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Variability and uncertainty in water demand and water footprint assessments of fresh algae cultivation based on case studies from five climatic regions

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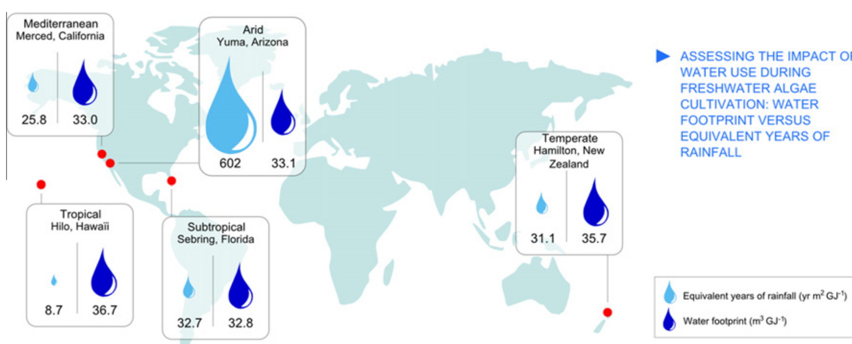
HIGHLIGHTS

- ▶ The water demand (WD) of algae cultivation for five case studies was quantified.
- ▶ Considerable variability and uncertainty regarding WD were found.
- ▶ The water footprint metric had poor geographical resolution and was biased towards high-productivity arid locations.

GRAPHICAL ABSTRACT



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ABSTRACT

Using case studies from five typical climatic locations, this study revealed that current quantification of water demand (WD) and water footprint (WF) of freshwater algae cultivation in raceway ponds suffer from uncertainty and variability in the methodologies and assumptions used. Of particular concern, the WF metric had an intrinsically poor geographical resolution and could be biased towards high-productivity arid locations because local levels of water stress are not accounted for. Applying current methodologies could therefore cause the selection of locations that are neither economically viable nor environmentally sustainable. An improved methodology should utilize more accurate evaporation models, determine realistic limits for the maximum hydraulic retention times and process water recycling ratios, and apply weighting to the WF to reflect localized water stress or use an alternative metric such as the equivalent years of rainfall required to support a productivity of 1 GJ m^{-2}.

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1. Introduction

Despite the vast potential of algae biotechnologies to provide food, animal feed, bioactive compounds, biofuels, and new capabilities for pollution control (Dismukes et al., 2008; Spolaore et al., 2006; Singh et al., 2011), commercial algae cultivation remains expensive and difficult to scale up due to issues such as nutrient availability, CO_2 supply and delivery, land availability, process stability, biomass separation, and environment impacts (Murphy and Allen, 2011; Clarens et al., 2010; Singh and Olsen, 2011). Therefore, if algal biofuels are to become a commercial reality, the fundamental issues associated with large-scale algae cultivation must be addressed. Since more than 1 metric ton of process water must be handled for each kg of algae biomass produced (Murphy and Allen, 2011), water use represents a challenge of particular significance.

Water use can be assessed in terms of the water demand (WD) required for operating the process, which has direct economic and technological relevance, and the water footprint (WF), which reflects the amount of freshwater resource that the ecosystem is deprived of and which is essentially a policy tool. Different methods and assumptions have been used in the literature to estimate the amount of water used during algae cultivation (S1) and these differences may have led to conflicting conclusions. For example,

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Clarens et al. (2010) reported that the impact of water use during algae cultivation at three different locations in the USA was not sensitive to location, whereas Yang et al. (2011) and Wigmosta et al. (2011) found significant differences across the USA. Diverging conclusions are not uncommon in Life Cycle Assessments (LCAs) (Reap et al., 2008; Williams et al., 2009). Liu et al. (2012) demonstrated that considerable differences in the net energy ratio and carbon footprint of algae biodiesel production were attributable to differences in modeling methodologies and assumptions.

While refinement of full LCAs is necessary, the need for accurate estimation of water use is particularly pressing, not just for impact assessment but to simply allow accurate feasibility assessment of appropriate locations and process economics. With this perspective, the objective of this paper was to rigorously examine the impacts of assumptions and methods used in the literature on the accuracy and variability of the WD and WF of freshwater algae cultivation in open ponds, to determine where further experimental investigation is most needed, and to propose any necessary corrections or alternatives. The paper focuses on the application of WF to compare the feasibility of cultivating microalgae at different locations and does not benchmark freshwater algae cultivation in open ponds against technical alternatives.

2. Methods

2.1. Background

Many authors have highlighted that evaporation has a critical impact on the economics and sustainability of algae mass cultivation in open ponds (Pienkos and Darzins, 2009; Wijffels and Barbosa, 2010); therefore, and because the rate of free-surface evaporation from ponds is highly dependent on local meteorological conditions, emphasis was given to estimating the geographic variability of the WD and WF. For this purpose, algae cultivation was compared over five distinct climatic zones.

The indirect WF accounts for water consumption remote from the algae cultivation site such as, for example, water consumed during production of fertilizers needed to support algal growth (Clarens et al., 2010). Unless a component of the indirect footprint involves the same water basin used to supply water needed for algae cultivation, the indirect footprint should not be included in the comparison of the impacts of algae cultivation on local water resources. This component was therefore not considered in the comparative assessment.

For simplicity, biomass processing was excluded from the system boundary (Fig. 1). This approach is acceptable when focusing on direct water use because the WD associated with biomass processing is negligible: 2–10 L L^{-1} of biodiesel (Yang et al., 2011), or 0.06–0.28 m^3 GJ^{-1} assuming a biodiesel density and heat value of 0.92 kg L^{-1} and 38 kJ g^{-1}, respectively (Wigmosta et al., 2011). Furthermore, expressing the functional unit per GJ of biomass cultivated eliminates potential variability and uncertainty associated with parameters that are not strictly necessary for the purpose of comparing the geographic variability of the WD across different climatic regions (e.g. biomass separation efficiency, lipid extraction and biodiesel synthesis, and biomass heat value used for conversion).

Emphasis was given to variability and uncertainty in WD and WF assessments of freshwater algae cultivation in open ponds because this production system has been extensively discussed (Cooney et al., 2011; Lardon et al., 2009; Wigmosta et al., 2011; Yang et al., 2011). Algae cultivation in closed photobioreactors and the use of wastewater or saline water as a growth medium have undoubtedly great potential to significantly reduce freshwater consumption (Clarens et al., 2010; Pate et al., 2011); however, this paper will not benchmark freshwater algae cultivation in open ponds against these alternatives because such a comparison would require the assessments of all environmental impacts (e.g. climate change, eutrophication, etc.) in order to consider potential trade-offs (Clarens et al., 2010; Lardon et al., 2009; Murphy and Allen, 2011). In addition, computing the WD and WF of algae cultivation for alternative process configurations may be challenging due to limitations arising from, for example, freshwater requirements for cooling closed photobioreactors (e.g. 0.24–0.8 m^3 m^{-2} yr^{-1} in a Mediterranean climate) (Béchet et al., 2010).

2.2. Water demand

Within the system boundary (Fig. 1), the WD (m^3 m^{-2} yr^{-1}) can be calculated as the sum of the amount of freshwater required to make up for evaporation losses (Q_{ev}, m^3 m^{-2} yr^{-1}), leak losses (Q_{leak}, m^3 m^{-2} yr^{-1}) and the process water that is not recycled into the pond (Q_{pw}, m^3 m^{-2} yr^{-1}). The amounts of water consumed during the reaction of photosynthesis and evaporated during CO_2 supply are negligible (S2).

Leak rates of 0.0011–0.0036 m^3 m^{-2} yr^{-1}have been reported by Weissman et al. (1989) for lined ponds and this range was used in the sensitivity analysis with the median value of 0.00235 m^3 m^{-2} yr^{-1} used as base case.

Most of the approaches that have either been used to predict evaporation losses from algal ponds are based on empirical data or empirically-derived formulas that may be too site-specific to be universally applicable (S3). While not yet experimentally validated for algal ponds (and therefore still unproven as the most accurate), the evaporation model of Béchet et al. (2011) (S3) used in the base-case studies is based on a theoretical approach recommended by Sartori (2000) in his comprehensive review of

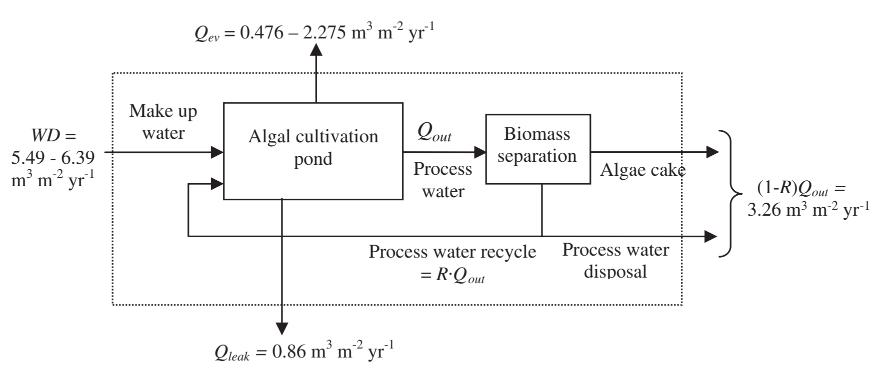

Fig. 1. Schematic representation of the water fluxes considered when computing the water demand (WD) of algae biomass cultivation. Numbers show the data computed in the base case scenario.

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