Analysis of Water Footprint of a Photobioreactor Microalgae Biofuel Production System from Blue, Green and Lifecycle Perspectives

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Abstract

Microalgae are currently being investigated as a feedstock for the commercial production of transportation fuels, due to their potential scalability and sustainability advantages over conventional feedstocks. The water consumption of microalgae has been postulated to be a resource barrier for large-scale production. This study presents an assessment of the water footprint (WF) of a closed photobioreactor-based biofuel production system, where microalgae cultivation is simulated with geographical and temporal resolution. The assessment focuses on the WF as modeled for four different fuel conversion pathways, and in 10 continental US locations corresponding to high productivity yields. The WF is comprehensively assessed using a hybrid approach which combines process and economic input-output lifecycle analysis method, using three metrics: blue, green and lifecycle WF. Results show that the blue WF of microalgae biofuels varies between 23 and 85 $m^3 \cdot GJ^{-1}$ depending on process and geographic location. The green WF shows that microalgae cultivation may reduce the required local water withdrawals. Water credits from the co-products vary with allocation methods and end uses, from credits of less than 4 $m^3 \cdot GJ^{-1}$ up to credits of 334 $m^3 \cdot GJ^{-1}$. Results for the net lifecycle WF with coproduct credits varies between 80 and -291 $m^3 \cdot GJ^{-1}$. Discussion focuses on the sensitivity of microalgae biofuels WF and highlights potential local and national strain of water resources relative to other fuels and biofuels.

Keywords: water footprint, water use, life cycle analysis, microalgae, biofuels, sustainability

1 Introduction

Water is a stressed resource in many regions of the US, and future increases in biofuels production are predicted to dramatically increase the water intensity and consumption of the transportation and energy sectors [1, 2]. In general, current commercially available biofuels have been found to be less greenhouse gas (GHG) intensive and more water intensive than conventional petroleum fuels production [3-5], although there exists a great deal of uncertainty regarding the water requirements for next-generation biofuels.

Microalgae-based biofuels are one of a third generation of biofuels whose environmental impacts have come under continued scrutiny [6-10]. For example, the water consumption in large-scale microalgae-to-biofuel systems may be a potential limitation to its scalability and environmental compatibility [10-16]. Previous evaluations of the water consumption of microalgae biofuels have not developed a lifecycle methodology comparable to other biofuels studies in literature, and have concentrated on open-pond cultivation systems as opposed to photobioreactor (PBR) microalgae cultivation systems [13, 17-19]. Clarens et al. (2009) analyzed microalgae biofuels water footprint (WF) including direct water consumption and water consumption associated with processes upstream of cultivation, but excluding consumption in the stages of fuel conversion, transportation and distribution. Yang et al. (2010) studied the WF from microalgae biodiesel derived from open-pond cultivation systems, but only accounted for the actual water consumed in process, excluding the water requirements associated with energy and consumable materials. Vasudevan et al. (2012) performed a thorough LCA with a focus on freshwater consumption for dry and wet extraction technologies, excluding upstream water use related to energy and material inputs. Wigmosta et al. (2011) constructed a geographically-resolved water consumption analysis of microalgae feedstock production and fuel conversion, but distribution, transportation and co-product allocations were not included as would be required for a conventional lifecycle accounting. Harto et al. (2010) performed a comparison of the lifecycle water footprint of open pond and tubular PBR cultivation systems, but incorporated higher productivities than has been reported in studies of near-term, industrially-realizable cultivation systems [20-22]. In general, the synthesis of the results of water consumption analyses among studies is complicated by the many modeled conversion processes, by geographical and climactic variability, and by differences in study scopes, system boundaries, and metrics.

To address these challenges, this article describes a detailed analysis of the WF of microalgae-based biofuels. This WF assessment includes detailed models of industrial feedstock cultivation, de-water, extraction, conversion, transportation and delivery to derive a geographically- and temporally-resolved model of the water requirements for four different fuel production pathways. These four pathways represent the production pathways for biodiesel, green diesel type 1, green diesel type 2 and renewable gasoline [23]. The study focuses on 10 locations in the continental US that have been identified with high productivity potential based on lipid yields and land availability. Climatic variation in the WF is modeled using precipitation and pan evaporation rate data and a biomass productivity and lipid accumulation model based on 15 years of historical, hourly meteorological data. To facilitate comparison to the fractured literature, three WF metrics are analyzed for microalgae-based biofuels: green, blue and lifecycle WF [5, 24]. Discussion focuses on a comparison of these results to the water consumption of other petroleum-based fuels and biofuels, and presents the sensitivity of the analyses to geography and climate.

2 Methods

2.1 Water Footprint Functional Unit, Boundaries, and Metrics

Water consumption is defined as the total water that is not returned to a water body or source for reuse [3]. WF is the freshwater consumption of a process or product per functional unit [5, 25, 26]. The functional energy unit for this study is a unit of biofuel based on its lower heating value (LHV). The WF is therefore quantified as cubic meters of water per unit of energy of biofuel produced ($m^3 \cdot GJ^{-1}$). The LHV of biodiesel, green diesel type 1, green diesel type 2 and renewable gasoline are assumed to be 37.6 $MJ \cdot kg^{-1}$, 43.6 $MJ \cdot kg^{-1}$, 44.0 $MJ \cdot kg^{-1}$ and 43.4 $MJ \cdot kg^{-1}$, respectively [23].

The temporal unit for this study is 1 calendar year, with the number of cultivation days varying for each cultivation facility due to regional climatic conditions. The cultivation season is approximated using a thermal model of the cultivation system [21]. This study assumes the growth facility is dormant from the first formation of ice on the growth system until the first full thaw.

Three different metrics of WF are analyzed in this study: blue WF, green WF and lifecycle WF [5, 24]. The blue WF is a metric of the direct water withdrawal of a process, for either consumptive or non-consumptive use. The green water footprint is a metric representing the difference between the water lost through soil moisture evaporation, feedstock evapotranspiration, and the water gained through precipitation. The total WF is defined as the sum of blue and green WFs. The lifecycle WF metric is the most comprehensive metric, accounting for the direct water consumption in the process, the upstream water consumed in materials and energy production, and the water credits that are returned to the accounting due to the displacement of marketable products by the co-products generated in the biofuel production process.

A model of water inputs to the microalgae-to-biofuels process is used to apply these WF metrics to microalgae-based biofuels. The process boundary for this study is the fuel cycle or "strain-to-pump" which is equivalent to "well to pump" for traditional diesel. The stages studied within this boundary include cultivation, harvesting, dewatering, oil extraction, fuel conversion and fuel transportation and distribution [7]. Energy and materials to manufacture infrastructure, vehicles, and facilities are not included in this analysis. For the modeled microalgae-to-biofuel processes, the direct water withdrawal represents the water that is consumed by each stage in the microalgae-to-biofuel process including, for instance, water for microalgae cultivation, water required to make up for pond evaporation, water lost from the process during filtration, and water reacted during fuel conversion. Internal water recycling of the microalgae-to-biofuel process (for example, centrate recycling) displaces direct water consumption. For this microalgae-to-biofuels process, green water footprint only accounts for precipitation as basin evaporation is directly accounted for through makeup water, and disturbances to soil quality or moisture content are assumed negligible. The lifecycle boundary includes upstream water use, which is defined as the water consumed to produce materials and energy inputs to the microalgae-to-biofuel process, such as electricity, fertilizers and photobioreactor material. Co-product water allocations represent the water consumption that is avoided because of the availability of microalgae-based co-products.

For the blue and green WF calculations, this study uses a process approach, wherein the water consumption is modeled or measured at each stage of the microalgae-to-biofuels process. For the lifecycle WF calculations, this study uses a hybrid method combining process and economic input-output approaches to estimate the water inventory for each process stage. Under this hybrid method, the process approach is applied to the process water consumption and water consumption associated with energy inputs, while the economic input-output approach is applied to estimate the upstream water consumption associated with all material inputs including fertilizers and other consumables. The WFs of conventional energy inputs, such as electricity, gasoline, and diesel are based on process WFs as calculated in the lifecycle assessment literature [3, 27, 28].

2.2 Process WF Assessment Details

The process approach to microalgae WF requires the quantitative measurement of the direct water input into each process of biofuels production. For this study, quantitative measurements of water, energy and material inputs for each process is based on a detailed engineering model of the Solix Biosystems Generation 3 photobioreactor (PBR) cultivation system, a centrifugal de-watering system, and conventional hexane/ethanol based lipid extraction systems [7, 20]. The WF associated with the four fuel pathways' conversion, transportation, and distribution systems are based on the ANL GREET model [23]. This study assumes that there is no energy associated with the transport of microalgae feedstock to a co-sited extraction and conversion facility, but does consider the energy required for transport and distribution of fuel to pump stations, and for transport of coproducts.

2.3 Economic Input-Output Lifecycle Assessment Details

For some materials, a process lifecycle approach to WF estimation has not been performed, or does not appear in open literature. In these cases, the Economic Input-Output lifecycle assessment (EIO-LCA) approach is used to estimate the lifecycle water footprint of the material. The EIO-LCA approach uses an economic model that comprehensively maps the interrelationships among the main sectors of the US economy and enables identification of direct economic inputs, indirect economic inputs, products and service supply chains. Economic data are combined with resource consumption, environmental emissions, and waste data to map connections between economic expenditures and corresponding resource consumptions [29]. For this study, the EIO-LCA approach is applied to estimate the WF of fertilizers, and polyethylene for PBRs and liners used in the microalgae cultivations system. The EIO-LCA model data are based on the US economy as measured in 2002, thus 2011 prices are used to adjust the EIO-LCA data [30-33].

2.4 Microalgae-to-Biofuel Process Model

This study analyses an industrial-scale PBR microalgae-to-biofuels production plant cultivating *Nannochloropsis salina*. The PBR are vertically oriented polyethylene panels with thermal and structural support provided by a water basin [22]. The PBR cultivation facility has a footprint of 315 hectares that includes growing and processing facilities [7]. De-watering is accomplished through the use of a centrifuge with centrate recycling. The microalgae oil is extracted through an ethanol/hexane solvent extraction process [7].

Microalgae fatty acid composition suggests some advantages in conversion, treatment and fuel properties of microalgae oil over vegetable oils, but there is no public data quantifying the WF of industrial-scale lipid-to-biofuel conversion using microalgae-derived lipids.[1] Instead, the data for the four conversion processes considered in this study are based on four models of soybean oil-to-biofuels conversion: (i) biodiesel (BD), (ii) green diesel type 1 (GD1), (iii) green diesel type 2 (GD2) and (iv) renewable gasoline (RG). BD is the biofuel obtained with simple transesterification of crude oil. GD1 is the biofuel obtained through hydrocracking, hydrotreating and hydrogenation of lipids using the *Supercetane* process [37]. GD2 is the biofuel obtained through dehydroxygenation and decarboxilation of lipids, using the *Ecorefining* process [38]. RG is the fuel obtained from catalytic cracking of lipids. Refining data are drawn from the ANL GREET 1.8d model and its associated process inventories [23].

The microalgae growth model inputs hourly meteorological data . Microalgae biomass and lipid production is modeled as a function of time, temperature, photosynthetically active radiation, nutrient levels, culture density and a variety of other biological variables [20]. Water for producing growth media and for filling the water basin is assumed to be freshwater. Wastewater produced by the growth system is nitrogen-depleted and is assumed to require no treatment before discharging [22, 39].

Coproduct credits play a key role in lifecycle WF assessment, as each coproduct incorporates water credits that must be accounted for. Coproducts from the microalgae-to-biofuels process vary with the fuel pathway considered but can include lipid-extracted microalgae biomass, glycerin, and various hydrocarbon coproducts from the refining process. Both energy and displacement allocation methods are analyzed in turn for this study. The energy allocation method uses the energy embedded in the coproducts to calculate water credits. In this allocation method, the algal extract and glycerin are used as co-firing material to generate bioelectricity, therefore, water credits are based on the WF of the produced electricity [3, 40]. The displacement allocation method assumes that the microalgae biofuel coproducts will substitute for conventional products in the market. Using displacement allocation, lipid-extracted algal biomass substitutes for microalgae as an aquaculture fish or shrimp feed. The water credit assigned to microalgae biomass is equal to the water needed to produce microalgae conventionally cultivated in an open-pond system. The other coproducts displace the equivalent types of gas, heavies and other energy fuel carriers, and their water credit is based on the water footprint of the conventional energy fuel carriers that they replace. Market saturation due to coproducts generated by microalgae-to-biofuel process is not analyzed in this study.

Average national distances, fuel transportation means and capacities from ANL GREET 1.8d are adopted for this study [23]; where the diesel consumed to operate trucks is converted into an equivalent water footprint [3].

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[1] The fatty acid composition of *Nannochloropsis* is composed, in average values, of 30.96% of saturated lipids and 59.2% of unsaturated lipids. Microalgae oil has a non-detectable amount of linolenic acid (C18:3) and the polyunsaturated lipids range between 2 - 22% [34-36].

2.5 Geographical and Climatic Resolution

Land availability limits the regions of the US where large scale microalgae-based biofuels can be cultivated. To model the potential siting of microalgae biofuel cultivation facilities, this study defines a set of geographical locations in the US where land is available for microalgae cultivation. The baseline scenario includes production on barren land, shrubland, grassland, and herbaceous covered land, and excludes production on agricultural land, urban areas, wetlands, open water, and forested land. Other exclusions are wilderness areas, federal research areas, national parks, forests, recreation areas, and high-slope areas. Large-scale microalgae cultivation requires a slope of 2% or less for economic reasons related to the cost of construction of photobioreactors and water basins [41-43].

For each geographic location, solar radiation, dry-bulb temperature, dew-point temperature, wind speed, wind direction, cloud cover and atmospheric pressure are used to model the radiative, conductive and convective heat balance and temperature of the water basin. Large-scale cultivation is assumed to preclude artificial heating and cultivation is assumed to shut down when the water basin freezes. Therefore, the length of the cultivation season is a function of the weather at each geographic location, and varies from year to year.

Analysis of the WF requires the modeling of both evaporation and precipitation. Evaporation is a significant component of the water consumption in the modeled PBR system because the water basin is an open pool, where water evaporation can occur from the basin's free surface. To maintain the function of the water basin, water must be added to make up for water evaporation. As recommended in Farnsworth (1982a), water evaporation rate is assumed to be 75% of the measured pan evaporation rate, with mean monthly pan evaporation rate modeled as the average of a 15 year database of Class A pan evaporation data [44, 45]. The open basin collects water from precipitation during the cultivation period, thus avoids additional water withdrawal to supply evaporated water. Mean monthly precipitation data is estimated from a 20-year average database [46]. Extreme weather conditions and smaller-scale meteorological variations, such as drought, flood, monsoons and hurricanes are not representable using these methods.

To characterize the WF of microalgae biofuels for this baseline scenario, ten locations (listed in Table 1) were chosen in states with the highest algae biofuels production. Some of the chosen locations do not have a high area-specific productivity, but have high land availability, and therefore high production [21].

3 Results and Discussion

3.1 Biomass and Oil Yield

The biofuel WF is sensitive to the temporal and areal productivity of biofuel, because WF is defined as water consumption per unit of biofuel energy. This section presents and discusses the biomass and oil yield results as modeled in this study.

Across the 10 locations modeled in this study, yearly averaged biomass yields range from 29.5 to 53 $\mathrm{ton \cdot ha^{-1} \cdot year^{-1}}$, and microalgae oil yields range from 13 to 23.7 $\mathrm{m^3 \cdot ha^{-1} \cdot year^{-1}}$. The results are compatible with productivity as measured under large-scale production [20, 22, 47]. The average productivity among the 10 sites is 40.9 $\mathrm{ton \cdot ha^{-1} \cdot year^{-1}}$ of biomass yield and 18.3 $\mathrm{m^3 \cdot ha^{-1} \cdot year^{-1}}$ of lipid yield. As shown in Table 1, the Arizona and California locations present the longest cultivation seasons, corresponding to the highest oil productivities. Montana and Wyoming are the least productive locations with as few as 66% of days available for cultivation.

3.2 Blue and Green Water Footprint

For microalgae-based biofuels, the blue WF is the sum of the water directly used to supply cultivation and process needs, the water retained in the open basins, and the water used to make up for evaporated water. The blue WF represents the local water requirements for the microalgae-to-biofuels process. The average blue WF of microalgae biofuel among all locations and conversion pathways is 42 $m^3 \cdot GJ^{-1}$. Blue WF varies as a function of fuel conversion pathway and location between 23 and 85 $m^3 \cdot GJ^{-1}$, as shown in Table 2. Averaged among the locations and conversion pathways, the process water use for feedstock cultivation, harvesting and extraction accounts for 97.6% of the blue WF, the fuel conversion accounts for 2.4% of the blue WF and transportation and distribution for 0.002% of the blue WF.

For microalgae-based biofuels the green WF is negative, representing a water gain in the water basin due to precipitation. The green WF is therefore a ratio of the precipitation that each geographic location receives and the energetic productivity of the location. The green WFs for BD and GD2 are the lowest among the four fuel conversion pathways, varying among the geographies between 1.3 and 8.9 $m^3 \cdot GJ^{-1}$.The green WFs for GD1 and RG are higher, varying among the geographies between 1.7 and 17 $m^3 \cdot GJ^{-1}$.

The total WF is the sum of blue and green WFs and varies among the geographies and processes considered between 18 and 82 $m^3 \cdot GJ^{-1}$. Figure 1a shows the allocation of the total WF to each component of the microalgae-to-biofuels process for the four conversion pathways considered, and averaged among locations.

3.3 Lifecycle Water Footprint

Whereas the blue, green and total WFs provide metrics of local water use or withdrawal, the lifecycle WF provides a system-level metric of net water consumption for the process of producing microalgae-based biofuels. The lifecycle WF includes the inventories of the process water consumed, the upstream water consumption associated with energetic and material inputs for each stage of the fuel cycle, and the water credits associated with the coproducts. The lifecycle WF excludes the water retained in the water basin, as this water is presumed to be returned to original source after cultivation, and is considered not consumed in this perspective.

Before considering coproduct credits, the microalgae lifecycle WFs vary among geographies and fuel conversion pathways between 21 and 83 $m^3 \cdot GJ^{-1}$, as shown in Table 3. This variation is primarily due to the effects of the fuel conversion pathways. The GD1 pathway is the least water-consumptive, with lifecycle WF varying between 21 and 46 $m^3 \cdot GJ^{-1}$. The RG pathway has the highest water-consumptive pathway with lifecycle WF varying from between 35 and 83 $m^3 \cdot GJ^{-1}$. BD and GD2 have intermediate conversion efficiencies and water consumptions, as shown in Table 3.

The set of available coproducts from the four production pathways are lipid extracted algae (LEA), and petroleum coproducts including product gas, light cycle oil and clarified slurry oil. In this analysis, glycerin is treated as a waste product and is allocated none of the WF[2]. The water credits allocated to coproducts varies depending on the allocation method. The two methods considered in this study are the energy allocation and the displacement allocation methods.

Under the energy allocation method, water consumption is allocated to coproducts according to their LHVs. LEA is assumed to be used as a co-firing material to generate electricity. The water credit allocated to co-firing of LEA is 0.03 m^3 of water per kilogram of LEA, based on the lifecycle WF of the displaced electricity [3, 7]. For other coproducts, water credits are allocated based on the ratio of their LHV to the LHV of petroleum-based diesel, based on a WF of petroleum-based diesel at 0.08 m^3 water per GJ [3].

Under the displacement allocation method, LEA partially displaces conventionally cultivated microalgae as a fish and shrimp feed. After lipid extraction, the LEA has higher protein content per unit mass than conventional microalgae, for which 1 kg of LEA can substitute 1.3 kg of microalgae

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[2] Although not negligible, byproduct glycerin after transesterification is impure and of low value [43]

aquaculture feed. LEA water credits are based on the water consumption required to cultivate the displaced microalgae biomass using open-ponds. Harto et al. (2010) is used for estimating LEA water credits. An efficiency of fuel conversion and lipid extraction of 96% and 85%, respectively, were assumed to obtain the lifecycle WF for 1 unit of displaced LEA [17, 18]. The water credits for LEA are 0.13 and 3.67 m^3 kg^{-1} of LEA, based on the Harto et al. low and high cases, respectively; all other coproducts are assumed to displace products on a mass basis and calculation details are shown in Supplementary material. A summary of coproduct displacement and energy allocations is shown in Table 4.

Table 3 also presents the lifecycle WF of the microalgae-to-biofuels production process for all locations and coproduct displacement methods. The ranges represent the range of WFs associated with the four conversion pathways. The lifecycle WF for the microalgae-to-biofuels process can vary between a maximum WF of 80 $m^3 \cdot GJ^{-1}$ to a minimum WF of -291 $m^3 \cdot GJ^{-1}$, representing 291 $m^3 \cdot GJ^{-1}$ of water consumption avoidance. The variation among lifecycle WFs is also due to geographic and climactic variability among the locations. Those locations with shorter winters and warmer temperatures have a longer cultivation season, longer cultivation days, higher productivity, and consequentially higher energy and material consumptions. Averaged among all the fuel conversion pathways and locations, the upstream water accounts for 29.3% of lifecycle WF, the evaporation and process use accounts for 74.2%, while fuel conversion and precipitation water gain account for 10.3% and -13.9%, respectively. Transportation and distribution account for less than 0.002% of the lifecycle WF, as shown in Figure 1b.

3.4 Comparison with Fossil Fuel and Other Feedstock Fuels

To place these results in context, this section compares the results of this study to the literature on WFs of various biofuels and petroleum-based fuels. The comparison of microalgae biofuels' WFs to those WFs present in the literature must be made using the same WF metrics, although no additional harmonization is performed in this study. These comparisons are detailed in Table 5.

Using the same total WF (blue WF plus green WF) metric that is used in the most cited petroleum fuel WF studies, the WF of microalgae based biofuels is found to be higher than that of conventional petroleum-based fuels. The WFs of petroleum-based diesel and gasoline are between 0.04 and 0.2 $m^3 \cdot GJ^{-1}$, where the range of values are due to various scenarios of water use including the use of desalinated seawater, the use of water recycling, or the re-injection of produced water for oil recovery [3, 48]. This can be compared to the findings of this study where the total WF of microalgae based biofuels is between 18 and 82 $m^3 \cdot GJ^{-1}$, depending on the geographical location and conversion pathway.

Using the same WF metrics that are used in the most cited biofuel WF studies, the WF of microalgae-based biofuels is found to be roughly comparable to that of other starched-based biofuels. Dominguez-Faus et al. (2009) calculated the soybean BD total WF as 287 $m^3 \cdot GJ^{-1}$, including evapotranspiration. Mekonnen et al. (2011) calculated soybean BD total WF as 337 $m^3 \cdot GJ^{-1}$, using global weighed averages and including water from precipitation. Studies that show a lower WF for soy-based BD do not adhere to any of the WF definitions presented above, in that partial irrigation is assumed and evapotranspiration is not included in the WF accounting [3, 17]. BD from palm oil, rapeseed and other oilseeds are shown to have higher total WFs (>150 $m^3 \cdot GJ^{-1}$) than microalgae biofuels, [26, 49].

Comparison of this study's findings to those of previous microalgae biofuel WF studies is more complicated, as no studies adhere to these WF metrics or boundaries. Clarens et al. (2010) estimated microalgae biofuel for an open-pond cultivation system at between 303 and 454 $m^3 \cdot GJ^{-1}$, but does not apply the same lifecycle boundaries as this study. Instead, the boundary for Clarens is cradle-to-gate for cultivation of feedstock, and does not include lipid extraction, fuel conversion and distribution. Yang et al. (2011) estimated a WF for microalgae biofuel of between 14 and 87 $m^3 \cdot GJ^{-1}$, although their lifecycle analysis did not include upstream water use from energy and materials. Harto et al. (2010) calculated the microalgae biofuel WF from open-ponds (ORP) as between 1 and 20 $m^3 \cdot GJ^{-1}$ and a microalgae WF from enclosed photobioreactors as between 1 and 2 $m^3 \cdot GJ^{-1}$. The latter study used boundaries and metrics comparable to those of this study, but the modeled microalgae productivity is between 72 and 130 $m^3 \cdot ha^{-1} \cdot year^{-1}$, which is 3 to 10 times higher than is feasible with modern open ponds and photobioreactor systems [22]. These calculations are described in detail in the supplementary material.

3.5 Geographic and Climactic Sensitivity of Microalgae Biofuels WFs

Whereas, most of the studies cited above present national average WFs, the resource intensity of microalgae-based biofuels production makes it so that microalgae WFs may be particularly affected by geographical and climatic factors. Qualitatively, regions of the US with warm temperatures and larger cultivation seasons result in higher evaporation rates and more process water use, but also result in higher biomass and oil yields. Whether the tradeoff between these effects makes a particular location beneficial for low-WF microalgae biofuels production depends on the WF metric of interest.

On average among locations and fuel pathways, the blue WF of the microalgae-based biofuels is composed of 75.3% make-up water due to evaporation from the open basin, 22.3% water retained in open basin, 0.02% direct water use for algal cultivation, harvesting and extraction processes, and 2.4% fuel conversion water consumption. Evaporation is the major component of the WF, causing total WF to be strongly linked to local evaporation rate and precipitation. Therefore, sites located in California, Nevada, Texas and New Mexico, have high blue WFs despite their high biomass and oil yields.

Lifecycle WF is shown to be most sensitive to its energy and material inputs. Averaging the results for the four fuel pathways, the lifecycle WF of microalgae-based biofuels is composed of less than 0.05% direct process water use, 10.4 % fuel conversion water consumption, 74.2% make-up water due to evaporation, 29.3% upstream water consumption, and 14% water gain through precipitation. Lifecycle WF is very sensitive to the coproduct allocation method due to the significance of upstream water consumption. Energy allocation methods result in lower water credits compared to displacement allocation methods, and various coproduct displacement scenarios result in a wide range of lifecycle WFs. These variations among these values of WF are primarily due to variation in the water credits available for LEA, the effect of geographic and climatic differences on biomass yields, and the differences among fuel conversion pathways.

3.6 Scalability of Production

Microalgae have been proposed as an oil feedstock with the potential to meet future alternative fuel goals [50]. Based on the results of this study, if microalgae biofuel production relies only on freshwater to meet the EISA 2022 target of 136 million m^3 of biofuel, it would require between 91 and 420 billion m^3 of water (using the total WF metric), for the best and worst scenarios, respectively. These values are equivalent to an additional direct water consumption of 0.7 to 3 times the amount of water currently used directly for US grain farming [2].

In the lifecycle perspective, the WF of microalgae biofuel production could range from a water consumption avoidance of 1.5 trillion m^3, to a water consumption of 410 billion m^3, for the best and worst scenarios, respectively. The lowest water consumption scenario corresponds to the use of LEA to displace conventional microalgae already cultivated for fish or shrimp feed. The highest water consumption scenario corresponds to the use of LEA as a co-firing material for bioelectricity generation.

4 Conclusions

The problems with first generation biofuels in terms of marginal environmental benefit, and resource intensity are well documented in literature [51], whereas the environmental impacts and resource limitations of microalgae-based biofuels are the subject of continued research. To quantify the water resource impacts of microalgae-based biofuels, this study has calculated their WF using a variety of biofuel pathways, geographic locations, and WF metrics. This comprehensive accounting for the water consumption of microalgae-based biofuels allows for a rigorous WF comparison among fuel pathways, among geographic locations, and against other biofuel feedstocks. When comparisons to other available fuels are made using the same WF metrics, this study has shown that the production of microalgae biofuels is more water intensive than petroleum-based fuels, is comparable to that of bioethanol from most types of biomass, and is less water intensive than that of oilseed-based biodiesel. The productivity of microalgae and its corresponding WF is shown to vary across geographical regions of the US. From the lifecycle WF perspective, the water intensity of microalgae-based biofuels is highly dependent on the uses to which the coproducts are put. Although microalgae biofuels scenarios can be constructed with low WF, the results of this study show that under a variety of metrics, both local water consumption and lifecycle water consumption will be a significant resource constraint for large-scale microalgae biofuels production.

Table 1. Location and corresponding production characteristics for the 10 US locations evaluated

STATE	**LOCATION NAME**	**LOCATION**		**GROWING**	**BIOMASS YIELD**	**OIL YIELD**
		Latitude	**Longitude**	**days**	**kg·ha^{-1}·year^{-1}**	**m^{3}· ha^{-1}·year^{-1}**
ARIZONA	TEMPE	33.5°N	-111.9°W	365	52,947	23.70
CALIFORNIA	HAYFIELD PUMP PLANT	33.6°N	-114.7°W	365	52,616	23.51
COLORADO	JOHN MARTIN	37.9°N	-100.7°W	274	36,400	16.29
MONTANA	YELLLOWTAIL	45.5°N	-100.4°W	236	29,481	12.97
NEBRASKA	NORTH PLATTE	40.7°N	-99.0°W	254	33,736	15.11
NEVADA	BOULDER CITY	36.0°N	-112.1°W	280	38,285	17.26
NEW MEXICO	STATE UNIVERSITY	32.3°N	-104.2°W	355	46,795	20.52
TEXAS	GRAND FALLS	31.8°N	-103.2°W	355	47,460	20.91
UTAH	FISH SPRINGS	40.2°N	-111.7°W	277	38,520	17.47
WYOMING	FARSON	42.8°N	-108.7°W	241	32,921	14.85

Table 2. Blue, green and total WF for the 10 US sites evaluated. All values are presented in m^{3}·GJ^{-1}with results averaged across all 4 conversion pathways. Negative values appear in parenthesis.

	Blue WF		**Green WF**	**Total WF**
LOCATION NAME	**Process water**	**Fuel conversion**		
TEMPE, AZ	23 – 44	0 – 1.5	(2) – (5)	20 – 40
HAYFIELD PUMP PLANT, CA	39 – 76	0 – 1.5	(1) – (2)	38 – 74
JOHN MARTIN, CA	32 – 62	0 – 1.5	(6) – (12)	26 – 52
YELLLOWTAIL, MT	30 – 59	0 – 1.5	(9) – (17)	22 – 43
NORTH PLATTE, NE	27 – 51	0 – 1.5	(9) – (17)	18 – 35
BOULDER CITY, NV	43 – 84	0 – 1.5	(2) – (3)	42 – 82
STATE UNIVERSITY, NM	31 – 61	0 – 1.5	(3) – (6)	28 – 55
GRAND FALLS, TX	34 – 66	0 – 1.5	(7) – (13)	27 – 53
FISH SPRINGS, UT	28 – 53	0 – 1.5	(3) – (5)	25 – 49
FARSON, WY	25 – 48	0 – 1.5	(3) – (6)	22 – 44

Figure 1. Geographically averaged water footprint for each conversion pathway. Total water footprint (1a) and lifecycle water footprint without coproduct allocation (1b) are presented in $m^3 \cdot GJ^{-1}$

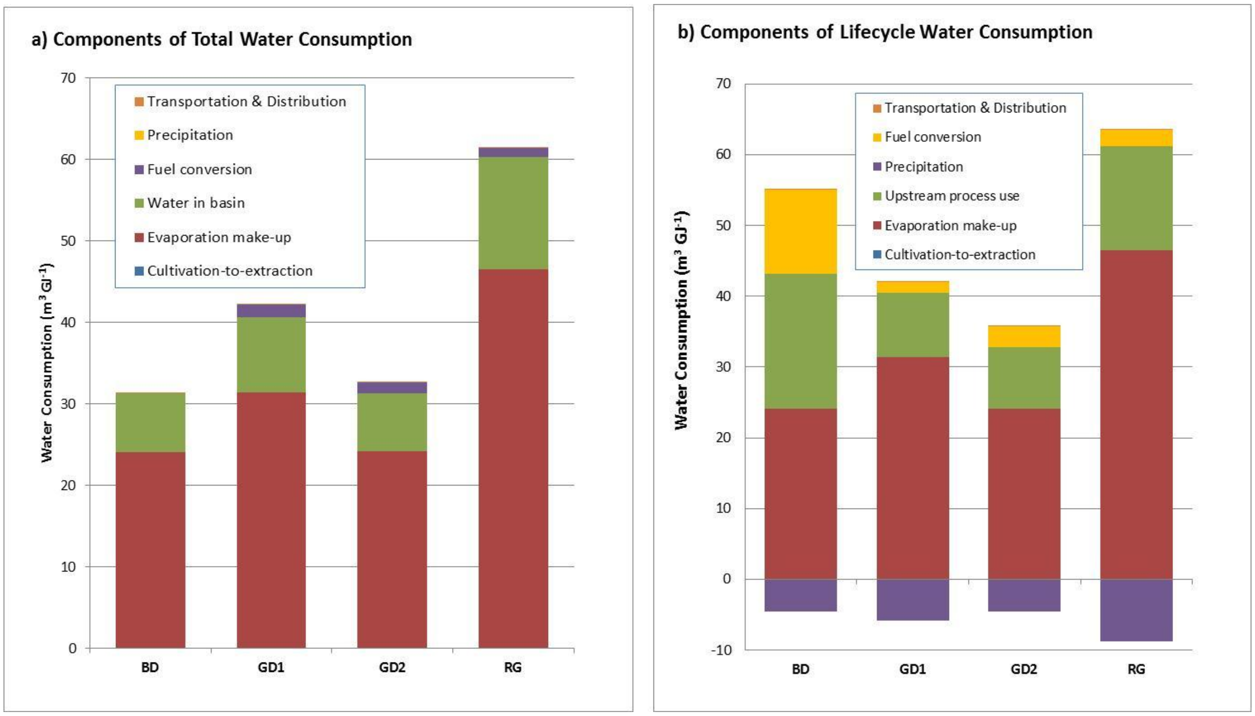

Table 3. Lifecycle water footprint, coproduct credits and net lifecycle water footprint for the 10 US sites evaluated for four fuel pathways. All values are presented in $m^3 \cdot GJ^{-1}$. Negative values appear between parentheses.

	Lifecycle Water Footprint	**Coproduct credits**				**Lifecycle Water Footprint**
Locations	**Without coproduct credits**	Energy allocation		Displacement allocation		**With coproduct credits**
		Min.	**Max.**	**Min.**	**Max.**	
TEMPE, AZ	26 – 46	1.0	3.7	5.9	327	**(282) – 44**
HAYFIELD PUMP PLANT, CA	44 – 79	1.0	3.7	5.9	328	**(249) – 75**
JOHN MARTIN, CO	30 – 53	1.0	3.7	5.9	327	**(274) – 49**
YELLLOWTAIL, MT	24 – 44	1.0	3.7	5.9	333	**(291) – 43**
NORTH PLATTE, NE	21 – 41	1.0	3.7	5.9	327	**(291) – 40**
BOULDER CITY, NV	46 – 83	1.0	3.7	5.8	325	**(241) – 80**
STATE UNIVERSITY, NM	34 – 60	1.0	3.7	6.0	333	**(274) – 56**
GRAND FALLS, TX	33 – 58	1.0	3.7	6.0	332	**(274) – 54**
FISH SPRINGS, UT	29 – 50	1.0	3.6	5.8	322	**(272) – 47**
FARSON, WY	25 – 44	1.0	3.6	5.8	324	**(282) – 43**

Table 4. Coproduct water credits

Microalgae Biofuel Pathway	**Coproducts**	**Water credits**	
		Energy allocation ($m^3 \cdot kg^{-1}$)	**Displacement allocation ($m^3 \cdot kg^{-1}$)**
Green diesel type 1	Fuel gas	0.122	0.008
	Heavies	0.090	0.004
Green diesel type 2	Propane fuel mix	0.081	0.003
Renewable gasoline	Product gas	0.080	0.003
	Light-cycle oil	0.084	0.004
	Clarified slurry oil	0.081	0.004
All fuel pathways	Lipid Extracted Algae (LEA)	0.03	0.13 – 3.67

Table 5. Comparison of microalgae biofuels blue (B), green (G) and lifecycle (LC) WF with petroleum-based diesel and other biodiesel feedstocks.

TYPE OF FUEL	TYPE OF WF	WF ($m^3 \cdot GJ^{-1}$) *	REFERENCE	MAJOR DIFFERENCE AND ASSUMPTIONS
Petroleum-based diesel	B	0.04 – 0.08	[3]	
Petroleum based-gasoline	B	0.08 – 0.20	[48]	King & Webber included extraction, prospection and oil refining.
	B	0.04 – 0.09	[3]	Wu et al. accounted for U.S. national production, Saudi crude oil and Canadian sand oils
Bioethanol from				
- Sugar beet	B+G	41	[5]	Mekonnen et al. estimated blue and green WF, includes rain-fed and irrigated crops. Excludes though water burden from refining process and transportation and distribution burdens.
	B+G	89	[49]	
- Sugar cane	B+G	85	[5]	
	B+G	139	[49]	
- Potatoes	B+G	73	[5]	
	B+G	86	[49]	
- Maize	B	4.5	[48]	Dominguez-Faus et al. Estimated WF, that Includes actual process water use and evapotranspiration per type of crop.
	B+G	86	[49]	
	B+G	102	[5]	
- Cassava	B+G	106	[5]	
- Rice, paddy	B+G	147	[5]	Wu et al. estimated production-weighted average for ethanol WF.
- Barley	B+G	127	[5]	
- Wheat	B+G	160	[5]	
- Rye	B+G	142	[5]	
- Sorghum	B+G	95	[49]	
	B+G	291	[5]	
- Switchgrass	B	0.1- 0.5	[48]	
	B+G	66	[49]	
Biodiesel from				
- Coconuts	B+G	4723	[5]	
- Groundnuts	B+G	188	[5]	
- Oil palm	B+G	150	[5]	
- Rapeseed	B+G	165	[5]	
- Seed cotton	B+G	487	[5]	
- Soybeans	B+G	287	[49]	
		337	[5]	
- Sunflower	B+G	449	[5]	
Biodiesel from				
- Microalgae (open system)	B+G	14 – 87	[18]	Yang et al. estimated all lifecycle stages, but did not include upstream water.
	LC	1 – 20	[17]	
	LC	30	[10]	Clarens et al. calculated actual process water and upstream water for algae WF from cradle-to-gate.
	LC	43	[19]	
	LC	303 - 454	[13]	Harto et al. assumed high fuel yields: 72 to 130 m3 fuel per year per hectare.
- Microalgae (closed system)	LC	1 – 2	[17]	

* Some references units were converted into m3 water per GJ, for comparison reasons.

References

[1] S.L. Postel. Entering an Era of Water Scarcity: The Challenge Ahead. Ecological Application 10 (2000) 941-8.
[2] M. Blackhurst, C. Hendrickson, J.S.I. Vidal. Direct and Indirect Water Withdrawals for US Industrial Sectors. Environ Sci Technol 44 (2010) 2126-30.
[3] C.W. King, M.E. Webber. Water Intensity of Transportation. Environ Sci Technol 42 (2008) 7866-72.
[4] Y.W. Chiu, B. Walseth, S. Suh. Water Embodied in Bioethanol in the United States. Environ Sci Technol 43 (2009) 2688-92.
[5] M.M. Mekonnen, A.Y. Hoekstra. The green, blue and grey water footprint of crops and derived crop products. Hydrol Earth Syst Sci 15 (2011) 1577-600.
[6] P.T. Pienkos, A. Darzins. The promise and challenges of microalgal-derived biofuels. Biofuels Bioproducts & Biorefining-Biofpr 3 (2009) 431-40.
[7] L. Batan, J. Quinn, B. Willson, T. Bradley. Net Energy and Greenhouse Gas Emission Evaluation of Biodiesel Derived from Microalgae. Environ Sci Technol 44 (2010) 7975-80.
[8] L. Brennan, P. Owende. Biofuels from microalgae-A review of technologies for production, processing, and extractions of biofuels and co-products. Renew Sust Energ Rev 14 (2010) 557-77.
[9] P.K. Campbell, T. Beer, D. Batten. Life cycle assessment of biodiesel production from microalgae in ponds. Bioresour Technol 102 (2011) 50-6.
[10] V. Vasudevan, R.W. Stratton, M.N. Pearlson, G.R. Jersey, A.G. Beyene, J.C. Weissman, et al. Environmental Performance of Algal Biofuel Technology Options. Environ Sci Technol 46 (2012) 2451-9.
[11] X. Liu, A.F. Clarens, L.M. Colosi. Algae biodiesel has potential despite inconclusive results to date. Bioresour Technol 104 (2012) 803-6.
[12] R. Davis, D. Fishman, E.D. Frank, M.S. Wigmosta. Renewable Diesel from Algal Lipids: An Integrated Baseline for Cost, Emissions, and Resource Potential from a Harmonized Model. ANL/ESD/12-4; NREL/TP-5100-55431;PNNL-21437. Argone, IL: Argonne National Laboratory; Golden, CO: National Renewable Energy Laboratory; Richland, WA: Pacific Northwest National Laboratory2012.
[13] A.F. Clarens, E.P. Resurreccion, M.A. White, L.M. Colosi. Environmental Life Cycle Comparison of Algae to Other Bioenergy Feedstocks. Environ Sci Technol 44 (2010) 1813-9.
[14] L. Lardon, A. Helias, B. Sialve, J.P. Stayer, O. Bernard. Life-Cycle Assessment of Biodiesel Production from Microalgae. Environ Sci Technol 43 (2009) 6475-81.
[15] E.D. Frank, J. Han, I. Palou-Rivera, A. Elgowainy, M.Q. Wang. Life-Cycle Analysis of Algal Lipid Fuels with the GREET Model. ANL/ESD/11-5. Energy Systems Division, Argonne National Laboratory. 2011a.
[16] E.D. Frank, J. Han, I. Palou-Rivera, A. Elgowainy, M.Q. Wang. User Manual for Algae Life-Cycle Analysis with GREET: Version 0.0. ANL/ESD/11-7. Argonne National Laboratory. 2011b.
[17] C. Harto, R. Meyers, E. Williams. Life cycle water use of low-carbon transport fuels. Energy Policy 38 (2010) 4933-44.
[18] J. Yang, M. Xu, X.Z. Zhang, Q.A. Hu, M. Sommerfeld, Y.S. Chen. Life-cycle analysis on biodiesel production from microalgae: Water footprint and nutrients balance. Bioresour Technol 102 (2011) 159-65.
[19] M.S. Wigmosta, A.M. Coleman, R.J. Skaggs, M.H. Huesemann, L.J. Lane. National microalgae biofuel production potential and resource demand. Water Resour Res 47 (2011) W00H4.
[20] J. Quinn, L. de Winter, T. Bradley. Microalgae bulk growth model with application to industrial scale systems. Bioresour Technol 102 (2011) 5083-92.
[21] J. Quinn, K. Catton, N. Wagner, T.H. Bradley. Current Large-Scale US Biofuel Potential from Microalgae Cultivated in Photobioreactors. BioEnergy Research 5 (2012) 49-60.
[22] J. Quinn, T. Yates, N. Douglas, J. Butler, T.H. Bradley, K. Weyer, et al. Nannochloropsis Production Metrics in an Scalable Outdoor Photobioreactor for Commercial Applications. Bioresour Technol (2012).

[23] H. Huo, M. Wang, C. Bloyd, V. Putsche. Life-Cycle Assessment of Energy Use and Greenhouse Gas Emissions of Soybean-Derived Biodiesel and Renewable Fuels. Environ Sci Technol 43 (2009) 750-6.
[24] S. Yeh, G. Berndes, G.S. Mishra, S.P. Wani, A. Elia Neto, S. Suh, et al. Evaluation of water use for bioenergy at different scales. Biofuels, Bioproducts and Biorefining 5 (2011) 361-74.
[25] A.Y. Hoekstra, A.K. Chapagain. Water footprints of nations: Water use by people as a function of their consumption pattern. Dordrecht, Springer, 2007.
[26] W. Gerbens-Leenes, A.Y. Hoekstra, T.H. van der Meer. The water footprint of bioenergy. Proceedings of the National Academy of Sciences of the United States of America 106 (2009) 10219-23.
[27] M.E. Webber. The water intensity of the transitional hydrogen economy. Environ Res Lett 2 (2007).
[28] C.W. King, M.E. Webber, I.J. Duncan. The water needs for LDV transportation in the United States. Energy Policy 38 (2010) 1157-67.
[29] C.M.U.G.D. Institute. Economic Input-Output Life Cycle Assessment (EIO-LCA). US 1997 Industry Benchmark model [Internet] Available from:<http://wwweiolcanet> (2008). Accessed 15 January, 2012.
[30] A.V. Borruso. High-Density Polyethylene Resins. Chemical Economics Handbook. SRI Consulting. 2011. p. p.109.
[31] USDA. National Agricultural Statistics Services - Agricultural Prices. 2011.
[32] E. Linak, H. Janshekar, Y. Inoguchi. Ethanol. Chemical Economics Handbook - Marketing Research Report. SRI Consulting.2011. p. 236.
[33] J. Glauser. Ammonium Nitrate. Chemical Economics Handbook. SRI Consulting. 2011. p. 156.
[34] A. Sukenik, O. Zmora, Y. Carmeli. Biochemical Quality of Marine Unicellular Algae with Special Emphasis on Lipid Composition. II. Nannochloropsis sp. Aquaculture 117 (1993) 313- 26.
[35] L. Gouveia, A.C. Oliveira. Microalgae as a Raw Material for Biofuels Production. J Ind Microbiol Biotechnol 36 (2009) 269-74.
[36] B.C. Fischer, A.J. Marchese, J. Volckens, T. Lee, J.L. Collett. Measurement of Gaseous and Particulate Emissions from Algae-Based Fatty Acid Methyl Esters. SAE Int J Fuels Lubr 3 (2010) 292 - 321.
[37] NRC. Technologies and Applications: The CETC SuperCetane Technology. In: http://www.canren.gc.ca/tech_appl/index.asp?CaID=2&PgId=1083, (Ed.). Natural Resources Canada2003.
[38] UOP. Opportunities for Bionerewables in Oil Refineries. In: DOE, (Ed.). Contributors: Terry Marker, John Petri, TOm Kalnes, Micke McCall, Dave Mackowiak, Bob Jerosky, Bill Reagan, Lazlo Nemeth, Mark Krawczyk (UOP), Stefan Czernick (NREL), Doug Elliott (PNNL), David Shonnard (Michigan Technological University)2006.
[39] K.D. Fagerstone, J.C. Quinn, T.H. Bradley, S.K. De Long, A.J. Marchese. Quantitative Measurement of Direct Nitrous Oxide Emissions from Microalgae Cultivation. Environ Sci Technol 45 (2011) 9449-56.
[40] K.L. Kadam. Environmental implications of power generation via coal-microalgae cofiring. Energy 27 (2002) 905-22.
[41] J.R. Benemann, R.P. Goebel, J.C. Weissman, D.C. Augesntein. Microalgae as a source of liquid fuels. In: U.S.DOE, (Ed.). Office of Research: DOE/ER/30014-TR1982.
[42] R. Lansford, J. Hernandez, P. Enis, D. Truby, C. Mapel. Evaluation of Available Saline Water Resources in New Mexico for the Production of Microalgae. Solar Energy Research Institute1990.
[43] J. Muhs, S. Viamajala, B. Heydorn, M. Edwards, Q. Hu, R. Hobbs. A summary of opportunities, challenges and research needs: algae biofuels & carbon recycling. www.utah.gov/ustar/documents/63.pdf.2009.
[44] R.K. Farnsworth, E.S. Thompson, E.L. Peck. Evaporation Atlas for th 48 Contiguous United States. In: N.W. Service, (Ed.) NOAA Technical Report NWS 33, Washington, DC, 1982a.
[45] R.K. Farnsworth, E.S. Thompson. Mean Monthly, Seasonal, and Annual Pan Evaporation for the United States. In: N.W. Service, (Ed.) NOAA Technical Report NWS 34, Washington, DC, 1982b.
[46] NOAA. Western U.S. Historical Summaries. Regional Climate Center.

[47] USDOE. National Algal Biofuels Technology Roadmap. In: U.S.DOE, (Ed.). Biomass Program, Off. of Energy Efficiency and Renewable Energy, Washington, D.C., 2010.
[48] M. Wu, M. Wang, M. Mintz, S. Arora. Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline. Argonne National Laboratory2009.
[49] R. Dominguez-Faus, S.E. Powers, J.G. Burken, P.J. Alvarez. The Water Footprint of Biofuels: A Drink or Drive Issue? Environ Sci Technol 43 (2009) 3005-10.
[50] Y. Chisti. Biodiesel from microalgae. Biotechnol Adv 25 (2007) 294-306.
[51] P.M. Schenk, S.R. Thomas-Hall, E. Stephens, U.C. Marx, J.H. Mussgnug, C. Posten, et al. Second Generation Biofuels: High-Efficiency Microalgae for Biodiesel Production. Bioenergy Research 1 (2008) 20-43.