

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 $\text{m}^3 \cdot \text{GJ}^{-1}$ 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 $\text{m}^3 \cdot \text{GJ}^{-1}$ up to credits of 334 $\text{m}^3 \cdot \text{GJ}^{-1}$. Results for the net lifecycle WF with coproduct credits varies between 80 and -291 $\text{m}^3 \cdot \text{GJ}^{-1}$. 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

42 cultivation, but excluding consumption in the stages of fuel conversion, transportation and distribution.
43 Yang et al. (2010) studied the WF from microalgae biodiesel derived from open-pond cultivation systems,
44 but only accounted for the actual water consumed in process, excluding the water requirements associated
45 with energy and consumable materials. Vasudevan et al. (2012) performed a thorough LCA with a focus
46 on freshwater consumption for dry and wet extraction technologies, excluding upstream water use related
47 to energy and material inputs. Wigmosta et al. (2011) constructed a geographically-resolved water
48 consumption analysis of microalgae feedstock production and fuel conversion, but distribution,
49 transportation and co-product allocations were not included as would be required for a conventional
50 lifecycle accounting. Harto et al. (2010) performed a comparison of the lifecycle water footprint of open
51 pond and tubular PBR cultivation systems, but incorporated higher productivities than has been reported
52 in studies of near-term, industrially-realizable cultivation systems [20-22]. In general, the synthesis of the
53 results of water consumption analyses among studies is complicated by the many modeled conversion
54 processes, by geographical and climactic variability, and by differences in study scopes, system
55 boundaries, and metrics.

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

69 2 Methods

70 2.1 Water Footprint Functional Unit, Boundaries, and Metrics

71 Water consumption is defined as the total water that is not returned to a water body or source for
72 reuse [3]. WF is the freshwater consumption of a process or product per functional unit [5, 25, 26]. The
73 functional energy unit for this study is a unit of biofuel based on its lower heating value (LHV). The WF
74 is therefore quantified as cubic meters of water per unit of energy of biofuel produced ($\text{m}^3 \cdot \text{GJ}^{-1}$). The
75 LHV of biodiesel, green diesel type 1, green diesel type 2 and renewable gasoline are assumed to be 37.6
76 $\text{MJ} \cdot \text{kg}^{-1}$, 43.6 $\text{MJ} \cdot \text{kg}^{-1}$, 44.0 $\text{MJ} \cdot \text{kg}^{-1}$ and 43.4 $\text{MJ} \cdot \text{kg}^{-1}$, respectively [23].

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

81 Three different metrics of WF are analyzed in this study: blue WF, green WF and lifecycle WF
82 [5, 24]. The blue WF is a metric of the direct water withdrawal of a process, for either consumptive or
83 non-consumptive use. The green water footprint is a metric representing the difference between the water
84 lost through soil moisture evaporation, feedstock evapotranspiration, and the water gained through
85 precipitation. The total WF is defined as the sum of blue and green WFs. The lifecycle WF metric is the
86 most comprehensive metric, accounting for the direct water consumption in the process, the upstream
87 water consumed in materials and energy production, and the water credits that are returned to the

88 accounting due to the displacement of marketable products by the co-products generated in the biofuel
89 production process.

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

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

115 **2.2 Process WF Assessment Details**

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

125 **2.3 Economic Input-Output Lifecycle Assessment Details**

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

135 are based on the US economy as measured in 2002, thus 2011 prices are used to adjust the EIO-LCA data
136 [30-33].

137 2.4 Microalgae-to-Biofuel Process Model

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

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

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

159 Coproduct credits play a key role in lifecycle WF assessment, as each coproduct incorporates
160 water credits that must be accounted for. Coproducts from the microalgae-to-biofuels process vary with
161 the fuel pathway considered but can include lipid-extracted microalgae biomass, glycerin, and various
162 hydrocarbon coproducts from the refining process. Both energy and displacement allocation methods are
163 analyzed in turn for this study. The energy allocation method uses the energy embedded in the coproducts
164 to calculate water credits. In this allocation method, the algal extract and glycerin are used as co-firing
165 material to generate bioelectricity, therefore, water credits are based on the WF of the produced electricity
166 [3, 40]. The displacement allocation method assumes that the microalgae biofuel coproducts will
167 substitute for conventional products in the market. Using displacement allocation, lipid-extracted algal
168 biomass substitutes for microalgae as an aquaculture fish or shrimp feed. The water credit assigned to
169 microalgae biomass is equal to the water needed to produce microalgae conventionally cultivated in an
170 open-pond system. The other coproducts displace the equivalent types of gas, heavies and other energy
171 fuel carriers, and their water credit is based on the water footprint of the conventional energy fuel carriers
172 that they replace. Market saturation due to coproducts generated by microalgae-to-biofuel process is not
173 analyzed in this study.

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

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 $\text{ton}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$, and microalgae oil yields range from 13 to 23.7 $\text{m}^3\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$. 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 $\text{ton}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ of biomass yield and 18.3 $\text{m}^3\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ 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

222 evaporated water. The blue WF represents the local water requirements for the microalgae-to-biofuels
223 process. The average blue WF of microalgae biofuel among all locations and conversion pathways is 42
224 $\text{m}^3 \cdot \text{GJ}^{-1}$. Blue WF varies as a function of fuel conversion pathway and location between 23 and 85 $\text{m}^3 \cdot \text{GJ}^{-1}$,
225 as shown in Table 2. Averaged among the locations and conversion pathways, the process water use for
226 feedstock cultivation, harvesting and extraction accounts for 97.6% of the blue WF, the fuel conversion
227 accounts for 2.4% of the blue WF and transportation and distribution for 0.002% of the blue WF.

228 For microalgae-based biofuels the green WF is negative, representing a water gain in the water basin
229 due to precipitation. The green WF is therefore a ratio of the precipitation that each geographic location
230 receives and the energetic productivity of the location. The green WFs for BD and GD2 are the lowest
231 among the four fuel conversion pathways, varying among the geographies between 1.3 and 8.9 $\text{m}^3 \cdot \text{GJ}^{-1}$.
232 The green WFs for GD1 and RG are higher, varying among the geographies between 1.7 and 17 $\text{m}^3 \cdot \text{GJ}^{-1}$.
233

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

238 3.3 Lifecycle Water Footprint

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

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

252 The set of available coproducts from the four production pathways are lipid extracted algae (LEA),
253 and petroleum coproducts including product gas, light cycle oil and clarified slurry oil. In this analysis,
254 glycerin is treated as a waste product and is allocated none of the WF². The water credits allocated to
255 coproducts varies depending on the allocation method. The two methods considered in this study are the
256 energy allocation and the displacement allocation methods.

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

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

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

266 aquaculture feed. LEA water credits are based on the water consumption required to cultivate the
267 displaced microalgae biomass using open-ponds. Harto et al. (2010) is used for estimating LEA water
268 credits. An efficiency of fuel conversion and lipid extraction of 96% and 85%, respectively, were
269 assumed to obtain the lifecycle WF for 1 unit of displaced LEA [17, 18]. The water credits for LEA are
270 0.13 and 3.67 m³ kg⁻¹ of LEA, based on the Harto et al. low and high cases, respectively; all other
271 coproducts are assumed to displace products on a mass basis and calculation details are shown in
272 Supplementary material. A summary of coproduct displacement and energy allocations is shown in Table
273 4.

274 Table 3 also presents the lifecycle WF of the microalgae-to-biofuels production process for all
275 locations and coproduct displacement methods. The ranges represent the range of WFs associated with
276 the four conversion pathways. The lifecycle WF for the microalgae-to-biofuels process can vary between
277 a maximum WF of 80 m³·GJ⁻¹ to a minimum WF of -291 m³·GJ⁻¹, representing 291 m³·GJ⁻¹ of water
278 consumption avoidance. The variation among lifecycle WFs is also due to geographic and climatic
279 variability among the locations. Those locations with shorter winters and warmer temperatures have a
280 longer cultivation season, longer cultivation days, higher productivity, and consequentially higher energy
281 and material consumptions. Averaged among all the fuel conversion pathways and locations, the
282 upstream water accounts for 29.3% of lifecycle WF, the evaporation and process use accounts for 74.2%,
283 while fuel conversion and precipitation water gain account for 10.3% and -13.9%, respectively.
284 Transportation and distribution account for less than 0.002% of the lifecycle WF, as shown in Figure 1b.

285 3.4 Comparison with Fossil Fuel and Other Feedstock Fuels

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

290 Using the same total WF (blue WF plus green WF) metric that is used in the most cited petroleum
291 fuel WF studies, the WF of microalgae based biofuels is found to be higher than that of conventional
292 petroleum-based fuels. The WFs of petroleum-based diesel and gasoline are between 0.04 and 0.2 m³·
293 GJ⁻¹, where the range of values are due to various scenarios of water use including the use of desalinated
294 seawater, the use of water recycling, or the re-injection of produced water for oil recovery [3, 48]. This
295 can be compared to the findings of this study where the total WF of microalgae based biofuels is between
296 18 and 82 m³·GJ⁻¹, depending on the geographical location and conversion pathway.

297 Using the same WF metrics that are used in the most cited biofuel WF studies, the WF of
298 microalgae-based biofuels is found to be roughly comparable to that of other starched-based biofuels.
299 Dominguez-Faus et al. (2009) calculated the soybean BD total WF as 287 m³·GJ⁻¹, including
300 evapotranspiration. Mekonnen et al. (2011) calculated soybean BD total WF as 337 m³·GJ⁻¹, using global
301 weighed averages and including water from precipitation. Studies that show a lower WF for soy-based
302 BD do not adhere to any of the WF definitions presented above, in that partial irrigation is assumed and
303 evapotranspiration is not included in the WF accounting [3, 17]. BD from palm oil, rapeseed and other
304 oilseeds are shown to have higher total WFs (>150 m³·GJ⁻¹) than microalgae biofuels, [26, 49].

305 Comparison of this study's findings to those of previous microalgae biofuel WF studies is more
306 complicated, as no studies adhere to these WF metrics or boundaries. Clarens et al. (2010) estimated
307 microalgae biofuel for an open-pond cultivation system at between 303 and 454 m³·GJ⁻¹, but does not
308 apply the same lifecycle boundaries as this study. Instead, the boundary for Clarens is cradle-to-gate for
309 cultivation of feedstock, and does not include lipid extraction, fuel conversion and distribution. Yang et
310 al. (2011) estimated a WF for microalgae biofuel of between 14 and 87 m³·GJ⁻¹, although their lifecycle
311 analysis did not include upstream water use from energy and materials. Harto et al. (2010) calculated the
312 microalgae biofuel WF from open-ponds (ORP) as between 1 and 20 m³·GJ⁻¹ and a microalgae WF from

313 enclosed photobioreactors as between 1 and 2 m³·GJ⁻¹. The latter study used boundaries and metrics
314 comparable to those of this study, but the modeled microalgae productivity is between 72 and 130 m³·ha⁻¹·year⁻¹,
315 which is 3 to 10 times higher than is feasible with modern open ponds and photobioreactor
316 systems [22]. These calculations are described in detail in the supplementary material.

317 3.5 Geographic and Climactic Sensitivity of Microalgae Biofuels WFs

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

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

330 Lifecycle WF is shown to be most sensitive to its energy and material inputs. Averaging the
331 results for the four fuel pathways, the lifecycle WF of microalgae-based biofuels is composed of less than
332 0.05% direct process water use, 10.4 % fuel conversion water consumption, 74.2% make-up water due to
333 evaporation, 29.3% upstream water consumption, and 14% water gain through precipitation. Lifecycle
334 WF is very sensitive to the coproduct allocation method due to the significance of upstream water
335 consumption. Energy allocation methods result in lower water credits compared to displacement
336 allocation methods, and various coproduct displacement scenarios result in a wide range of lifecycle WFs.
337 These variations among these values of WF are primarily due to variation in the water credits available
338 for LEA, the effect of geographic and climatic differences on biomass yields, and the differences among
339 fuel conversion pathways.

340 3.6 Scalability of Production

341 Microalgae have been proposed as an oil feedstock with the potential to meet future alternative fuel
342 goals [50]. Based on the results of this study, if microalgae biofuel production relies only on freshwater to
343 meet the EISA 2022 target of 136 million m³ of biofuel, it would require between 91 and 420 billion m³
344 of water (using the total WF metric), for the best and worst scenarios, respectively. These values are
345 equivalent to an additional direct water consumption of 0.7 to 3 times the amount of water currently used
346 directly for US grain farming [2].

347 In the lifecycle perspective, the WF of microalgae biofuel production could range from a water
348 consumption avoidance of 1.5 trillion m³, to a water consumption of 410 billion m³, for the best and worst
349 scenarios, respectively. The lowest water consumption scenario corresponds to the use of LEA to displace
350 conventional microalgae already cultivated for fish or shrimp feed. The highest water consumption
351 scenario corresponds to the use of LEA as a co-firing material for bioelectricity generation.

352 4 Conclusions

353 The problems with first generation biofuels in terms of marginal environmental benefit, and resource
354 intensity are well documented in literature [51], whereas the environmental impacts and resource
355 limitations of microalgae-based biofuels are the subject of continued research. To quantify the water
356 resource impacts of microalgae-based biofuels, this study has calculated their WF using a variety of

357 biofuel pathways, geographic locations, and WF metrics. This comprehensive accounting for the water
358 consumption of microalgae-based biofuels allows for a rigorous WF comparison among fuel pathways,
359 among geographic locations, and against other biofuel feedstocks. When comparisons to other available
360 fuels are made using the same WF metrics, this study has shown that the production of microalgae
361 biofuels is more water intensive than petroleum-based fuels, is comparable to that of bioethanol from
362 most types of biomass, and is less water intensive than that of oilseed-based biodiesel. The productivity
363 of microalgae and its corresponding WF is shown to vary across geographical regions of the US. From
364 the lifecycle WF perspective, the water intensity of microalgae-based biofuels is highly dependent on the
365 uses to which the coproducts are put. Although microalgae biofuels scenarios can be constructed with low
366 WF, the results of this study show that under a variety of metrics, both local water consumption and
367 lifecycle water consumption will be a significant resource constraint for large-scale microalgae biofuels
368 production.

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

STATE	LOCATION NAME	LOCATION		GROWING days	BIOMASS YIELD kg·ha ⁻¹ ·year ⁻¹	OIL YIELD m ³ ·ha ⁻¹ ·year ⁻¹
		Latitude	Longitude			
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	YELLOWTAIL	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

370

371 Table 2. Blue, green and total WF for the 10 US sites evaluated. All values are presented in m³·GJ⁻¹ with
372 results averaged across all 4 conversion pathways. Negative values appear in parenthesis.

LOCATION NAME	Blue WF		Green WF	Total WF
	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
YELLOWTAIL, 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

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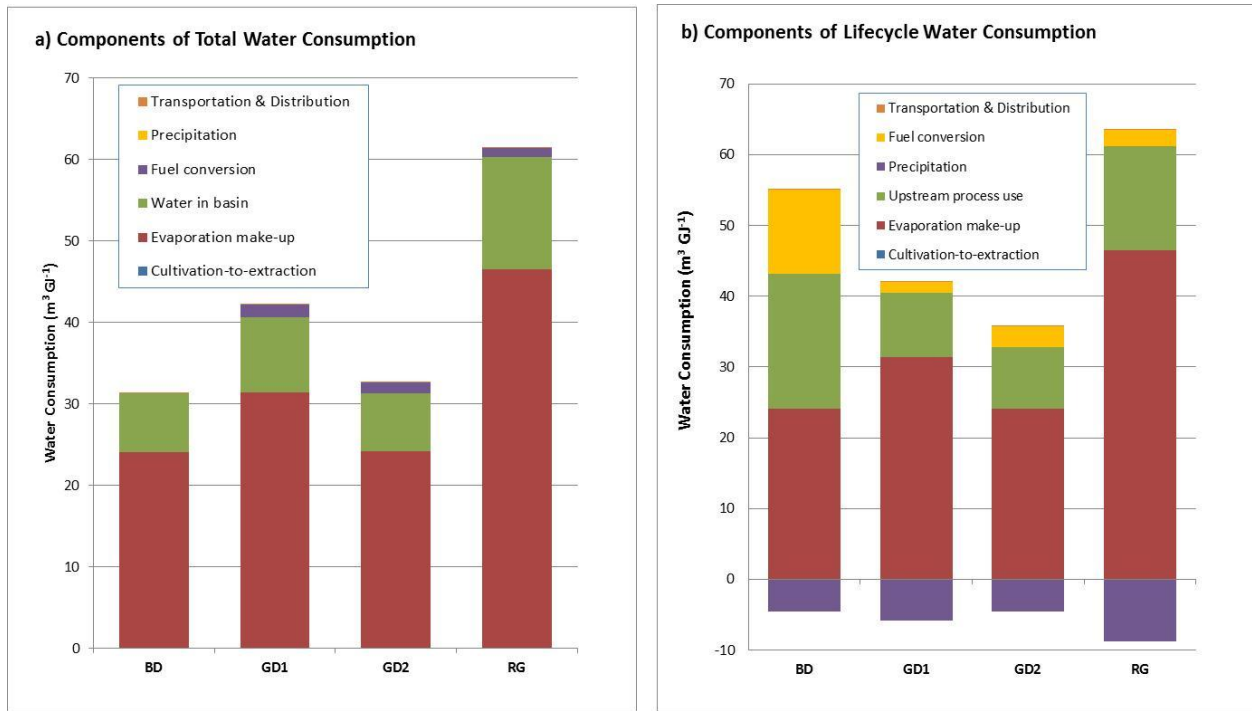
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379 Figure 1. Geographically averaged water footprint for each conversion pathway. Total water footprint
 380 (1a) and lifecycle water footprint without coproduct allocation (1b) are presented in $\text{m}^3 \cdot \text{GJ}^{-1}$



381

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 $\text{m}^3 \cdot \text{GJ}^{-1}$. Negative values appear between parentheses.

Locations	Lifecycle Water Footprint	Coproduct credits				Lifecycle Water Footprint		
		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		
YELLOWTAIL, 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 ($\text{m}^3 \cdot \text{kg}^{-1}$)	Displacement allocation ($\text{m}^3 \cdot \text{kg}^{-1}$)
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 ·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. Wu et al. accounted for U.S. national production, Saudi crude oil and Canadian sand oils
	B	0.04 – 0.09	[3]	
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]	Dominguez-Faus et al. Estimated WF, that Includes actual process water use and evapotranspiration per type of crop.
	B+G	86	[49]	
- Maize	B	4.5	[48]	
	B+G	86	[49]	
	B+G	102	[5]	Wu et al. estimated production-weighted average for ethanol WF.
- Cassava	B+G	106	[5]	
- Rice, paddy	B+G	147	[5]	
- 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 m ³ 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.

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