Global mapping of cost-effective microalgal biofuel production areas with minimal environmental impact

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Abstract
Sustainable alternatives to fossil fuels are urgently needed to avoid severe climate impacts and further environmental degradation. Microalgae are one of the most productive crops globally and do not need to compete for arable land or freshwater resources. Hence, they may become a promising, more sustainable cultivation alternative for the large-scale production of biofuels provided that substantial reductions are achieved in their production costs. In this study, we identify the most suitable areas globally for siting microalgal farms for biodiesel production that maximize profitability and minimize direct competition with food production and direct impacts on biodiversity, based on a spatially explicit multiple-criteria decision analysis. We further explore the relationships between microalgal production, agricultural value, and biodiversity, and propose several solutions for siting microalgal production farms, based on current and future targets in energy production using integer linear programming. If using seawater for microalgal cultivation, biodiesel production could reach $4.17 \times 10^{11}$ L/year based on top suitable lands (i.e., between 10% and 12% of total transport energy demands in 2030) without directly competing with food production and areas of high biodiversity value. These areas are particularly abundant in the dry coasts of North and East Africa, the Middle East, and western South America. This is the first global analysis that incorporates economic and environmental feasibility for microalgal production sites. Our results can guide the selection of best locations for biofuel production using microalgae while minimizing conflicts with food production and biodiversity conservation.

KEYWORDS
biodiversity, biofuel, energy, food, fossil fuel, GIS, microalgae, renewable, sustainability

1 | INTRODUCTION

Rapid climate change is having profound impacts on social and environmental systems globally, and these threats are expected to become substantially more severe in the coming decades (MEA, 2005; Scheffers et al., 2016). In 2016, the energy sector emitted around 32 Gt CO$_2$ into the atmosphere, mostly from fossil fuel use (IEA, 2017b). The replacement of fossil fuels is an urgent component of efforts to prevent global warming from exceeding 2°C compared to
pre-industrial levels, a commitment that has been ratified by 185 parties following the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (IPCC, 2015). Through the transformation of biomass into bioenergy (McKendry, 2002), biofuel systems can provide an alternative to fossil fuels in the transport sector, especially for the shipping and aviation industries, which in the midterm cannot be fully powered by electricity (Fulton, Lynd, Körner, Greene, & Tonachel, 2015).

However, first-generation biofuels, which derive from food crops (e.g., maize, sugarcane, soybean, and oil palm), compete with food production (Pimentel et al., 2009; Tilman et al., 2009) and drive environmental degradation (Correa, Beyer, Possingham, Thomas-Hall, & Schenk, 2017; Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008; Fargione, Plevin, & Hill, 2010; Immerzeel, Verweij, Hilst, & Faaij, 2014; Searchinger et al., 2008), directly competing for agricultural lands and leading to habitat loss for native species (Correa et al., 2017; Fargione et al., 2010; Immerzeel et al., 2014; Koh, 2007; Koh, Miettinen, Liew, & Ghazoul, 2011). Furthermore, they have been linked to increases in CO₂ emissions after carbon-rich systems (e.g., forests and native grasslands) are transformed into biofuel monocultures, which can negate their potential for climate change mitigation (Searchinger et al., 2008; 2015, 2008). At a projected population of nine billion people and a 60% increase in food demand by 2050 compared to 2006 (FAO, 2016), biofuel systems not only need to offer climate change mitigation (IPCC, 2015) but also must have limited competition with food production and biodiverse lands (CBD, 2011; Foley et al., 2011). These goals could be achieved by increasing the productivity of first-generation biofuels and their coproducts (e.g., food and animal feed) within current production areas (IEA, 2017a; Souza, Victoria, Joly, & Verdade, 2015; Tomei & Helliwell, 2016) while preventing their expansion into agricultural lands and biodiverse regions (Foley et al., 2011; Souza et al., 2015), coupled with the adoption of systems that do not rely on arable lands (e.g., wastes and microalgae) (Correa et al., 2017; Tilman et al., 2009) able to gradually replace less sustainable biofuel production alternatives (Correa et al., 2019). Microalgal biofuel production systems (i.e., third-generation biofuels) are based on the cultivation of prokaryotic and eukaryotic photosynthetic microorganisms (i.e., microalgae) in recirculation channels open to the atmosphere (i.e., open ponds) or in enclosed culture devices (i.e., photobioreactors), making use of water (fresh, brackish, or saltwater) and nutrients (Chisti, 2007; Lundquist, Woertz, Quinn, & Benemann, 2010; Mata, Martins, & Caetano, 2010; Schenk et al., 2008). The lipids and carbohydrates contained in microalgal cells can be respectively converted into biodiesel and bioethanol, helping to offset liquid fossil fuels (i.e., diesel and gasoline) (Mata et al., 2010; Schenk et al., 2008) as well as produce biohydrogen or biogas (Schenk et al., 2008). These systems are a promising alternative for future biofuel production (Aro, 2016), primarily because they need less land for producing the same amount of energy compared to first-generation biofuels, and additionally because they do not need fertile soils for their cultivation (Chisti, 2007; Correa et al., 2017; Mata et al., 2010; Quinn & Davis, 2015; Schenk et al., 2008). These advantages could decrease direct competition with agricultural and biodiverse lands, leading to lower competition with food production and reduced habitat loss for native species (Correa et al., 2017), or free lands for further agricultural production, ecological restoration, and biodiversity conservation (Walsh et al., 2015).

While technological advances in the cultivation, harvesting, and conversion of microalgae into biofuels increase the cost-effectiveness and sustainability of microalgal production systems (González-González et al., 2018; Mu et al., 2014; Uggetti, Sialve, Trably, & Steyer, 2014; Venteris, Skaggs, Wigmosta, & Coleman, 2014; Yang et al., 2011), further steps are needed to identify the most profitable areas for microalgal biofuel production without competing for arable lands or biodiverse landscapes.

With 16% of transport energy demands potentially fulfilled by biofuels in 2040 (IEA, 2017b), microalgal biofuel production systems could become an important alternative for offsetting fossil fuels in the transport sector, provided that significant reductions in their production costs are achieved (Acién, Molina, & Fernández-Sevilla, 2018; Chia et al., 2018; Norsker, Barbosa, Vermue, & Wijffels, 2011; Slade & Bauen, 2013). Costs reductions can derive from the development of biorefinery systems that produce high-value coproducts (e.g., food and animal feed) along with biofuels (Chia et al., 2018; Ruiz et al., 2016); the identification, development, and cultivation of fast-growing microalgal strains (Ajjadi et al., 2017; Mata et al., 2010); the colocation of microalgal production systems with free nutrient and CO₂ sources (e.g., from wastewater operations and industries) (Beal, Archibald, Huntley, Greene, & Johnson, 2018; Mu et al., 2014; Orfield, Keoleian, & Love, 2014; Roostaei & Zhang, 2017); the production of biogas and the recycling of nutrients (i.e., by anaerobic digestion) (González-González et al., 2018; Uggetti et al., 2014); and the implementation of governmental incentives based on the relative environmental benefits of biofuel production alternatives (Correa et al., 2019). However, considerable land areas will still be required to offset fossil fuels by microalgal cultivation, although lower compared to first-generation biofuels (Chisti, 2008; Correa et al., 2017). Here, we evaluate global opportunities for large-scale microalgal biodiesel production while minimizing direct competition with agricultural lands and biodiverse areas, taking into account attributes that maximize the profitability in microalgal biodiesel production: water availability, lipid productivity, flat land availability, proximity to main transport networks,
gross national income (GNI) per capita (as a substitute for labor costs), and proximity to known industrial CO₂ sources. Based on four scenarios for microalgal cultivation, which combine two main approaches to decrease microalgal production costs and freshwater use (i.e., availability of free CO₂ and availability of seawater)—Scenario 1 (i.e., use of fresh, brackish, or saltwater), Scenario 2 (i.e., use of fresh, brackish, or saltwater adjacent to known industrial CO₂ sources), Scenario 3 (i.e., use of seawater), and Scenario 4 (i.e., use of seawater adjacent to known industrial CO₂ sources)—we: (a) Identify the most suitable areas globally for siting microalgal farms for biodiesel production (i.e., microalgal cultivation systems along with the associated infrastructure), while avoiding direct competition with food production and direct impacts on biodiversity, which are considered the two main impacts of first-generation biofuels, (b) Explore the relationships between microalgal production, agricultural value, and biodiversity, and (c) Explore solutions for siting microalgal production farms based on current and future targets in energy production. Because we aim at finding areas globally for siting microalgal production farms, we assume free trade for microalgal biofuel commercialization in the context of a globalized economy.

2 | MATERIALS AND METHODS

2.1 | Development of microalgal suitability model

A GIS-based multiple-criteria decision analysis (MCDA) was developed for selecting suitable areas for large-scale microalgal biodiesel production at a pixel resolution of 5 x 5 km, allowing the identification of large areas (i.e., 25 km²/pixel) that meet suitable conditions for microalgal production. GIS-based MCDAs have been widely used in natural resource management and land-use planning (Mendoza & Martins, 2006) as they allow the solution of complex decision-making problems through the combination of multiple geographic criteria (Malczewski & Rinner, 2015). Three main objectives were considered in the analysis: maximization of profitability in microalgal biodiesel production, minimization of direct competition with food production, and minimization of direct impacts on biodiversity (Figure S1). Based on the reviewed literature (Bennett, Turn, & Chan, 2014; Borowitzka et al., 2012; Boruff, Moheimani, & Borowitzka, 2015; Bravo-Fritz, Sáez-Navarrete, Herrera, & Ginocchio, 2015; Chiu & Wu, 2013; Coleman et al., 2014; Fortier & Sturm, 2012; Klise, Roach, & Passell, 2011; Lundquist et al., 2010; Mohseni, Fishvae, & Sahebi, 2016; Niblick & Landis, 2016; Orfield et al., 2014; Prasad, Pullar, & Pratt, 2014; Quinn, Catton, Johnson, & Bradley, 2013; Quinn, Catton, Wagner, & Bradley, 2012; Roostaei & Zhang, 2017; Sharma et al., 2015; Venteris, McBride, Coleman, Skaggs, & Wigmosta, 2014a; Venteris, Skaggs, Coleman, & Wigmosta, 2012, 2013; Venteris et al., 2014; Venteris, Skaggs, Wigmosta, & Coleman, 2014b; Wigmosta, Coleman, Skaggs, Huesemann, & Lane, 2011), a set of attributes that capture the complexity of microalgal biodiesel production were selected, either because they are essential for microalgal cultivation or because they have shown to maximize the profitability of microalgal biodiesel production (Sharma et al., 2015): water availability, lipid productivity, availability of flat lands, proximity to main transport networks (i.e., main roads and railroads), GNI per capita (used as a substitute for the availability of low labor costs), and proximity to known industrial CO₂ sources. Water availability is essential for microalgal cultivation (Chisti, 2007; Schenk et al., 2008) while lipid productivity is proportional to biodiesel production, increasing the profitability of microalgal biofuel production (Moody, McGinty, & Quinn, 2014; Quinn, Winter, & Bradley, 2011; Slade & Bauen, 2013). Water can be obtained from freshwater sources (i.e., water from precipitation, rivers, irrigation dams, or fresh groundwater sources), brackish water sources (e.g., brackish groundwater sources), and saltwater sources (i.e., salt groundwater sources or seawater) (Chisti, 2007; Schenk et al., 2008; Venteris, Skaggs, Coleman, & Wigmosta, 2013). The use of flat lands decreases the costs for ground leveling when constructing microalgal ponds, as well as the costs related to water pumping (Borowitzka et al., 2012; Darzins, Pienkos, & Edye, 2010; Lundquist et al., 2010; Quinn et al., 2012; Venteris, Skaggs, Coleman, & Wigmosta, 2012; Wigmosta et al., 2011). The proximity to main transport networks allows connectivity between production areas, markets, and inputs (e.g., nutrients needed for microalgal cultivation) (Boruff et al., 2015; Slegers, Leduc, Wijffels, Straten, & Boxtel, 2015; Venteris, McBride, et al., 2014a; Venteris et al., 2014). The availability of low labor costs decreases overall operational costs (Slade & Bauen, 2013; Tredici, Rodolfi, Biondi, Bassi, & Sampietro, 2016), and the proximity to known industrial CO₂ sources allows the use of free CO₂ that increases biomass production (Borowitzka et al., 2012; Klise et al., 2011; Lundquist et al., 2010; Orfield et al., 2014; Quinn et al., 2013; Slade & Bauen, 2013; Venteris et al., 2014; Wigmosta et al., 2011). Although wastewater sources would decrease costs associated with nutrient obtaining, they were not included in the model as they are not consistently mapped globally.

For minimizing competition with food production, the selected attribute corresponded to the agricultural value of lands (i.e., potential annual gross economic rents from agricultural lands) (Naidoo & Iwamura, 2007). For minimizing impacts on biodiversity, the selected attribute corresponded to the biodiversity value. Biodiversity value was based on the number of vertebrate species and the number of threatened vertebrate species (i.e., considering amphibians, birds, and mammals) (Jenkins, Pimm, & Joppa, 2013),
the presence of islands (which harbor higher proportions of endemic and threatened species compared to the mainland) (McCreless et al., 2016; Tershy, Shen, Newton, Holmes, & Croll, 2015), and the presence of areas with low human pressures (which is related to the integrity of ecosystems) based on the Global Human Footprint (Venter et al., 2016). Water bodies (Lehner & Döll, 2004), protected areas (UNEP-WCMC, 2016), Key Biodiversity Areas (BirdLife International, 2016), and urban areas (i.e., based on built areas) (Schneider, Friedl, & Potere, 2009) were assumed to be unsuitable for microagal cultivation and excluded from final suitability maps (i.e., assigning No Data to water bodies and zero to the other layers).

We developed four scenarios for microalgal cultivation, based on the type of available water and the inclusion of known industrial CO₂ sources (Scenarios 1–4): Scenarios 1 and 2 included the use of fresh, brackish, or saltwater, while Scenarios 3 and 4 included the use of seawater, which is abundant and does not compete with scarce freshwater sources (Gleeson, Wada, Bierkens, & Beek, 2012; Vorosmarty et al., 2010). Scenarios 2 and 4 included the proximity to known industrial CO₂ sources (but not to anaerobic digesters as this information is currently not available), which is a cost-effective way to increase microalgal biomass productivities (Borowitzka et al., 2012; Klise et al., 2011; Lundquist et al., 2010; Orfield et al., 2014; Quinn et al., 2013; Slade & Bauen, 2013; Venteris et al., 2014; Wigmosta et al., 2011), while Scenarios 1 and 3 did not include the proximity to known industrial CO₂ sources (Figures S2–S5).

Land covers potentially replaced by microalgal production farms were identified for top suitable microalgal production lands (i.e., suitability values ≥0.7), using the MODIS-derived global mosaic for 2012 at a resolution of 5 arcminutes (Channan, Collins, & Emanuel, 2014). The proportion of top suitable lands within politically unstable countries, which could challenge potential large-scale microalgal biofuel production, was calculated based on the Fragile States Index in 2016 (FFP, 2017) for Scenarios 2–4, considering countries with total values ≥80 as politically unstable. This index is based on social, economic, and political risk indicators that lead to higher values in politically unstable countries. Potential biodiesel production was estimated for top suitable lands, along with the percentage of transport energy demands that could be fulfilled based on the most plausible production scenarios (i.e., Scenarios 2–4) in 2016, 2030, and 2040 (see Supporting Information for details). Future transport energy demands were based on the Current Policies, New Policies, and the Sustainable Development Scenarios for 2030 and 2040 (IEA, 2017b). The Current Policies Scenario takes into account policies that have been enacted in mid-2017 for reducing greenhouse emissions, while the New Policies Scenario additionally includes announced policy intentions for reducing global warming, and the Sustainable Development Scenario aims at limiting global warming consistent with the Paris Agreement and the United Nations 2030 Agenda for Sustainable Development.

2.2 Development of sensitivity analysis on slope and lipid productivities

In order to determine how changes in model parameters influence the siting of microalgal production farms and potential biodiesel production, a sensitivity analysis was developed based on slope and lipid productivities. For this, the slope was increased from a membership midpoint of 5° to 10°, and 15°; and lipid productivity was both increased and decreased in 20% and 40% from a midpoint of 13,000 L ha⁻¹ year⁻¹ (see Supporting Information for details on fuzzy memberships and midpoints). We used the one-at-a-time method, in which the changes in values for each factor were evaluated in turn (Malczewski & Rinner, 2015).

2.3 Relationships among microalgal production, agricultural value, and biodiversity

The percentage of distribution ranges of threatened vertebrates (i.e., vulnerable, endangered, and critically endangered amphibians, birds, mammals, and reptiles) (BirdLife International & NatureServe, 2016; IUCN, 2016) overlapping top suitable microalgal production lands (i.e., suitability values ≥0.7) was calculated for Scenarios 2–4. Potential conflicts among microalgal biodiesel production, agricultural production, and biodiversity were mapped using a color-grading scale for Scenario 1 (i.e., use of fresh, brackish, and saltwater).

2.4 Siting of microalgal production farms based on targets in transport energy demands

In order to find locations for siting microalgal production farms based on targets in transport energy demands, an integer linear optimization model (Beyer, Dujardin, Watts, & Possingham, 2016) was developed using the software R and Gurobi Optimizer (see Supporting Information for calculation details). The model aimed at maximizing profitability while minimizing direct competition with agricultural lands and biodiverse areas through the following formula:

\[
\text{maximize} \sum_i \frac{P_i^2 x_i}{\text{maximum} \left(A_i, B_i\right) + 1}
\]

subject to

\[
\sum_i D_i x_i = T
\]

\[0 \leq x_i \leq 0.8\]
where \( i \) corresponds to each pixel, \( P \) corresponds to microalgal profitability (ranging from 0 to 1), \( x \) corresponds to the decision variable given by the software (ranging from 0 to 0.8 and representing the available area for placing microalgal ponds), “maximum” corresponds to the maximum value among agricultural value \( A \) (ranging from 0 to 1) and biodiversity value \( B \) (ranging from 0 to 1), \( D \) corresponds to productivity values in units of energy (GJ pixel\(^{-1}\) year\(^{-1}\)), and \( T \) represents the targets in energy demands globally in 2016, 2030, and 2040 (GJ/year) based on the IEA (2017b) energy production estimates (i.e., Current Policies Scenario, New Policies Scenario, and Sustainable Development Scenario). Using the square of the profitability as the numerator and the maximum value between \( A \) and \( B \) as the denominator ensures that pixels with low or average profitabilities, and with high agricultural or high biodiversity value, are excluded in the final solutions.

We investigated alternative solutions in which the agricultural and biodiversity values were not taken into account (see Supporting Information), and in which targets in microalgal biodiesel production increased from 10% to 40% based on 2016’s transport energy demands. Finally, the amount of cultivation land needed to meet 10%, 20%, 30%, and 40% of total transport energy demands in 2016, 2030, and 2040 was determined based on the several IEA (2017b) energy production scenarios (Current Policies Scenario, New Policies Scenario, and Sustainable Development Scenario) and current estimated microalgal lipid productivities (Moody et al., 2014).

3 | RESULTS

The most suitable areas for microalgal biodiesel production, while avoiding direct competition with agricultural and biodiversity lands, were located in human-transformed dry tropical and subtropical mainlands (Figures 1 and 2). For Scenario 1 (i.e., cultivation based on fresh, brackish, or saltwater), top suitable microalgal production lands (suitability values \( \geq 0.7 \)) could reach around 1,422.8 thousand square kilometers, concentrated in dry areas in North and East Africa, the Middle East, South and Central Asia, and South America, mainly overlapping with barren and sparsely vegetated lands (60%), open shrublands (22%), and grasslands (9%) (Table 1). Significant competition with scarce freshwater resources would occur in dry areas, where low-density microalgal production farms could be established (Figure 3). Scenario 2, which is restricted to known industrial CO\(_2\) sources, could reach around 464.2 thousand
square kilometers mainly over barren and sparsely vegetated lands (57%), open shrublands (17%), and grasslands (8%). The cultivation Scenarios 3 and 4 (i.e., cultivation based on seawater) could reach around 305.3 thousand square kilometers and 132.9 thousand square kilometers, respectively, mainly over barren or sparsely vegetated lands and open shrublands.

For Scenarios 2–4, which are the most feasible options for widespread microalgal biodiesel production in terms of reduced competition with scarce freshwater, 61%, 45%, and 34% of top suitable lands (suitability values ≥0.7), respectively, fell within several politically unstable countries in Africa, the Middle East, and South
FIGURE 3 Top suitable areas for microalgal biodiesel production (suitability values ≥0.7) for Scenario 1 (use of fresh, brackish, or saltwater without considering known industrial CO₂ sources) in (a) North America, (b) South America, (c) Southern Europe, North and East Africa, the Middle East, and South and Central Asia. Orange represents potential low-density microalgal cultivation (LD), dependent on fresh/brackish water availability, while red represents potential high-density microalgal cultivation (HD) based on seawater use.
Correa et al. (i.e., Afghanistan, Egypt, Iran, Iraq, Lebanon, Libya, Mauritania, Niger, Pakistan, Somalia, Sudan, Syria, Turkey, and Yemen). Based on these scenarios, potential total microalgal biodiesel production ranged between $5.85 \times 10^{11}$ and $1.81 \times 10^{11}$ L/year, representing between 17% and 6% of total transport energy demands in 2016, respectively (Table 2). Among these scenarios, maximum levels of biodiesel production would be achieved in Scenario 2, followed by Scenarios 3 and 4, which are restricted to the use of seawater.

Less than 0.5%, 5.8%, 3.5%, and 5.1% of threatened amphibians, birds, mammals, and reptiles, respectively, would overlap top suitable microalgal production lands (i.e., suitability values ≥0.7) for Scenarios 2–4. Around 25% and less than 2.5%, 2.8%, and 3.6% of this set of threatened amphibians, birds, mammals, and reptiles, respectively, would face competition with microalgal production in more than 20% of their distribution ranges (Figure 4). This competition would be highest for Scenario 3 compared to Scenarios 2 and 4 (Table S3).

At a global scale, potential conflicts could arise among microalgal production and areas of high agricultural and biodiversity value, mainly in Central America, tropical and subtropical South America, Africa, India, and Southeast Asia (Figure 5). If agricultural and biodiversity values are not considered, microalgal cultivation for one of the most feasible cultivation scenarios (i.e., Scenario 3, which is based on seawater) would include larger tracts of humid lands in the tropics (e.g., in Southeast Asian islands and Madagascar when just avoiding areas of high agricultural value; and in Central and South America, Southeast Africa, India, and Southeast Asian mainland when just avoiding areas of high biodiversity value) (Figure 6). Locations for microalgal cultivation would change as a function of targets in microalgal biofuel production (Figure 7). Potential conflicts with areas of higher agricultural and biodiversity value (e.g., in Central and South America, Africa, South and Southeast Asia, and China) would increase if fulfilling higher targets in microalgal biofuel demands (i.e., from 10% to 40% of total transport energy demands in 2016). Finally, more lands would be needed to fulfill higher targets in microalgal biofuel demands based on current and future energy consumption scenarios (IEA, 2017b; Figure 8).

4 | DISCUSSION

We provide the first global analyses on cost-effective areas for microalgal biodiesel production that minimize direct competition with food production and biodiversity, considering variables that increase the profitability in microalgal biofuel production. Our analyses are based on four scenarios for microalgal cultivation (i.e., use of fresh, brackish, or saltwater; use of fresh, brackish, or saltwater adjacent to known industrial CO$_2$ sources; use of seawater; use of seawater adjacent to known industrial CO$_2$ sources). Furthermore, we explore how microalgal production, agricultural value, and biodiversity are related, and how changes in current and future targets

| Cultivation scenarios | Potential biodiesel production (L/year) | 2016 Shares (%) | 2030 | 2040 |
|-----------------------|----------------------------------------|-----------------|------|------|
|                       |                                        | Current Policies Scenario | New Policies Scenario | Sustainable Development Scenario | Current Policies Scenario | New Policies Scenario | Sustainable Development Scenario |
| Scenario 2            | $5.85 \times 10^{11}$                 | 16.7            | 13.5 | 14.3 | 16.1 | 11.8 | 13.0 | 16.8 |
| Scenario 3            | $4.17 \times 10^{11}$                 | 11.9            | 9.7  | 10.2 | 11.5 | 8.4  | 9.3  | 12.0 |
| Scenario 4            | $1.81 \times 10^{11}$                 | 5.6             | 4.2  | 4.4  | 5.0  | 3.6  | 4.0  | 5.2  |

### Table 2
Estimates of microalgal biodiesel production for Scenarios 2–4 in top suitable microalgal production lands (suitability values ≥0.7) (see Supporting Information for calculation details). The percentages of transport energy consumption fulfilled by each cultivation scenario are shown for 2016, 2030, and 2040. Scenarios of transport energy consumption (Current Policies Scenario, New Policies Scenario, and Sustainable Development Scenario) are based on the IEA (2017b) energy production estimates.

**FIGURE 4** Boxplots showing the percentage of distribution ranges of threatened vertebrates (i.e., vulnerable, endangered, and critically endangered amphibians, birds, mammals, and reptiles) overlapping top suitable microalgal production lands (suitability values ≥0.7) based on Scenarios 2–4. The maximum outliers were identified after multiplying the interquartile range by 1.5.
in energy demands alter the siting of microalgal production farms. These results can help in decision making toward the selection of best areas for microalgal biodiesel production at lower conflicts with food production and biodiversity.

Based on a MCDA, our results show that dry tropical and subtropical mainlands in areas subject to high human pressures on the environment (i.e., human-transformed dry tropical and subtropical mainlands) are the most suitable areas for large-scale microalgal biodiesel production. While avoiding direct competition with agricultural and biodiverse lands (i.e., based on the richness of vertebrates, presence of threatened vertebrates, presence of islands, and presence of areas with low human pressures), these areas still provide access to water and flat lands for microalgal cultivation, access to transport networks that ensure supply of inputs and distribution of biodiesel, and low labor costs (here measured as GNI per capita) that reduce production costs. As expected, microalgal suitability increases where high solar irradiance and temperature facilitate larger microalgal biomass and lipid yields (Lundquist et al., 2010; Moody et al., 2014; Quinn et al., 2012; Venteris, McBride, et al., 2014a; Wigmosta et al., 2011), which occurs in tropical and subtropical regions of the world. The use of drylands for microalgal production, which in general are less suitable for cropping (Alexandratos & Bruinsma, 2012) and hold lower biodiversity values compared to more humid regions (Gaston, 2000), would decrease direct competition with high-value agricultural and biodiverse lands. In contrast, several studies developed in the United States show that humid regions are the most feasible locations for large-scale microalgal production (Coleman et al., 2014; Venteris, McBride, et al., 2014a; Venteris et al., 2013; Wigmosta et al., 2011). These studies indicate that the consumption of water per liter of microalgal oil and the costs associated with water pumping would be lower in the Southeastern United States (i.e., mainly around the Gulf and East Coasts) compared to the drier southwestern lands, where water demands and water pumping costs increase as a result of higher evaporation rates relative to precipitation. Notwithstanding, the use of humid areas for microalgal production would inevitably lead to direct competition with food production and biodiversity (although lower compared to first-generation biofuels because of their higher biofuel productivities per unit area) (Correa et al., 2017). Furthermore, targeting humid areas for carbon sequestration, where forests can grow (Saatchi et al., 2011), is an effective solution for climate change mitigation (Canadell & Raupach, 2008).

The establishment of low-density microalgal production farms would be a more sustainable option in regions where significant competition with freshwater resources is expected to occur, including dry areas around the Nile river in North Africa and the Tigris and Euphrates rivers in the Middle East,
FIGURE 6  Microalgal cultivation areas for meeting 30% of global transport energy demand in 2016 for Scenario 3 (i.e., use of seawater without considering known industrial CO₂ sources). These areas were identified using an integer linear programming model (see Methods and Supporting Information for details) and four sets of weights for agricultural value and biodiversity: (a) Maximization of profitability and minimization of direct competition with high-value agricultural lands and biodiverse areas; (b) Maximization of profitability and minimization of direct competition with high-value agricultural lands; (c) Maximization of profitability and minimization of direct competition with biodiverse lands, (d) Maximization of profitability irrespective of agricultural value or biodiversity. Within each pixel (i.e., 25 km²), a maximum proportion (Prop.) of 0.8 is permitted to be used for microalgal cultivation.

FIGURE 7  Microalgal cultivation areas for meeting (a) 10%, (b) 20%, (c) 30%, and (d) 40% of total transport energy demands in 2016 for Scenario 3 (i.e., use of seawater without considering known industrial CO₂ sources), identified using an integer linear programming model (See Methods and Supporting Information for details). Within each pixel (i.e., 25 km²), a maximum proportion (Prop.) of 0.8 is permitted to be used for microalgal cultivation.
Potential microalgal biodiesel production is a function of the cultivation scenarios and changes in membership midpoints applied to the different variables. Between 5.85 × 10^{11} and 1.81 × 10^{11} L/year could be produced in top suitable lands (suitability values ≥0.7) for the most feasible cultivation scenarios (i.e., Scenarios 2–4). For these scenarios, changing the midpoint in slope from 5° to 15° would increase potential microalgal biodiesel production by between 8% and 10%, while decreasing the midpoint in lipid productivity from 13,000 to 7,800 L ha⁻¹ year⁻¹ (i.e., in 40%) would increase potential microalgal biodiesel production by between 8% and 32%, and increasing the midpoint in lipid productivity from 13,000 to 18,200 L ha⁻¹ year⁻¹ (i.e., in 40%) would decrease potential microalgal biodiesel production by between 45% and 82% (Figures S6 and S7). Biodiesel production estimates are expected to increase with the cultivation of fast-growing and high-lipid-producing microalgal strains (Ajjawi et al., 2017; Mata et al., 2010; Slade & Bauen, 2013), along with the adoption of more efficient cultivation, harvesting, and processing techniques that increase microalgal biomass and lipid productivities (González-González et al., 2018; Pierobon et al., 2017). Reducing the uncertainty in global microalgal potential biodiesel production would require the refinement of models based on resource availability (e.g., inclusion of nutrients from wastewater sources, inclusion of CO₂ sources from anaerobic digesters, and inclusion of freshwater restrictions) and economic feasibility (e.g., considering land costs, opportunity costs with other economic activities, and several microalgal production technologies).

### 4.1 Relationships among microalgal production, agricultural value, and biodiversity value

Potential conflicts among microalgal production and areas of high agricultural and biodiversity value could arise within the tropical region (Figure 5), which faces the highest deforestation rates globally as agricultural activities expand for meeting food and biofuel demands (Hansen et al., 2013; Laurance, 2015; Laurance, Sayer, & Cassman, 2014), in spite of harboring most of Earth’s biodiversity (Dirzo & Raven, 2003; Kier et al., 2005). In fact, if agricultural and biodiversity values are not considered, microalgal production for Scenario 3 (i.e., use of seawater) would shift to areas of higher agricultural value and ecological importance (e.g., in Central and South America, Africa, India, and Southeast Asia), similarly to food
4.2 Locations for siting microalgal farms for biodiesel production based on energy targets

Locations for microalgal biodiesel production would not only change as a function of trade-offs among profitability, water availability, agricultural value, and biodiversity but also along with targets in microalgal biofuel production. As expected, more lands would be needed to fulfill higher targets in microalgal biofuel demands. Furthermore, as targets in microalgal biofuels increase, regions of higher agricultural and biodiversity value would be considered suitable for microalgal cultivation. In fact, increasing microalgal production from fulfilling 10% to 40% transport energy demands in 2016 would lead to the inclusion of regions with higher agricultural and ecological importance within Central and South America, Africa, South and Southeast Asia, and China, potentially compromising food production and biodiversity in these areas.

Future assessments based on global and national targets in energy and food production, economic development (e.g., urbanization, mining, tourism), biodiversity conservation, and provision of ecosystem services (e.g., carbon sequestration and coastal protection), in the context of climate change, can improve the understanding of the socioeconomic and environmental role of microalgal biofuels. Spatially explicit comparisons with biofuel production alternatives (e.g., first- and second-generation biofuels) can guide the identification and adoption of more sustainable biofuel production systems (Correa et al., 2019). These comparisons can help to assess the impacts of microalgal biofuels in dry regions, in contrast to systems that rely on agricultural lands and more biodiverse areas for crop production (e.g., oil palm and sugarcane) (Jaiswal et al., 2017; Ocampo-Peñuela, García-Ulloa, Ghazoul, & Etter, 2018).

Although we propose that avoiding the cultivation of microalgae within agricultural and biodiverse areas would be the best option for reducing direct competition with food production and biodiversity, further assessments on the overall environmental impacts of microalgal production in humid areas are needed. These assessments could consider the replacement of areas of currently established biofuel crops by microalgal biofuel systems—which offer higher biofuel yields per unit area (Chisti, 2008; Correa et al., 2017)—along with the colocation of microalgal systems with free nutrient sources (e.g., from wastewater and agricultural residues) (Chiu & Wu, 2013; Fortier & Sturm, 2012; Mu et al., 2014; Orfield et al., 2014; Roostaei & Zhang, 2017) and free CO2 sources (e.g., from industrial operations, including anaerobic digesters and biorefineries with fermenters) (Lundquist et al., 2010; Orfield et al., 2014; Wigmosta et al., 2011).

5 CONCLUDING REMARKS

We propose best locations for siting microalgal farms for biodiesel production that meet substantial biofuel production levels while avoiding direct land-use competition with
agricultural lands and biodiverse areas, through a GIS-based multiple-criteria decision analysis and integer linear programming. We conclude that potential conflicts with food production and biodiversity conservation, as well as with freshwater consumption, can be reduced if cultivation is restricted to human-transformed dry mainland coasts in tropical and subtropical regions of the world, in contrast to first-generation biofuels, which need agricultural lands and freshwater (Correa et al., 2017). However, even in these areas, the prevention of environmental impacts associated with microalgal production would be required. This includes halting direct habit loss for threatened species, by avoiding microalgal production within habitat patches while preserving functional connections among ecosystems (e.g., terrestrial dry ecosystems, mangroves, mudflats, saltmarshes, and coral reefs). Potential total biofuel production decreases with the accumulative number of constraints (i.e., from 5.85 × 10^{11} to 1.81 × 10^{11} L/year for Scenarios 2 and 4, respectively, based on top suitable microalgal production lands). Locations for microalgal biodiesel production would not only change as a function of trade-offs between profitability, water availability, agricultural value, and biodiversity but also along with targets in microalgal biofuel production. Higher targets in microalgal biofuels would inevitably lead to competition with areas of higher agricultural and biodiversity value, mainly within the tropics and subtropics. Future assessments that include optimized cultivation technologies, cultivation of more productive microalgal strains, availability of nutrients (e.g., from wastewater sources and agricultural residues), availability of CO_2 (e.g., from anaerobic digesters), restrictions on freshwater use, regional changes in land costs, and trade-offs among ecosystem services (e.g., carbon storage and coastal protection) can further refine the assessment of opportunities for microalgal biofuel production at a global scale. Microalgal production could become an important economic alternative in areas with little potential for agricultural development and relatively low biodiversity value (i.e., human-transformed dry tropical and subtropical mainlands), thereby helping in poverty alleviation while reaching substantial energy and environmental targets.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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