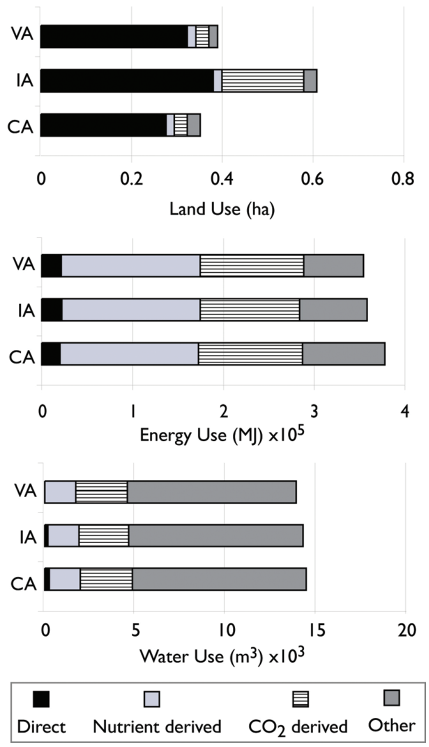

FIGURE 2. Land, energy, and water use impacts for production of algae in three different geographic locations (CA = California, IA = Iowa, VA = Virginia).

modeled here represents a first-generation approach to "algae farming". While it seems unlikely that dramatic improvements in corn, canola, or switchgrass cultivation will occur in the near future, significant improvements in algae cultivation could increase the favorability of energy production from algae over the next several decades. Eutrophication potential is the other impact category in which algae performs favorably relative to terrestrial crops. This quantity accounts for direct nutrient discharge from the algae ponds as well as upstream eutrophication (e.g., from production of fertilizers). Algae's lower impact relative to the terrestrial crops seems reasonable given that use of engineered ponds allows for better runoff control than terrestrial cultivation.

Comparison among Locations. Conventional wisdom holds that abundant sunlight is more important than access to abundant water in selecting a suitable location for algae cultivation. Previous demonstration project locations, including Southern California and New Mexico, were presumably selected because they experience abundant sunlight for most parts of the year. This is undoubtedly an important consideration since insolation is directly linked to yield. Still, access to abundant water is important because locations experiencing abundant sunlight tend to have particularly significant net evaporation losses. Thus, in selecting an optimal location for algae production, it is necessary to decide whether sunlight or water availability should be the principal consideration. For the case of our analyses, annual precipitation and evaporation were utilized as surrogates for evaluating geographic access to abundant water.

Figure 2 summarizes the relative suitability of Virginia, Iowa, and Southern California for production of one functional unit from algae and offers several insights related to the impacts of geography on cultivation impact. First and foremost, the overall magnitude of total energy use, total water use for algae production is approximately the same in each location. Comparison of 95% confidence intervals for the mean values presented in Table 1 (refer to Table S18 in the Supporting Information for comparison of confidence intervals at each location) indicates that the only statistically significant difference in any impact factor is the difference in land use between Iowa, which has the highest land requirement for algae, and California, which has the lowest. This arises because such a large fraction of each total burden comprises "upstream" use, i.e., the amounts of land, water, and energy required to produce CO_2, fertilizers, and electricity at some offsite location. The large magnitudes of these upstream values effectively swamp out different among direct (onsite) water and energy use. Still, if it were somehow possible to significantly reduce the need for CO_2 and chemical fertilizers, several subtle geographic differences in direct energy, water, and land use would become more apparent. First among these is the inverse relationship between direct energy use and direct land use. This arises because locations experiencing more intense sunlight (e.g., CA) are able to produce a higher density of algae per unit area, reducing energy consumption associated with biomass processing (e.g., centrifugation). Second, the most suitable location for algae production on the basis of land area is least suitable on the basis of water consumption. For the case of CA (best land use) versus VA (best water use), a 17% increase in direct land use mediates a 112% decrease in direct water use because average net evaporation is less than zero in Virginia.

Identifying Critical Burden Drivers. In light of algae's surprisingly poor performance relative to corn, canola, and switchgrass, a sensitivity analysis was undertaken to identify which components of the algae life cycle contribute most directly to its burdensome footprint. Arguably, these should be areas of active research if algae are to become a feasible, carbon-neutral replacement for fossil fuels. The results of this sensitivity analysis are presented as tornado plots in Figure 3. These figures can be interpreted as follows: the magnitude of each bar indicates the difference in average output (e.g., energy use) associated with a 10% change of a single input from its average value. All other inputs are held constant. Changes in output associated with an increase or decrease of input values are indicated on each side of the centerline (base case) using dark and light shading, respectively.

As seen in Figure 3, energy use and GHG emissions during algae cultivation are sensitive to, and thus in some sense driven by, the following inputs: algae high heating value (HHV) (i.e., the energy content embodied by algal biomass and released during combustion), CO_2 production/use, and fertilizer requirements. The first two of these compare well with algae research to date, which has sought to utilize flue gas as a carbon source or increase HHV by increasing algal lipid content (*13, 38*). In contrast, fertilizer demand has a clear effect on both energy use and GHG emissions, but this has not received as much attention. For this reason, nutrient delivery represents a significant opportunity for improving the overall sustainability of large-scale algae cultivation.

Evaluating Synergies with Power Production. As indicated in Table 1, this study finds that first-generation algae production systems release more CO_2 to the atmosphere than is taken up during growth of the biomass. This is in stark contrast to corn, canola, and switchgrass production, which are decidedly carbon "negative" as modeled in our system. However, these results capture only production and preliminary transportation of the biomass required to generate one functional unit from each crop. The life cycle burdens associated with conversion of each crop into a usable energy carrier will result in further increases among each of the studied impact areas. It has been suggested, and to some extent demonstrated, that colocating ponds for algae production in the immediate vicinity of a coal-fired power plant and using the flue gas as CO_2 source could reduce the overall life cycle burden of algae production (*20*). This is an appealing proposition from the perspective of algae farmers because CO_2 procurement is a significant cost driver (*8*) and also

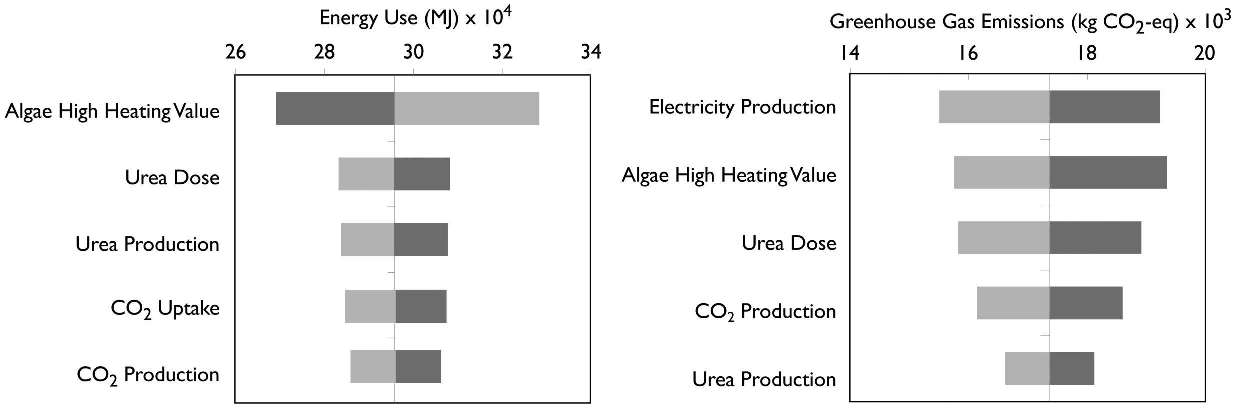

FIGURE 3. Tornado plots reveal the extent to which energy use (left) and greenhouse gas emissions (right) for algae cultivation are sensitive to a ±10% change in input parameters. The centerline represents the baseline case. The dark- and light-shaded values indicate direct and inverse relationships, respectively. A 10% increase in the nitrogen fertilizer dose, for example, increases the total energy use from 26.6 × 10^4 to 32.5 × 10^4 MJ, or ∼4%. Tornado plots for the other impact factors can be found in the Supporting Information.

accounts for roughly 40% of energy consumption and 30% of GHG emissions during algae cultivation. Importantly, there would also be significant potential benefits for the participating power plant, including production of a local, inexpensive biomass suitable for cocombustion with coal, reduced toxicity of its airborne emissions, and reduced financial outlay for carbon tariffs (*20*).

Despite the mutual benefits for colocation of algae cultivation with power production, Figure 3 underscores the interconnectedness between carbon and nitrogen within the context of large-scale algae production. Specifically, the data suggest that it will be possible to achieve significant energy and GHG reductions for coal-fired power plants only by cultivating very large quantities of biomass. This will require significant amounts of nitrogen fertilizer, and production of chemical fertilizers is the principal burden driver among algae production processes. When the algae cultivation LCA model was modified to incorporate use of flue gas rather than industrial-grade CO_2, the total energy consumption and GHG emissions were still larger than corn, canola, and switchgrass. In light of this observation, use of algae ponds to grow next-generation biofuels or sequester CO_2 from power plants cocombusting coal and algae will not be environmentally sustainable until a carbon-neutral, less energy-intensive replacement for chemical fertilizers can be identified. Additionally, it remains unclear what effects flue gas constituents (e.g., SO_X, NO_X, mercury) might have on algae growth rates. Preliminary investigations suggest that the productivity of flue-fed algae relative to CO_2-fed algae may range from 0% (no growth) to 100% (no reduction in productivity) with an average value of roughly 50% (*39–42*).

Evaluating Synergies with Wastewater Treatment (WWT). In order to highlight the significant improvements which could be achieved if chemical fertilizers were not required, Figure 2 summarizes the contributions of several algae cultivation inputs. Some 50% of energy use and GHG emissions are associated with fertilizer production. One obvious mechanism for reducing chemical fertilizer use is coupling algae cultivation with municipal wastewater treatment (WWT). This idea has been evaluated in the past, although previous work was not driven by life cycle analysis (*43, 44*). The algae production life cycle model described here was therefore expanded to quantify the potential offsets associated with use of algae to perform operations otherwise carried out in municipal wastewater treatment plants. Three specific scenarios were evaluated, each using a different type of partially treated wastewater. These wastewaters included (1) secondary effluent from an activated sludge treatment plant with biological nutrient removal for N and P (BNR), (2) secondary effluent from a conventional activated sludge treatment plant with nitrification (CAS), and (3) a 3.5% solution of hydrolyzed source-separated urine (SSU). The first two of these were selected on the basis of availability. The US EPA reports that US WWTPs produce some 16 500 and 14 600 million gallons per day of CAS and BNR effluents, respectively (*45*). In contrast, SSU is not generally collected in the United States; however, its very nutrient density, particularly its high nitrogen content, makes it very appealing for use as algae fertilizer (see Table S11, Supporting Information, for wastewater nutrient concentrations). A collection and distribution infrastructure for SSU would certainly require a significant investment that in many ways parallels the challenges associated with collection and transport of large volumes of waste CO_2. While this infrastructure is currently not in place, it may ultimately be desirable from a reuse perspective.

The results of each WWT coupling scenario are summarized in Table 2 using the VA case as point of reference. These data demonstrate that algae's life cycle burdens can be substantially reduced via use of partially treated wastewater to supplant chemical fertilizers. Not surprisingly, the energy burden offset associated with use of BNR effluent (3%) is less extensive than that associated with CAS effluent (22%) and much less extensive than that associated with SSU (134%). This is due to dramatic variation among available nutrient concentrations in each wastewater (*33, 46*). For the case of SSU, environmental impacts are reduced well below those of corn, canola, or switchgrass. Importantly, the differences in energy burden offsets between modeled WWT cases reflect not only an avoidance of fertilizer production but also the extremely energy-intensive nature of municipal WWT. Although urine makes up less than 1% of municipal wastewater flow by volume, it contains a disproportionately large amount of the nutrients ultimately processed at a WWTP (e.g., 80% of N and 50% of P) (*46*). Thus, some 60−80% of energy consumption during WWT is associated with nutrient removal (*33*), and wastewaters with higher nutrient concentrations (e.g., SSU versus BNR) are more environmentally burdensome to treat at a WWTP. Rerouting a portion of a WWTP's nutrient load to algae cultivation is one way to reduce energy consumption during municipal WWT. We see a similar reduction, to a lesser extent, for water consumption. This quantity becomes net negative for the CAS, BNR, and SSU scenarios because the methanol, iron(II) sulfate, and electricity required to remove nitrogen and phosphorus during WWT require significant water inputs. Finally, it should be noted that reductions in each life cycle impact associated with avoidance of WWT nutrient removal account for 50−70%

TABLE 2. Life Cycle Burdens for Production of One Functional Unit of Energy (317 GJ) from Algae in Virginia without and with Three Different Types of Partially-Treated Wastewaters Being Used in Place of Chemical Fertilizers[a]

	base case	biological nutrient removal (BNR)	conventional activated sludge (CAS)	source-separated urine (SSU)
land (ha)				
direct	0.34 ± 0.03	0.3 ± 0.03	0.3 ± 0	0.3 ± 0
upstream	0.07 ± 0.05	0.1 ± 0.02	0 ± 0.1	0 ± 0
total	0.41 ± 0.05	0.4 ± 0.04	0.3 ± 0.1	0.3 ± 0
energy (MJ) × 10^4				
direct	2.2 ± 0.31	2.2 ± 0.31	2.2 ± 0.31	2.2 ± 0.31
upstream	28 ± 6.4	27 ± 5.8	2.2 ± 6.1	−1.2 ± 6.1
total	30 ± 6.6	29 ± 5.9	2.4 ± 6.2	−9.9 ± 6.1
greenhouse gas emissions (kg CO_2 equiv) × 10^4				
direct	−2.2 ± 0.5	−2.2 ± 0.5	−2.2 ± 0.5	−2.2 ± 0.5
upstream	3.9 ± 0.74	3.9 ± 0.7	3.3 ± 0.7	0.18 ± 0.7
total	1.8 ± 0.58	1.7 ± 0.52	1.1 ± 0.56	−1.9 ± 0.54
water (m^3) × 10^4				
direct	−0.027 ± 0.066	−0.03 ± 0.07	−0.03 ± 0.07	−0.03 ± 0.07
upstream	12 ± 2.4	12 ± 2.2	9.4 ± 2.2	1.3 ± 1.9
total	12 ± 2.4	12 ± 2.2	9.4 ± 2.2	1.3 ± 1.9
eutrophication potential (kg PO_4)				
direct	0.074 ± 0.035	0.1 ± 0	0.1 ± 0	0.1 ± 0
upstream	3.3 ± 0.86	3.2 ± 0.9	3.0 ± 0.9	2.3 ± 0.9
total	3.3 ± 0.86	3.2 ± 0.9	3.1 ± 0.9	2.4 ± 0.9

[a] The standard deviation of each value is also presented (±).

of the total offsets presented in Table 2, whereas the avoidance of fertilizer production accounts for only 30−50%. This is critical insofar as it ensures that municipal WWTPs will have as much or more incentive than their partnering algae production facilities to couple these two processes.

Use of wastewater effluent as pond medium could significantly reduce not only the need for chemical fertilizers and their associated life cycle burdens but also the use of freshwater during algae cultivation. Real water use impacts associated with the BNR and CAS cases would be reduced to practically zero if effluents were routed through a raceway pond prior to disinfection and discharge. This is not the case for SSU because hydrolyzed urine will need to be significantly diluted prior to use in the ponds. Thus, the apparent trade off between land use and water use efficiency during algae site selection, as highlighted in the discussion of geographic impacts, is yet another important reason for research emphasis on synergies between WWT and algae cultivation. Ultimately, successful utilization of wastewater effluents in locations with abundant sunlight would make algae cultivation more efficient with respect to both land use and real water use. In this way, application of life cycle assessment and the principles of industrial ecology, whereby waste streams from one process are utilized as input streams for a different process, may be pivotal in making algae-to-energy systems a practicable reality.

Outlook and Recommendations. The life cycle impacts of algae cultivation are sensitive to several inputs that have been largely overlooked to date, namely, the availability of renewable sources of nutrients and carbon dioxide. In contrast, the model is largely insensitive to inputs widely associated with algae productivity such as water and sunlight availability. While the dominance of these upstream impacts may seem trivial in light of recent life cycle results for other biofuels (*47*), they were not obvious for algae. In practice, first-generation algae ponds will supply their nutrients and CO_2 from fossil-based sources. Almost all commercially available CO_2 comes from steam reforming of hydrocarbons, while the majority of the world's reactive nitrogen comes from the Haber−Bosch process. To reduce the impacts of algae cultivation to make it on par with terrestrial crops, producers will not only need to decide to use waste streams, they will have to develop means by which to deliver these waste streams to their production facilities since these are generally not available. The need to minimize the upstream impacts is the first overarching outcome from this analysis.

The second overarching outcome is that downstream processing is unlikely to change the life cycle assessment for the entire fuel cycle given how large the cultivation differences are. The cradle-to-gate boundaries selected here intentionally exclude the downstream conversion processes required to turn the biomass into a useful form of energy. While it is reasonable to expect that algae biomass could be cofired with coal to produce electricity, other conversion processes may be desirable. In this sense not all types of biomass are equal, and the MJ/kg basis for comparison presented here could exclude important life cycle stages (*5*). For example, if the energy associated with converting switchgrass to ethanol is quite a bit higher than the energy required to convert algae to biodiesel, then the high cultivation impacts of algae may be acceptable. It would also be reasonable to expect that transportation logistics and the temporal elements of biomass production and fuel conversion could influence the impacts of the overall fuel cycle. Nevertheless, the huge impact differences reported here suggest that at a minimum cultivation will be a significant part of the overall life cycle burden. This work is not intended to supplant important future analysis in other life cycle stages. However, an exhaustive study of existing and proposed conversion technologies does not change the realities of the cultivation impacts. The authors anticipate that such analysis will find algae to be easier to convert into liquid fuels than some of the other biomass sources studies here because of their inherently high lipid content, semi-steady-state production, and suitability in a variety of climates.

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Supporting Information Available

More information regarding the life cycle inventory data and sources, the impact factors, and the modeling approach of algae production processes. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Antoni, D.; Zverlov, V. V.; Schwarz, W. H. Biofuels from microbes. *Appl. Microbiol. Biotechnol.* **2007**, *77* (1), 23–35.

(2) Li, X.; Xu, H.; Wu, Q. Large-scale biodiesel production from microalga Chlorella protothecoides through heterotrophic cultivation in bioreactors. *Biotechnol. Bioeng.* **2007**, *98* (4), 764–771.

(3) Sheehan, J.; Dunahay, T.; Benemann, J.; Roessler, P. *A Look Back at the U.S. Department of Energy Aquatic Species Program: Biodiesel from Algae*; National Renewable Energy Laboratory: Golden, CO, July 1998; p 328.

(4) Chisti, Y. Biodiesel from microalgae. *Biotechnol. Adv.* **2007**, *25* (3), 294–306.

(5) Hill, J.; Nelson, E.; Tilman, D.; Polasky, S.; Tiffany, D. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proc. Natl. Acad. Sci. U.S.A.* **2006**, *103* (30), 11206–11210.

(6) Banse, M.; van Meijl, H.; Tabeau, A.; Woltjer, G. Will EU biofuel policies affect global agricultural markets. *Eur. Rev. Agric. Econ.* **2008**, *35* (2), 117–141.

(7) Runge, C. F.; Senauer, B. How Biofuels Could Starve the Poor. *Foreign Affairs* **2007**, May/June.

(8) Benemann, J.; Oswald, W. *Systems and Economic Analysis of Microalgae Ponds for Conversion of CO_2 to Biomass - Final Report*; Department of Energy: Pittsburgh, PA, 1996; p 201.

(9) Powell, N.; Shilton, A. N.; Pratt, S.; Chisti, Y. Factors influencing luxury uptake of phosphorus by microalgae in waste stabilization ponds. *Environ. Sci. Technol.* **2008**, *42* (16), 5958–5962.

(10) Rosenberg, J. N.; Oyler, G. A.; Wilkinson, L.; Betenbaugh, M. J. A green light for engineered algae: redirecting metabolism to fuel a biotechnology revolution. *Curr. Opin. Biotechnol.* **2008**, *19* (5), 430–436.

(11) Ramli, U. S.; Baker, D. S.; Quant, P. A.; Harwood, J. L. Control analysis of lipid biosynthesis in tissue cultures from oil crops shows that flux control is shared between fatty acid synthesis and lipid assembly. *Biochem. J.* **2002**, *364* (2), 393–401.

(12) Godos, I. d.; González, C.; Becares, E.; García-Encina, P.; Muñoz, R. Simultaneous nutrients and carbon removal during pretreated swine slurry degradation in a tubular biofilm photobioreactor. *Appl. Microbiol. Biotechnol.* **2009**, *82* (1), 187–194.

(13) Miao, X.; Wu, Q. Biodiesel production from heterotrophic microalgal oil. *Bioresour. Technol.* **2006**, *97* (6), 841–846.

(14) Goudriaan, F.; van de Beld, B.; Boerefijn, F. R.; Bos, G. M.; Naber, J. E.; van der Wal, S.; Zeevalkink, J. A. Thermal efficiency of the HTU process for biomass liquefaction. *Progress in Thermochemical Biomass Conversion*, Austria, 2000.

(15) Larson, E. D. A review of life-cycle analysis studies on liquid biofuel systems for the transport sector. *Energy Sustainable Dev.* **2006**, *X*, 2.

(16) Campbell, J. E.; Lobell, D. B.; Field, C. B. Greater Transportation Energy and GHG Offsets from Bioelectricity Than Ethanol. *Science* **2009**, *324* (5930), 1055−1057.

(17) Dominguez-Faus, R.; Powers, S. E.; Burken, J. G.; Alvarez, P. J. The Water Footprint of Biofuels: A Drink or Drive Issue. *Environ. Sci. Technol.* **2009**, *43* (9), 3005–3010.

(18) Farrell, A. E.; Plevin, R. J.; Turner, B. T.; Jones, A. D.; O'Hare, M.; Kammen, D. M. Ethanol Can Contribute to Energy and Environmental Goals. *Science* **2006**, *311* (5760), 506–508.

(19) Aresta, M.; Dibenedetto, A.; Barberio, G. Utilization of macro-algae for enhanced CO_2 fixation and biofuels production: Development of a computing software for an LCA study. *Fuel Process. Technol.* **2005**, *86*, 1679–1693.

(20) Kadam, K. L. Environmental implications of power generation via coal-microalgae cofiring. *Energy* **2002**, *27* (10), 905–22.

(21) Lardon, L.; HeÃÅlias, A.; Sialve, B.; Steyer, J.-P.; Bernard, O. Life-Cycle Assessment of Biodiesel Production from Microalgae. *Environ. Sci. Technol.* **2009**, *43* (17), 6475–6481.

(22) Weissman, J. C.; Tillett, D. M. *Design and Operation of an Outdoor Microalgae test Facility: Large-Scale System Results*; NREP: Golden, CO, 1990.

(23) Yang, Y. F.; Feng, C. P.; Inamori, Y.; Maekawa, T. Analysis of energy conversion characteristics in liquefaction of algae. *Resour. Conserv. Recycl.* **2004**, *43* (1), 21–33.

(24) Miao, X.; Wu, Q.; Yang, C. Fast pyrolysis of microalgae to produce renewable fuels. *J. Anal. Appl. Pyrol.* **2004**, *71* (2), 855–863.

(25) Taylor, Y. *Consumption, Price, and Expenditure Estimates: State Energy Data System (SEDS)*; Energy Information Administration: Washington DC, 2008.

(26) Miller, S. A.; Landis, A. E.; Theis, T. L. Use of Monte Carlo Analysis to Characterize Nitrogen Fluxes in Agroecosystems. *Environ. Sci. Technol.* **2004**, *40*, 2324–2332.

(27) *NOAA, Surface Radiation Network (SURFRAD)*; National Oceanic and Atmospheric Administration: Boulder, CO, 2009.

(28) *NREL, National Solar Radiation Database (1961−1990)*; National Renewable Energy Laboratory: Golden, CO, 1994.

(29) Weidema, B. Ecoinvent Data v2.0; http://www.ecoinvent.org/.

(30) Pordesimo, L. O.; Edensa, W. C.; Sokhansanjb, S. Distribution of aboveground biomass in corn stover. *Biomass and Bioenergy* **2004**, *26* (4), 337–343.

(31) Knuckeya, R. M.; Brownb, M. R.; Robertc, R.; Framptonb, D. M. F. Production of microalgal concentrates by flocculation and their assessment as aquaculture feeds. *Aquacult. Eng.* **2006**, *35* (3), 300–313.

(32) Murray, A.; Horvath, A.; Nelson, K. Hybrid Life-Cycle Environmental and Cost Inventory of Sewage Sludge Treatment and End-Use Scenarios: A Case Study from China. *Environ. Sci. Technol.* **2008**, *42*, 3163–3169.

(33) Maurer, M.; Schwegler, P.; Larsen, T. A. Nutrients in urine: Energetic aspects of removal and recovery. *Water Sci. Technol.* **2003**, *48* (1), 37–46.

(34) VDEQ *Nutrients and the chesapeake bay*; Virginia Department of Environmental Quality: Richmond, VA, 2007.

(35) Landis, A. E.; Miller, S. A.; Theis, T. L. Life Cycle of the Corn and Soybean Agroecosystem for Biobased Production. *Environ. Sci. Technol.* **2007**, *41* (4), 1457–1464.

(36) Kim, S.; Dale, B. E. Cumulative Energy and Global Warming Impact from the Production of Biomass for Biobased Products. *J. Ind. Ecol.* **2004**, *7* (3−4), 147–162.

(37) Williams, P. D.; Inman, D.; Aden, A.; Heath, G. Environmental and Sustainability Factors Associated With Next-Generation Biofuels in the U.S.: What Do We Really Know? *Environ. Sci. Technol.* **2009** *43* (13), 4763−4775.

(38) Brown, L. M. Uptake of carbon dioxide from flue gas by microalgae. *Energy Convers. Manag.* **1996**, *37* (6−7), 1363–1367.

(39) Doucha, J.; Straka, F.; Lívanský, K. Utilization of flue gas for cultivation microalgae (Chlorella sp.) in an outdoor open thin-layer photobioreactor. *J. Appl. Phycol.* **2005**, *17*, 403–412.

(40) Hauck, J. T.; Scierka, S. J.; Perry, M. B. Effects of simulated flue gas on growth of microalgae. Proceedings of 212th ACS National Meeting, 25−30 August, Orlando, FL, **1996**, *41* (4), 1391−1396.

(41) Lee, J.-S.; Kim, D.-K.; Lee, J.-P.; Park, S.-C.; Koh, J.-H.; Cho, H.-S.; Kim, S.-W. Effects of SO_2 and NO on growth of Chlorella sp. KR-1. *Bioresour. Technol.* **2002**, *82* (1), 1–4.

(42) Maeda, K.; Owada, M.; Kimura, N.; Omata, K.; Karube, I. CO_2 fixation from the flue gas on coal-fired thermal power plant by microalgae. *Energy Convers. Manag.* **1995**, *36* (6−9), 717–720.

(43) Kim, M. K.; Park, J. W.; Park, C. S.; Kim, S. J.; Jeune, K. H.; Chang, M. U.; Acreman, J. Enhanced production of Scenedesmus spp. (green microalgae) using a new medium containing fermented swine wastewater. *Bioresour. Technol.* **2007**, *98* (11), 2220–2228.

(44) Ryther, J. H.; Dunstan, W. M.; Tenore, K. R.; Huguenin, J. E. Controlled Eutrophication: Increasing Food Production from the Sea by Recycling Human Wastes. *BioScience* **1972**, *22* (3), 144–152.

(45) *U.S. EPA Clean watersheds needs survey—Report to Congress*; U.S. EPA: Washington, DC, 2004.

(46) Dodd, M. C.; Zuleeg, S.; Von Gunten, U.; Pronk, W. Ozonation of source-separated urine for resource recovery and waste minimization: Process modeling, reaction chemistry, and operational considerations. *Environ. Sci. Technol.* **2008**, *42* (24), 9329–9337.

(47) Fargione, J.; Hill, J.; Tilman, D.; Polasky, S.; Hawthorne, P. Land Clearing and the Biofuel Carbon Debt. *Science* **2008**, *319* (5867), 1235–1238.

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