Modeling and Analysis

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Considering water availability and wastewater resources in the development of algal bio-oil

Yi-Wen Chiu and May Wu, Energy Systems Division, Argonne National Laboratory, Argonne, IL, USA

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Abstract: This study aims to quantify water appropriation and the potential production of algal bio-oil using freshwater and municipal wastewater effluent (MWW) as an alternative water resource. The county-level analysis focuses on open-pond algae cultivation systems located in 17 states in the southern United States. Several scenarios were developed to examine the water availability for algae bio-oil production under various water resource mixing MWW and freshwater. The results of the analysis indicate that water availability can significantly affect the selection of an algal refinery site and therefore the potential production of algal bio-oil. The production of one liter of algal bio-oil requires 1036–1666 L of water at the state level, in which 3% to 91% can be displaced by MWW, depending on the biorefinery location. This water requirement corresponds to a total of 25 billion liters of bio-oil produced if the spatially and temporally available MWW effluent together with 10% of total available freshwater are used. The production of algal bio-oil is only 14% of estimated production under the assumption that all of the water demand can be fulfilled without any restriction. In addition, if only the spatially and temporally available effluent is used as the sole source of water, the total bio-oil production is estimated to be 9 billion liters. This study not only quantifies the water demands of the algal bio-oil, but it also elucidates the importance of taking water sustainability into account in the development of algal bio-oil. © 2013 Society of Chemical Industry and John Wiley & Sons, Ltd

Supporting information may be found in the online version of this article.

Keywords: algal bio-oil; biofuel; freshwater; wastewater; sustainability; refinery

Introduction

Using algae as a fuel source was first proposed in 1960.[1] US interest in using algae as a fuel source has been renewed as the country seeks alternative energy sources to reduce its national dependence on foreign energy. Algae are a very promising source of oil and have significant potential to contribute to the national fuel pool. The advantages of using algae as an oil source include the low demands on land resources, high oil-conversion rate,[2–4] fast growth rates, and lack of impact on the demand for food.[5] Previous studies show that algae yields at least 7–341 times more biofuel than corn and 55–132 times more biofuel than soybean in volume on a per-area

Correspondence to: May Wu, Energy Systems Division, Argonne National Laboratory, 9700 S. Cass Ave., Argonne, IL 60439, USA.
E-mail: mwu@anl.gov

basis.[3,6] These yields suggest that using algae can produce at least 11 and 53 times more energy than using corn bioethanol and soybean bio-oil per area per year and yet require 99% less land than that needed for the production of corn and soybeans. However, this high energy yield does not come free. Previous studies have raised concerns about the intensity of water demand in the production of algal bio-oil, given the variable availability of water sources.[7–13] In these studies, water requirements for the production of algal bio-oil can vary significantly because of the disparities in technology assumptions, system boundaries, and targeted geographical locations (Table S1 in the Supporting Information). While most studies focus on water demand, few studies have addressed the availability of local water resources. Therefore, it is critical not only to quantify algal bio-oil water demand, but also to take into account local water resources while projecting potential oil production.

In addition, many previous studies have attempted to analyze the feasibility of growing algae by using municipal wastewater effluent (MWW) as a nutrient source and suggested that wastewater treatment can be integrated with an algae bio-oil refinery to establish a self-sustaining system.[14–16] However, the main purpose of previous studies was to examine the change in the environmental performance of algal bio-oil,[7] not to treat wastewater effluent as a source of water or water credits from a life-cycle perspective. In other words, water demand and water supply are decoupled in the realm of the production of algal bio-oil. As the demand for natural resources and sustainability remains a critical challenge in biofuel production,[17,18] there is an urgent need to study the potential of algal bio-oil production by pairing with sustainable water supply. Therefore, to bridge the gap between the water demand for the production of algal bio-oil and local water availability, we first locate the suitable areas for establishing an algae refinery on a county basis by applying topographical criteria and subsequently factoring in MWW and the availability of local freshwater. Because the highest oil production per area in the southern regions of the United States is 259% higher than the lowest value in the north,[10] we limit the analysis and focus solely on 17 southern states.

By integrating water resources constraints into the development of algal bio-oil, this work offers an objective analysis of how to achieve feasible algal bio-oil production, with an emphasis on sustaining resources and MWW availability. The results are presented on a county basis in order to highlight the spatial variations driven by available freshwater and MWW supplies.

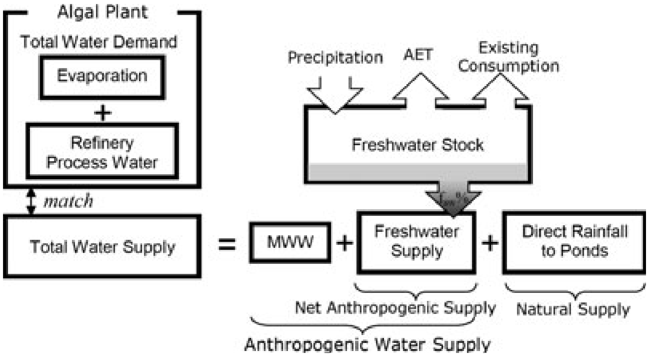

Figure 1. Water demand and supply associated with algal cultivation and biorefinery operation. By regulating the appropriation fraction (f_{aw}) in available freshwater, total water supply can play a feedback role in determining sustainable algal bio-oil production capacity.

Methodology

To better profile water flows in an algae-based system for oil production, we define the **total water demand** as the water loss through evaporation and system processes, including blowdown, leakage, and discharge for pond maintenance (Fig. 1). The total water demand through the entire production system can be fulfilled by three distinctive supply sources: precipitation, MWW effluent, and freshwater from surface and/or groundwater. Because ponds receive rainfall as a natural supply, the rest is defined as **water requirement,** which relies on anthropogenic delivery of MWW effluent and freshwater from available surface and/or groundwater stocks. The amount of water appropriated from the available water stocks – **net water requirement** – is the critical component that is of particular interest when considering the management of water resources. To avoid water competition and to ensure sustainability, the net water requirement should remain only a low fraction of the available water stocks (f_{aw}). In this study, the available water accounts for the remaining precipitation volume after deducting actual evapotranspiration (AET) and existing water consumption (Fig. 1).

By overlaying map layers of algae growth, land availability, and water requirements with temporal dimension, the explicit county-level water requirement for producing each liter of algal bio-oil from algae cultivation to mass-oil conversion stages is then calculated on a monthly basis.

The analysis starts with modeling algae growth potential, followed by identifying suitable sites (which are defined as the areas that meet the general criteria set on the basis of topography, land use, and ownership) and the minimal required area for an open-pond algae-production facility

(SI Section 2). We further take MWW into account as an alternative local water resource to displace the requirement for freshwater. Finally, we consider water constraints by using the available freshwater in a given county. Thus, by capping the maximum allowance in consuming available freshwater together with the MWW effluent supply, the number of actual algal refinery sites from those suitable areas can be determined. Given information on area size and location, water demand by the algae refinery can therefore be quantified by computing pond evaporation and water losses from algae cultivation and harvesting phases (Fig. S1). In this study, we focus on the water requirement on a per-liter oil basis (L L^{-1}) from the algae cultivation stages to the refinery process.

Determining algae growth potential

We adopted a biomass production model summarized by Wigmosta *et al.*[10] to calculate the algae mass growth rate per month per square meter (SI Section 3 – algae growth model). The model assumes that the production of algae biomass is a function of solar energy and climate. Required parameters proposed by previous studies[10,19,20] based on assumptions about current technology are employed (Table S2). By applying all of these assumptions, the county-level algal dry mass yield ranges from 1.33 to 15.55 kg m^{-2} yr^{-1} with an county-area weighted average of 9.06 kg m^{-2} yr^{-1} in the 17 studied states (Table S3), which falls within the reasonable ranges of 4.4 to 11.3 kg m^{-2} yr^{-1} estimated by previous studies.[6,21–25] County-level annual bio-oil production between 0.18 and 2.11 L m^{-2} yr^{-1}, with an average of 1.23 m^{-2} yr^{-1}, in the 17 studied states agrees conservatively with values presented in previous studies, which ranged from 0.5 to 13 L m^{-2} yr^{-1}.[10,19,20,26–28] This level of algal biomass growth potential and oil production is projected only on the basis of the given county-level climate variances before factoring in land selection and water constraints. The growing season normally ranges between March and October, but it can vary county by county, depending on local climate conditions.

Determining suitable lands and sustainable sites

This study considers a typical algae refinery requiring 490 ha of land – 400 ha of algae ponds and 90 ha for an operational facility.[10] To locate suitable land, additional considerations about land use are taken into account, including areas in relatively flat regions (slope ≤1%)[10] and excluding forests, cultivated lands, open water, federal- or state-owned properties, or populated areas (SI Section 4). The suitable lands are screened and identified by using GIS tools integrating digital maps and are further aggregated at the county level.

Meanwhile, alternative water resources from municipal wastewater treatment facilities are determined by assembling a dataset of effluent discharged by different methods. Next, the county-level available freshwater is determined by deducting actual evapotranspiration and existing water consumption from annual precipitation. The difference between precipitation and evapotranspiration is often employed to represent the available water stored in surface and groundwater compartments[29–31] from the perspective of water cycle and balance.[32] We further take existing consumption into account in order to minimize water conflicts. To ensure ecological service quality, only a fraction of the available freshwater can be appropriated for anthropogenic consumption. One previous study suggests that by maintaining at least 60% of the average stream flow as a minimum instantaneous flow, aquatic habitat can be well sustained.[33] However, literatures also suggested that the freshwater appropriation fraction should be evaluated on the basis of local ecological sensitivity and the hydrological complex,[33–36] which is beyond the scope of our study. Therefore, we investigate the number of refinery plants and algal-oil production potential corresponding to f_{aw} at the 10% level and lower, in addition to using MWW as an alternative water resource (Fig. S1 and Eqns (5) and (6) in SI).

Calculating algae refinery water demand

We explicitly estimate the total water demand associated with the algae-growing stage and the oil-processing phase (Fig. S2). Water loss from the algal pond is primarily through evaporation and operational processes (SI Section 5). The evaporation loss can be calculated by adopting a radiation-oriented Turc equation,[37–40] which requires solar radiation[41,42] and temperature as key inputs. The operational loss is regulated by the facility engineering design and management practices, which includes pond leakage, slurry removal from the pond and anaerobic digester, and blowdown. Together with the water loss through evaporation, the total loss may exceed what local precipitation can supply and requires additional water from MWW, surface water, and/or groundwater to make up the deficit (Fig. S2).

Because actual operational data from full-scale open-pond plants are limited, we use an estimated monthly operational water loss of 0.15 m^3 m^{-2} derived from a water balance for a wet-extraction algae oil-production process.[13] The water requirement of the algal oil production can be met by locally available wastewater effluent, which is deducted from the water requirement as a credit for reducing freshwater consumption. As a result, the net water requirement would fully rely on the freshwater resources derived from surface and/or groundwater (Fig. 1).

Wastewater availability

To examine the effect of using MWW effluent in reducing the water requirement of algal bio-oil, the effluent volumes from existing facilities are collected for the 17 southern states considered in this study and aggregated at the county level (SI Section 5.3). We assume all the MWW effluent can be used for algal cultivation. However, because some of the MWW has been directly reused for irrigation and industry applications,[43,44] only the fraction of discharge without being reused can be made available for algae production. Given these criteria, the average effluent volume is derived at monthly intervals to correspond with the calculation of algae growth. We assume the future algae cultivation facility can begin storing MWW one month before the start of the growing season. We also assume that the MWW effluent in a county is only available to the algae-production facility in the same county and that there is no cross-boundary effluent transportation. The conveyance loss in MWW transport within a county is negligible.

Data sources

Climate data required for estimating the growth of algae biomass and pond evaporation are available from the Texas A&M University,[45] National Climate Data Center,[46] and Goddard Space Flight Center of NASA.[47] The county-level climate data are averaged on a monthly basis by using historical data between 1970 and 2000. If a county does not have any weather monitoring stations, data from the nearest station in an adjacent county are used. To enable the computation of available freshwater, the actual evapotranspiration is derived from a satellite image dataset,[48] and the total water consumption is converted from withdrawals of all the water user sectors compiled from the USGS 2005 reports.[49,50] The withdrawal-consumption conversion factors are derived from the USGS 1995 Water Use report.[51] Information on effluent discharge volume is based on the Clean Watersheds Needs Survey and the temporal variation of the discharge patterns are available at the Discharge Monitoring Report managed by the US Environmental Protection Agency.[43,44] All levels of effluent treatment are considered including secondary, advanced treatment, advanced primary, primary, and raw discharge. All effluent reported at each county is further distinguished based on the discharge method of being reused or non-reused by other sectors.

Results and Discussion

The total demand for water in the production of algal bio-oil is calculated on a county basis for the southern 17 states studied by taking into account the MWW effluent and freshwater availability. By applying a systematic approach integrating land use, algae growth, and limitations of water resources, we assess the potential for sustainable bio-oil production given the constraints of water availability. In the following sections, the business-as-usual (BAU) case refers to a system with an unlimited supply of freshwater before the introduction of MWW. Thus, the BAU scenario takes into account only land use and climate characteristics governing algae growth and disregards the capacity of available freshwater in a given county. The change in algal bio-oil production is then examined under different water-supply scenarios, in addition to the BAU case.

Potential for algae bio-oil production under water availability constraints

Before the limitation of water resources is considered (the BAU scenario), there are 549 counties in the studied region identified as suitable candidates to support an algal refinery. On the basis of land criteria, these counties can produce 174 billion liters of algal bio-oil per year. We further examine how the production of algal bio-oil would vary in response to the availability of freshwater by capping the percentage of water appropriation (f_{aw}) at 0–10% with an interval of 1%. By factoring in the water criterion, 42 counties can be removed from the list if f_{aw} is capped at the 10% level, because these counties do not have excessive freshwater available or MWW effluent for supporting the algae bio-oil industry (Fig. 2). Capping f_{aw} at the 10% level also results in a decrease in the number of refineries from 31 525 to 4676. Under this assumption, approximately 48% of the 549 suitable counties from the BAU scenario require a reduction in production.

Capping f_{aw} at 10% with the additional supply from the available (non-reused) secondary MWW effluent reduces algal bio-oil production to 25 billion liters per year (Table 1). As a result of changing f_{aw} from 10% to 0%, the decline in bio-oil production is nonlinear, indicating variability in geographical distribution of available freshwater and MWW effluent at the county level.

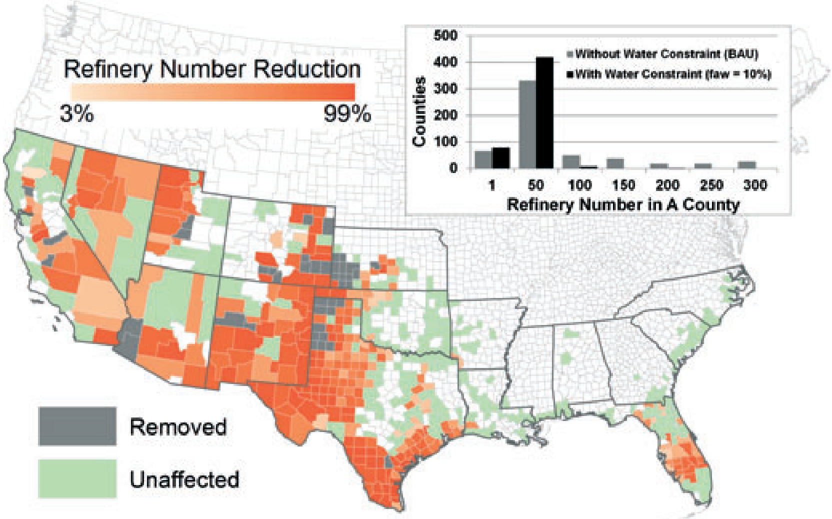

Figure 2. Estimated change in the number of refineries at the county level under the assumptions that 10% of the available freshwater (f_{aw}=10%) is appropriated for oil production and each refinery requires 0.15 m^3 m^{-2} of water per month for making up operational loss. The category 'removed' indicates that these counties can provide suitable land for producing algal bio-oil but are removed from the production list because of the lack of sufficient freshwater, given f_{aw}=10%. Some counties remain unaffected under the water constraint because the algae production demands less water or water resources are relatively abundant. The remaining candidate counties can experience different levels of reduction in the number of refineries. The histogram chart shows the frequency of counties in each class of refinery numbers. Thus, by introducing a water constraint to the analysis, most of the candidate counties can support up to 50 refineries, which is much lower than that under the BAU scenario.

Table 1. Algal bio-oil production and water required to make up the evaporation (EP) and operational losses (OP) associated with the production under different water scenarios. The MWW_{max} scenario represents using all MWW in a given state without spatial and temporal limitations, whereas the MWW_{base} case consumes the fraction of wastewater which is not currently reused by other sectors. Numbers may not sum to total because of rounding.

Scenario	Pond Area	Bio-oil Production	Water Demand		Water Supply			Scenario Assumption		
			EP	OP	MWW	Fresh Water	Precipitation	Effluent type*	Fresh Water	Cross-boundary Transportation
	10^9 m^2	10^9 L	10^9 L	10^9 L	10^9 L	10^9 L	10^9 L			
BAU	126	174	115620	168407	0	232471	51555	n/a	Yes	n/a
f_{aw}=10%	19	25	16401	25277	5664	27504	8510	Non-reused	Yes	No
f_{aw}=5%	12	16	10499	16342	5658	15648	5534	Non-reused	Yes	No
f_{aw}=1%	4.4	6.0	4077	6516	5533	2902	2158	Non-reused	Yes	No
MWW_{max}	6.7	9.1	6083	9254	12522	0	2815	All	No	Yes
MWW_{base}	6.4	8.6	5729	8725	11795	0	2660	Non-reused	No	Yes

*Non-reused = Fraction of effluent that is not currently used by other sectors; All = total effluent available from treatment facilities in the 17 states.

Under the BAU scenario, the production of each liter of the algal bio-oil from an open pond facility demands a production-weighted average of 1632 L of water, of which 1335 L are supported by surface and/or groundwater and the remaining water supply is fulfilled by precipitation. Given f_{aw} of 10%, the net water requirement is reduced

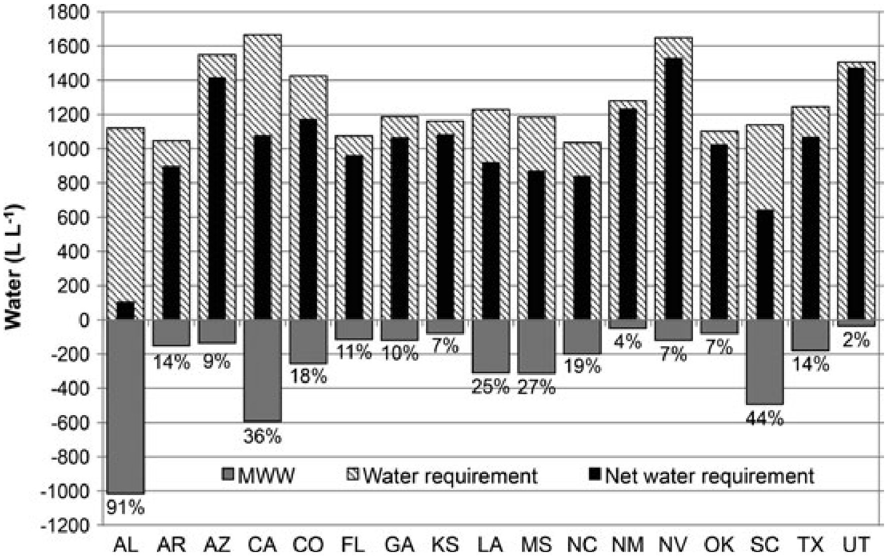

Figure 3. Composition of the water requirement associated with algal bio-oil production in different states under the f_{aw} = 10% scenario with the usage of MWW effluent. Percentage values indicate the fraction of MWW in total water requirement.

from 1335 to 1315 L of water per liter of bio-oil (L L^{-1}), or 1,108 L L^{-1} if MWW is introduced into the system. However, these values could vary state by state because of diverse parameters, including oil yield, climate, land resources, and water availability (Fig. 3).

In terms of water loss, operational water loss accounts for a majority of up to 59% of total water loss under the BAU scenario. Approximately 82% of the total loss would rely on freshwater supply extracted from surface water or groundwater other than precipitation. The contribution of water derived from surface water and/or groundwater in total water demand decreases from 82% to 66% if f_{aw} is capped at 10% and MWW is used, or 79% without effluent supply.

The Energy Independence and Security Act (EISA) has targeted the production of 80 billion liters (or 21 billion gallons) of advanced biofuels by 2022 – algal bio-oil can contribute up to 8% and 31% of the production pool if f_{aw} is capped at 1% and 10% with effluent supply, respectively (Table 1). These values show the importance of water in determining the contribution of algae with other proposed feedstock to meet EISA biofuel production goals.

Geographical distribution

By comparing regional fluctuations in bio-oil production responding to the change of water constraints, the magnitude of change in oil production may vary even more significantly at the state or county level. Figure 4 presents the county-level distribution of net water requirement for algal bio-oil production under the f_{aw} = 10% scenario. The effects of f_{aw} on changing algal bio-oil production vary state by state.

Texas and New Mexico, for example, are the top algal bio-oil producing states under the BAU scenario, contributing to 68% of the algal bio-oil production pool in the studied region. If f_{aw} is capped at the 10% level, the oil production of these two states will significantly decrease by 91% and 94%, driving their contribution to the total regional production down to 39%. Applying water resource constraints also narrows the gap between the highest and lowest producers of algal bio-oil at the county level, from 7.6 billion liters (BAU) to 1.0 billion liters (f_{aw}=10%).

By capping f_{aw} at the 10% level, the algal production in the 17 states studied requires 42 trillion liters of water, of which 33 trillion liters of water need to be supplied by freshwater and MWW. As a result, the net freshwater requirement ranges from 10 billion to 9 trillion liters at the state level or 8–2923 L L^{-1} on the county level after MWW effluent is utilized.

Treated municipal wastewater as water source

These 17 states studied can provide over 14 trillion liters of non-reused MWW effluent per year, of which 89% are temporally available for the algae growing season. To maximize the utilization of the temporally available MWW

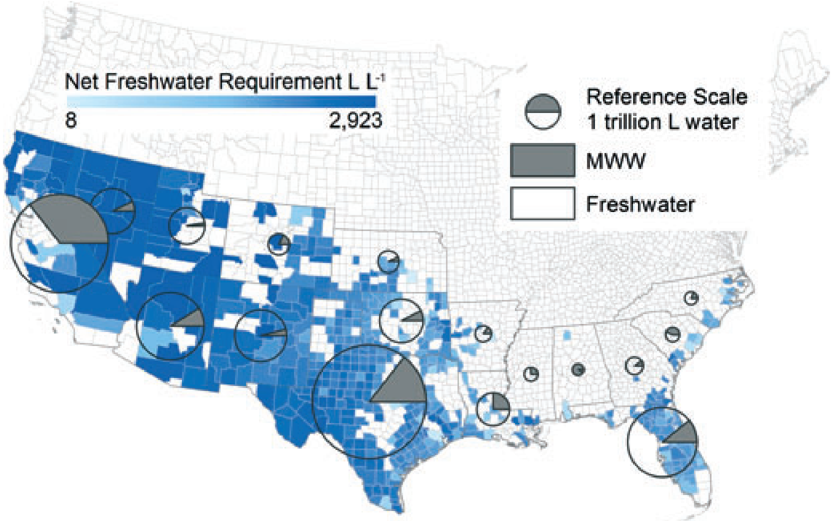

Figure 4. Net water requirement for algal bio-oil production by county and the fraction of water displaced by MWW effluent by state under the f_{aw}=10% scenario. The size of circles indicates the water requirement of the algal oil produced in each studied state.

effluent, each algae refinery plant needs to store the effluent discharged from the wastewater treatment plants for later use. In addition, freshwater is also expected to be needed temporarily during certain months to fill the gap between seasonal refinery water demand and effluent supply. Thus, without any additional freshwater support (f_{aw} = 0%), only 35% of the non-reused MWW effluent can be made available to produce 3 billion liters of bio-oil (Fig. 5).

There are substantial local variations in using MWW to displace freshwater (Figs 3 and 4). Using MWW effluent has the greatest effect on Alabama, displacing 91% of freshwater under the f_{aw} = 1% scenario, followed by California with a freshwater displacement of 79%. With the increase of freshwater appropriation resulting in higher water demand, Alabama can still benefit from the relatively abundant MWW and low total water requirement under the f_{aw} =10% scenario (Fig. 3).

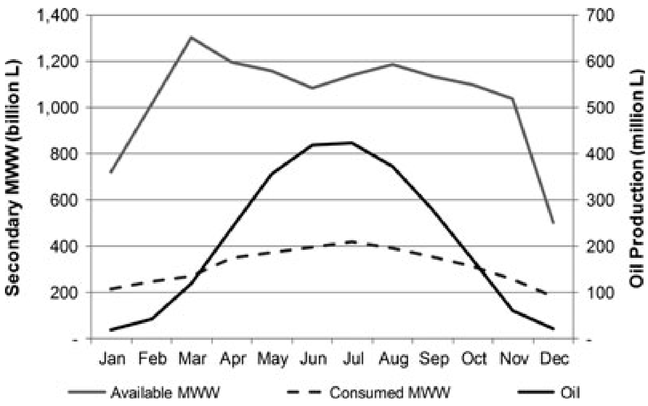

Figure 5. Temporal fluctuation of non-reused MWW and algal bio-oil production. A substantial portion of MWW can be 'wasted' if the transportation practices on optimizing MWW usage are not available.

However, the abundant MWW effluent in some areas may not be accessible for supporting the water demand associated with algae refineries because of the refineries and the wastewater plants are spatially decoupled (Fig. 6). By consuming effluent alone (f_{aw} = 0%) without cross-boundary wastewater transportation, California and Texas can be the top algal bio-oil producers. In contrast, Kansas will no longer be part of the production because suitable land for an algae facility is farther away from the county area in which wastewater plants are located. In another words, there is a lack of a geographical match (Fig. 6). Wastewater plants are often situated near populated areas, though, such as in urban areas where the land is excluded from algae production. The location of wastewater plants implies that an MWW transportation system will need to be addressed in the future to effectively distribute MWW among neighboring counties or states.

The scenarios of MWW_{max} and MWW_{base} in Table 1 further illustrate possible infrastructure issue in algae production pathway. If cross-county boundary transportation of MWW is not available (Table 1, cases of f_{aw} = 1%, 5%, and 10%), only up to 40% of the non-reused effluent (5533 to 5664 billion L) can be directly consumed

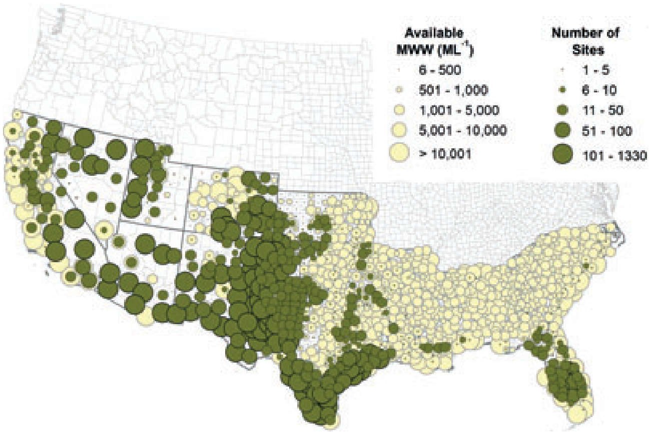

Figure 6. Geographical distribution of the MWW treatment plants and algae refineries under the BAU scenario.

for supporting algal oil production. If the MWW transportation is established within a state (MWW_{base} and MWW_{max}), the effluent utilization can be doubled. Notably, in the best-case scenario (MWW_{max}), when all of the MWW effluent is available and distributed in a state as the sole source of water, the MWW effluent can make up 38% of what is required under the f_{aw}=10% scenario in the 17 states studied. Under these conditions, approximately 9 billion liters of algal bio-oil can be produced annually.

In addition, we assume the minimum cultivation area of each algal refinery plant to be 400 ha, which is over three times larger than the first commercial algae-to-energy pioneer site of 120 ha.[52] A smaller plant size could, therefore, redefine the projection of available land resources for future algae refineries. In future studies, a strategy to engineer the concept of establishing algal-oil refinery encompassed by a wastewater treatment plant should be taken into account.

Uncertainty

In this study, we emphasize freshwater species of algae in estimating the water requirements for supporting bio-oil production. Although most published studies have chosen freshwater species as study cases, some may also investigate saline species as well. Unfortunately, species-specific bio-oil yield is not provided in some literature, which introduces uncertainty. Thus, the requirement for freshwater would be reduced when saline algae are cultured as a primary producer of oil. Saline algae ponds still require freshwater make-up because of frequent blowdown of the algae tank in order to stabilize salinity because many saline algae strains appear to be very sensitive to salinity levels.[53] Considering saline algae growth in water analysis would lead to very different water footprint because it directly limits the land-use criteria for saline-algae cultivation sites. Suitable sites can only be found either along the coastlines or where shallow saline aquifers are situated, such as New Mexico, northwest Texas, Oklahoma, and northern Alabama[54] in our studied region.

In addition to the uncertainty introduced by algae species and yield, the sensitivity analysis also indicates that water demand is more sensitive to the technical assumptions than climate parameters (SI Section 6). However, climate and environmental parameters are more likely to introduce geographical deviations in water demands. It is also important to assess water demands on a local basis because each state might show opposite fluctuations in water requirements with a non-linear relationship in response to different environmental parameters. The sensitivity analysis also highlights the importance of y using a systematic approach that incorporates temporal and spatial dynamics. The results can be further employed to improve water efficiency by prioritizing the targeted parameters.

Conclusions

This study not only provides findings on potential algal-oil production based on water availability, but also reveals the complexity of water requirement resulting from temporal and spatial variances in climate, water, and land resources. Results from our study indicate that the availability of natural and alternative water resources has a significant effect on the estimated production potential of algal bio-oil and that spatial distribution of the municipal wastewater source should be taken into account in planning algal biorefinery.

Using water availability as a site selection criterion primarily decreases the number of options for suitable land and proportionally reduces the production potential of algal bio-oil. Compared with the BAU scenario considering only land availability and climate constraint, the oil production would reduce from 174 billion L to 25 billion L, an 86% reduction, if the algal cultivation and refinery consumes only non-reused MWW effluent and appropriating 10% of the available freshwater. Although wastewater can directly contribute to a reduction in freshwater consumption, the magnitude of its effects is offset by the geographically mismatched patterns between the refinery and the locations of wastewater plants. In addition, the potential of MWW as an alternative water source also requires further investigation to enable the temporal patterns to be matched between the algae refinery water demand and effluent supply. To maximize the use of wastewater as alternative resource for algae development, infrastructure needs such as effluent storage and transportation should be further addressed. This study elucidates the importance of incorporating geographical and temporal characteristics of the land and wastewater resources in planning new algal oil facilities, which should be considered in the development and implementation of policies to advance biofuel development.

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Yi-Wen Chiu

Dr Yi-Wen Chiu is a postdoctoral appointee in the Energy System Division at the Argonne National Laboratory. As an interdisciplinary scientist, her main research focus is to understand the coupling and interaction of human and natural systems by applying integrated modeling tools. She has been involved in research related to water system dynamics, water footprint and water-energy nexus with broad interests related to scenario analysis and life cycle assessment. She also participates in several studies aiming to advance biofuels by determining the feasible pathways of achieving water sustainability goals. Dr Chiu holds a PhD degree in Water Resources Science from the University of Minnesota.

May M Wu

Dr May Wu, a principal energy systems analyst at Argonne National Laboratory, is the PI of biofuel sustainability research funded by the US Department of Energy. Her research interests are in the area of water quality and water quantity associated with large-scale development of biofuel, conventional fuel, electricity, and emerging fuels and life cycle analysis. Dr Wu is leading the effort to develop tools and large-scale watershed models to assess spatially explicit water footprint of biofuel produced from conventional, cellulosic, and advanced feedstock and impact of projected future production on regional nutrient, sediment and hydrology. Dr Wu served as an expert advisor to the Water Working Group of the Council on Sustainable Biomass Production (CSBP) and supported the National Biomass R&D Board, through its Sustainability Interagency Working Group. Before joining Argonne in 2004, she was a senior research microbiologist at Nalco Chemical. Prior to that position, Dr Wu conducted her postdoctoral work at Argonne National Laboratory. Dr Wu holds several US patents and a dual PhD in Environmental Engineering and Environmental Toxicology from Michigan State University.