


Freeing land from biofuel production through microalgal cultivation in the Neotropical region

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Supplementary material for this article is available [online](#)

Abstract

Biofuel production is a key strategy for reducing CO₂ emissions globally and is expected to increase substantially in the coming decades, particularly in tropical developing countries. The adoption of sustainable biofuel production technologies that do not place large demands on agricultural or forested lands, has the potential to make a substantial contribution to decreasing greenhouse gas emissions while reducing biodiversity losses and degradation of native ecosystems resulting from high demand for land. With their high productivity per unit area and ability to grow on non-arable lands, microalgal biofuel production systems could become a major sustainable alternative to biofuel production from food crops (first-generation biofuels). However, the potential impacts of microalgal biofuels on food production, biodiversity, and carbon storage, compared to other biofuel production alternatives, are largely unknown. In the present study, the most suitable areas for siting microalgae production farms to fulfill 30% of future transport energy demands were determined within four Neotropical countries with high population densities and high importance for agricultural expansion and biodiversity conservation globally (Colombia, Ecuador, Panama, and Venezuela). These results were contrasted with the best areas for siting oil palm and sugarcane crops to fulfill the same target in future transport energy demands. Microalgal production systems offer the most sustainable alternative for future biofuel production within the Neotropics. Meeting 30% of future transport energy demands with microalgal biofuels reduced land area requirements by at least 52% compared to oil palm and sugarcane. Furthermore, microalgal biofuel production reduced direct competition with agricultural lands, biodiverse areas, and carbon-rich systems within countries, with little overlap with the biodiverse and carbon-rich rainforests. This study can guide decision making towards the identification and adoption of more sustainable biofuel production alternatives in the Neotropics, helping in avoiding unnecessary environmental impacts from biofuel expansion in the region.

1. Introduction

Renewable energy sources have strong potential to replace fossil fuels and meet future energy demands (Jacobson and Delucchi 2011, IEA 2017, Obama 2017), thereby mitigating global warming and its

negative socioeconomic and environmental impacts (Pecl *et al* 2017, Nunez *et al* 2019). Among renewable energy sources, liquid biofuels could offset substantial amounts of fossil fuels (Smith *et al* 2014, Creutzig *et al* 2015), particularly in the transport sector, which will continue to need liquid fuels in ships, airplanes,

and long-haul trucks (Fulton *et al* 2015). Biofuel production could increase from 1.7 to 8.1 million Barrels of Oil Equivalent (BOE) day⁻¹ between 2016 and 2040, under the implementation of policies that favor the adoption of renewable energy sources for limiting global warming well below 2 °C in comparison to pre-industrial levels (IEA 2017) and under the Paris Agreement (IPCC 2015).

Biofuel production is currently based on food crops (i.e. first-generation biofuels) that compete with suitable land for agriculture (Lambin and Meyfroidt 2011). This drives direct and indirect land-use changes, often in biodiverse areas (Immerzeel *et al* 2014, Correa *et al* 2017). As a result, first-generation biofuels have been linked to habitat losses for native species (Danielsen *et al* 2009, Immerzeel *et al* 2014, Elshout *et al* 2019) and increases in greenhouse gas emissions when carbon-rich ecosystems (e.g. tropical forests and savannas) are transformed into monocultures for biofuel production (Fargione *et al* 2008, Searchinger *et al* 2008, 2015). Despite the high biodiversity (Antonelli *et al* 2018, Rull 2020) and carbon contents found in tropical areas of the world (Avitabile *et al* 2016), future biofuel production will expand within the tropical region, where large tracts of undeveloped and highly suitable lands for agriculture remain (Laurance *et al* 2014, Laurance 2015). The expansion of first-generation biofuels is likely to exacerbate competition with food production within the tropics (Smith *et al* 2014, Correa *et al* 2019a) and trigger biodiversity losses and CO₂ emissions as forests and savannas are replaced (Searchinger *et al* 2015, Elshout *et al* 2019).

Biofuel production alternatives that avoid direct or indirect land-use changes in agricultural areas and biodiverse lands can increase the sustainability in biofuel production while achieving future targets in energy demands (Tilman *et al* 2009, Correa *et al* 2019a). Microalgal biofuel production systems (i.e. third-generation biofuels) constitute a more sustainable alternative to first-generation biofuels, as they do not require fertile soils, and are thus not expected to directly compete with food production (Schenk *et al* 2008, Correa *et al* 2017). Microalgal cultivation requires sun, water (fresh, brackish, or salt-water), and nutrients (Schenk *et al* 2008, Anto *et al* 2020). Cultivation systems consist on open ponds or enclosed culture devices (i.e. plates, tubes, bags, columns, or domes that are arranged to maximize sunlight uptake denominated photobioreactors) (Anto *et al* 2020) set over flat lands to reduce capital costs (Lundquist *et al* 2010). Open raceway ponds, in which algae and growth media are mixed by paddlewheels in closed recirculation channels with a depth between 15 and 30 cm (Schenk *et al* 2008, Anto *et al* 2020), are considered the most cost-effective cultivation system to date (Slade and Bauen 2013, Fasaei *et al* 2018); nevertheless, microalgae can be initially grown in photobioreactors to avoid contamination

from other microorganisms and then cultivated in open ponds (i.e. hybrid microalgal cultivation systems) (Schenk *et al* 2008, Ación *et al* 2017b, Dickinson *et al* 2017). Microalgal cultivation does not require rainfall, which would decrease competition with areas more suited for agricultural production or biodiversity conservation (Correa *et al* 2017, 2019b). Furthermore, microalgal production systems have lower freshwater footprint per unit of energy produced compared to food crops, particularly when recycling water from microalgal cultivation (Gerbens-Leenes 2018). Additionally, microalgae can be co-located with wastewater systems (Ación *et al* 2018, Mathimani and Pugazhendhi 2019, Jacob *et al* 2020) and CO₂ pollution sources (e.g. industries) (Razzak *et al* 2017, Collotta *et al* 2018), helping in water remediation and CO₂ uptake while production costs decrease (Judd *et al* 2017).

Yet, little is known about the most suitable areas for siting microalgal biofuels production within countries to achieve high production and profits while decreasing environmental impacts, particularly in the tropics (Sharma *et al* 2015). Furthermore, spatial analyses comparing microalgal biofuel production systems with major biofuel production alternatives, are missing to date. These analyses can reduce unnecessary environmental impacts resulting from unplanned biofuel expansion in tropical areas of the world (Williams *et al* 2019) and before microalgal biofuels are implemented at larger scales (Khan *et al* 2018, Correa *et al* 2019a), provided reductions in production costs compared to fossil fuels and first-generation biofuels (Ación *et al* 2017a, Chen *et al* 2018).

The Neotropical region is considered promising to meet increasing global food demands (Laurance *et al* 2014), as a result of the presence of vast areas of undeveloped lands with high agricultural potential (Flachsbarth *et al* 2015). The Neotropics also harbors several of the most important areas for biodiversity conservation (Antonelli *et al* 2018, Rull 2020), containing several of the best-protected ecoregions with high conservation priority (Dinerstein *et al* 2017) and one of the last global wilderness areas globally (i.e. the Amazon rainforest) (Venter *et al* 2016, Watson *et al* 2018). Increased interest in replacing fossil fuels with low-cost and sustained production of energy has led to higher governmental support for biofuel production within Neotropical countries (Saravia-Matus *et al* 2018, Trindade *et al* 2019), even within countries with large fossil fuel reserves (e.g. Venezuela) (Ansari and Holz 2020). Nevertheless, poor spatial planning could intensify conflicts with agricultural lands, biodiversity, and carbon storage, driving further competition with food production, biodiversity losses, and increased CO₂ emissions if native ecosystems are replaced by biofuel crops in the region.

In the Neotropics, oil palm and sugarcane are considered the most cost-effective and productive

crops for biodiesel and bioethanol production, respectively, and as a result, future biofuel demands have been projected to be met based on their expansion (Furumo and Aide 2017, Jaiswal *et al* 2017, de Andrade Junior *et al* 2019). In the present study, a comparative assessment of best areas for siting three different biofuel production alternatives (i.e. microalgae, oil palm, and sugarcane) to meet a 30% target in domestic transport energy demands by 2050, was developed within four Neotropical countries (Colombia, Ecuador, Panama, and Venezuela), aiming at minimizing direct impacts on high-value agricultural lands and biodiverse areas. These countries represent around 15% of transport energy demands in the Americas (after excluding Canada and the USA) and three of them are considered megadiverse in terms of total and endemic number of species (Mittermeier 1997). In contrast to Correa *et al* (2019b), biofuel feedstocks were assumed to be produced within each country's boundaries to guarantee national energy security targets without imports and favor the creation of local jobs (Fragkos and Parousos 2018, Uría-Martínez *et al* 2018). Then, how each production alternative would compete with agricultural lands, biodiversity, and areas of high contents of aboveground biomass among countries, was analyzed. This novel spatially-explicit analysis can help in understanding how biofuel production alternatives compare to each other in the Neotropical region, in terms of impacts on food production, biodiversity, and carbon storage. The analysis can guide decision making towards the implementation of more sustainable biofuel production alternatives in a priority region for agricultural expansion and biodiversity conservation globally.

2. Methods

2.1. Development of optimization model for biofuel production alternatives

This study was developed in four densely populated Neotropical countries with high priority for agricultural expansion and biodiversity conservation (Colombia, Ecuador, Panama, and Venezuela). For each biofuel feedstock (microalgae, oil palm, and sugarcane) the best production areas to satisfy a 30% target of each country's future transport energy demands (i.e. 7.4, 3.9, 1.1, and 9.5 million tonnes of oil equivalent for Colombia, Ecuador, Panama, and Venezuela, respectively, by 2050), while avoiding areas of high agricultural and biodiversity value, were determined. The analysis modified the framework developed by Correa *et al* (2019b) to select best areas for microalgal biofuel production globally based on integer linear programming (Beyer *et al* 2016), aiming at maximizing microalgal biofuel profitability and minimizing the overlap with pixels of high agricultural and biodiversity value with a spatial resolution of 5×5 km. In the present study,

the objective function was applied to each country assuming that biofuel feedstocks (i.e. microalgae, oil palm, and sugarcane) should be cultivated within each country's boundaries to fulfill 30% of their future domestic transport energy demands. This led to the development of eight models on best microalgal biofuel production areas based on two microalgal cultivation scenarios within each of the four countries, and the development of eight models on best oil palm and sugarcane biofuel production areas based on the cultivation of these two biofuel feedstocks within each country. The maximum percentage of each pixel that could be converted to microalgal cultivation was set to 80%, assuming that 20% must be reserved for associated infrastructure (Wigmosta *et al* 2011). For oil palm and sugarcane, which can be more densely produced, the maximum percentage of conversion was set to 90%. Following Correa *et al* (2019b) these percentages were set after excluding water bodies (Lehner and Döll 2004), protected areas (UNEP-WCMC 2016), Key Biodiversity Areas (KBA) (BirdLife International 2016), and urban areas (Schneider *et al* 2009).

2.2. Development of profitability model under climate change scenarios

For microalgae, two cultivation scenarios were considered. Scenario 1: Cultivation using fresh, brackish, or saltwater sources, and Scenario 2: Cultivation using seawater that does not compete with freshwater (assuming the cultivation of microalgal strains tolerant to a wide range of salinity conditions, thereby avoiding the use of freshwater to maintain salinity as water evaporates) (Ishika *et al* 2017). The profitability was estimated by overlaying water availability, microalgal lipid productivity, availability of flat lands, and proximity to main transport networks (i.e. main roads and railroads) (See Supplementary Information for details (stacks.iop.org/ERL/15/094094/mmedia)). Future potential mean annual precipitation, mean annual potential evapotranspiration and mean annual temperature, which affect water availability and lipid productivities, were calculated for 2050, based on ensembles models for the climate change Representative Concentration Pathway (RCP) 8.5 (i.e. high emissions climate change scenario) (Riahi *et al* 2011). These ensemble models were constructed by averaging mean annual and monthly temperatures, minimum monthly temperatures, maximum monthly temperatures, and mean annual precipitation values among the General Circulation Models (GCMs) BCC-CSM1-1, CCSM4, GISS-E2-R, IPSL-CM5A-LR, HadGEM2-ES, MIROC-ESM-CHEM, MRI-CGCM3, and NorESM1-M (Hijmans *et al* 2005).

Oil palm and sugarcane profitability was estimated by overlaying water availability, agro-climatically attainable yield in dry weight by 2050 (IIASA/FAO 2012), the availability of flat lands, the proximity

Table 1. Land covers potentially replaced for fulfilling 30% of transport energy demands by 2050 in four Neotropical countries (Colombia, Ecuador, Panama, and Venezuela) by using microalgae, oil palm, and sugarcane. Land covers were obtained from the MODIS derived global mosaic for 2012 at a resolution of 5 arcminutes (Channan *et al* 2014). Microalgal cultivation scenario 1: use of fresh, brackish, or saltwater sources; microalgal cultivation scenario 2: use of seawater.

Land Cover	Scenario 1 (microalgae)		Scenario 2 (microalgae)		Oil palm		Sugarcane	
	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)
Cropland/Natural vegetation mosaic	6837.2	28.5	5994.7	24.9	17686.9	35.0	25687.5	35.6
Savannas	4929.2	20.5	4683.7	19.5	10038.8	19.9	13169.5	18.3
Grasslands	2582.6	10.8	2518.6	10.5	97.8	0.2	1712.5	2.4
Croplands	2543.1	10.6	3159.3	13.1	2912.8	5.8	1823.0	2.5
Open shrublands	1842.1	7.7	1888.4	7.9	890.6	1.8	5492.1	7.6
Woody savannas	1710.7	7.1	1753.8	7.3		0.0		0.0
Evergreen broadleaf forest (tropical rain-forest)	1034.9	4.3	1267.2	5.3	16373.1	32.4	22017.2	30.5
Deciduous broadleaf forest (tropical dry-forest)	110.8	0.5		0.0	190.1	0.4		0.0
Others	2409.5	10.0	2784.1	11.6	2334.9	4.6	2173.1	3.0
Total	24000.0	100.0	24050.0	100.0	50525.0	100.0	72075.0	100.0

to main transport networks (i.e. main roads and railroads), and the proximity to current cultivation areas (You *et al* 2014, Furumo and Aide 2017). Water availability included the proximity to rivers, irrigation dams, and fresh groundwater sources after taking into account water depletion within watersheds (Brauman *et al* 2016), along with the aridity index (Trabucco and Zomer 2009). While freshwater availability is fundamental for oil palm and sugarcane cultivation (Arshad 2014; FAO 2018), high agro-climatically attainable yields and flat lands (which favor farming intensification) increase profitability (Garnett *et al* 2013), the proximity to main transport networks facilitates access to fertilizers and markets (Laurance and Arrea 2017), and the proximity to current plantations facilitates the establishment of new cultivation areas (Garcia-Ulloa *et al* 2012). The agro-climatically attainable yields by 2050 were obtained from the Global Agro-Ecological Zones GAEZ database (IIASA/FAO 2012) by averaging the yields among the following climate change models for 2050: CCCma CGCM2 A2, CSIRO Mk2 A2, Hadley CM3 A2, and MPI ECHAM4 A2, which are representative of the high-emissions RCP 8.5 scenario used for future microalgal cultivation (Riahi *et al* 2011). It was assumed that freshwater can be readily obtained for crop cultivation and that a high level of intensification for crop production will be achieved.

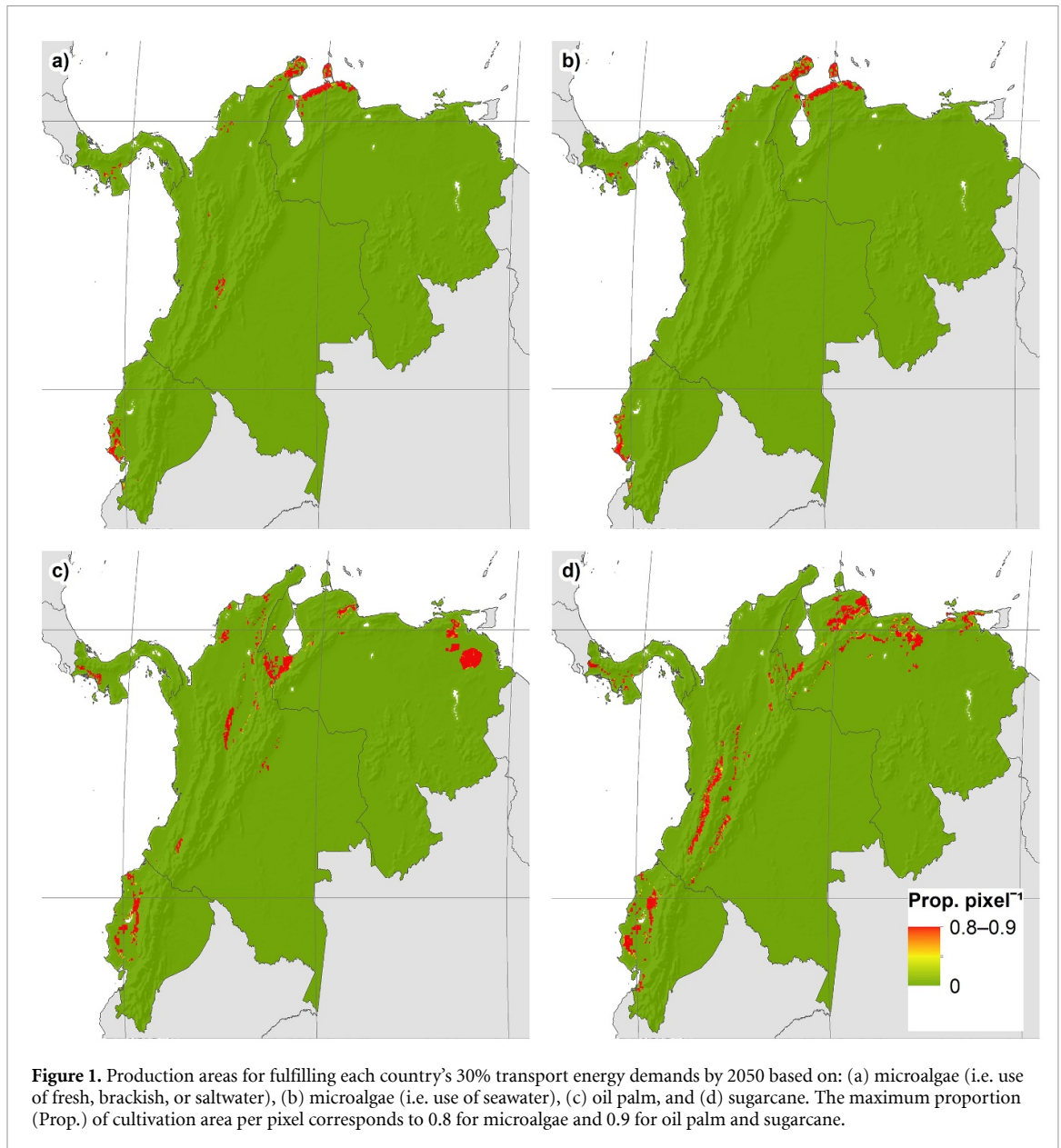
2.3. Estimation of future transport energy demands and overlapping with areas of high biodiversity, agricultural value, and soil carbon contents

Future transport energy demands were calculated for each country based on current transport energy demands (IEA 2018) and an estimated annual increase in transport energy consumption at 2.5% for non-OECD Americas (EIA 2016). Land-covers potentially replaced by microalgae, oil palm, and

sugarcane (Channan *et al* 2014) were estimated by overlapping them with proposed cultivation areas. Non-parametric Dunn's tests with Bonferroni corrections (Dino 2017) were performed to detect test differences among biofuel production alternatives per country, considering agricultural and biodiversity value, and aboveground biomass. Potential conflicts among each biofuel production alternative, agricultural value, biodiversity value, and aboveground biomass, were mapped.

3. Results

To fulfill 30% of each country's transport energy demands by 2050 would require three times as much land (based on sugarcane) and twice as much land (based on oil palm) as microalgal systems (table 1). Best areas for microalgal biofuel production at the lowest direct competition with high-value agricultural lands and biodiversity would correspond to drier lowlands (figure 1). For Scenarios 1 (use of fresh, brackish, or saltwater) and 2 (use of seawater), main cultivation areas would be located in the Colombian Caribbean region (i.e. mostly in the Guajira desert) and inter-Andean valleys (i.e. mainly in the Alto Magdalena Valley), in the Ecuadorian coastal region (i.e. mainly in the provinces of Santa Elena, Manabí, and Guayas), in the Panamanian Pacific coast (i.e. mainly in the provinces of Veraguas and Coclé), and in the Venezuelan Caribbean coastline (i.e. around the Gulf of Venezuela in the state of Falcón and around the Lake Maracaibo in the state of Zulia). Based on these cultivation scenarios, estimated replaced land-covers would correspond to cropland/natural vegetation mosaics (24.9–28.5%), followed by savannas (19.5–20.5%), grasslands (10.5–10.8%), croplands (10.6–13.1%), open

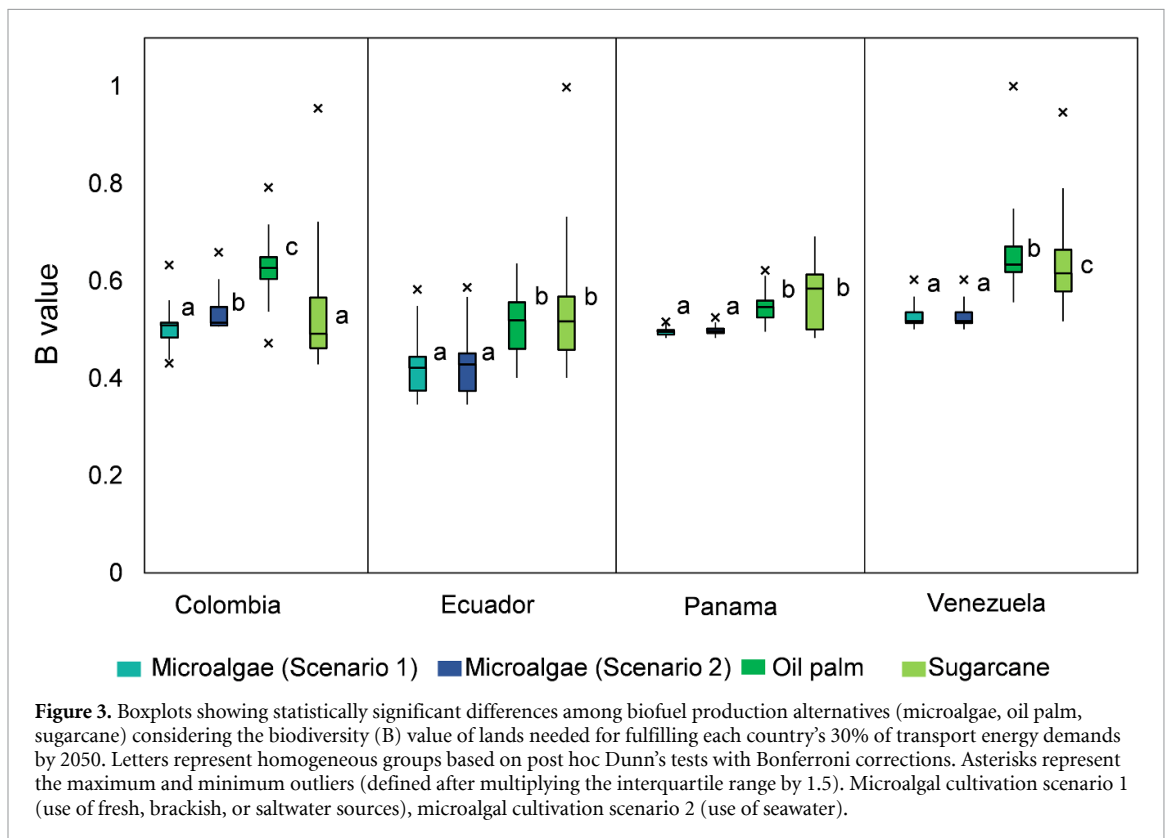
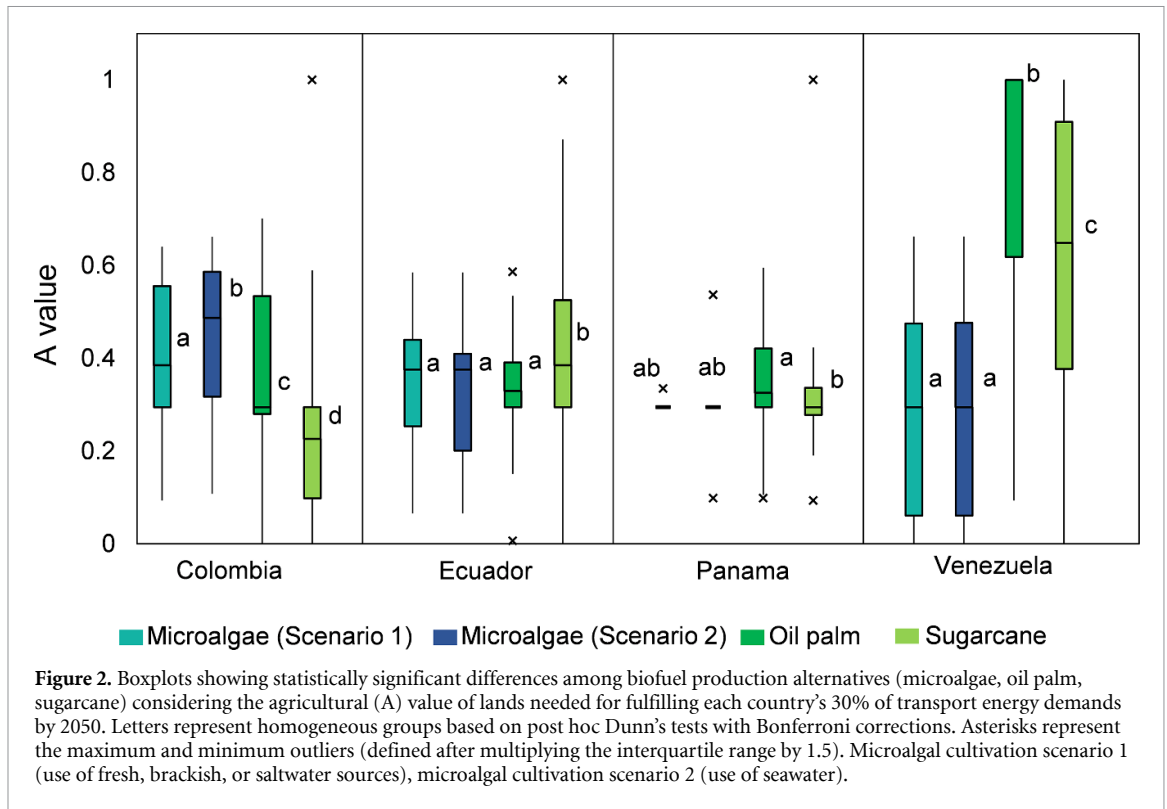


shrublands (7.7–7.9%), and woody savannas (7.1–7.3%) (table 1).

Best areas for oil palm production at the lowest direct competition with high-value agricultural lands and biodiversity would be mainly located in humid areas within the Colombian Caribbean and Catatumbo regions and Middle Magdalena Valley, the Ecuadorian Pacific lowlands (i.e. mainly in the provinces of Esmeraldas, Pichincha, Manabí, Los Ríos, and Guayas), the Panamanian Pacific coast (i.e. mainly in the province of Chiriquí), and the Venezuelan northern lowlands (i.e. mainly the states of Zulia, Táchira, Monagas, and Delta Amacuro). Areas for sugarcane production at the lowest direct competition with high-value agricultural lands and biodiversity would be located in humid foothills, mainly in the Colombian Cauca and Magdalena valleys, the Ecuadorian Pacific lowlands (i.e. mainly in the provinces of Pichincha, Los Ríos, Manabí, and Guayas), the Panamanian Pacific coast (i.e. mainly in the provinces of Chiriquí

and Veraguas), and the Venezuelan northern foothills (i.e. mainly in the states of Lara, Falcón, Guárico, and Sucre). Land-covers potentially replaced by oil palm and sugarcane include cropland/natural vegetation mosaics (35% and 35.6% for oil palm and sugarcane, respectively), followed by evergreen broadleaf forests (32.4% and 30.5% for oil palm and sugarcane, respectively), and savannas (19.9% and 18.3% for oil palm and sugarcane, respectively).

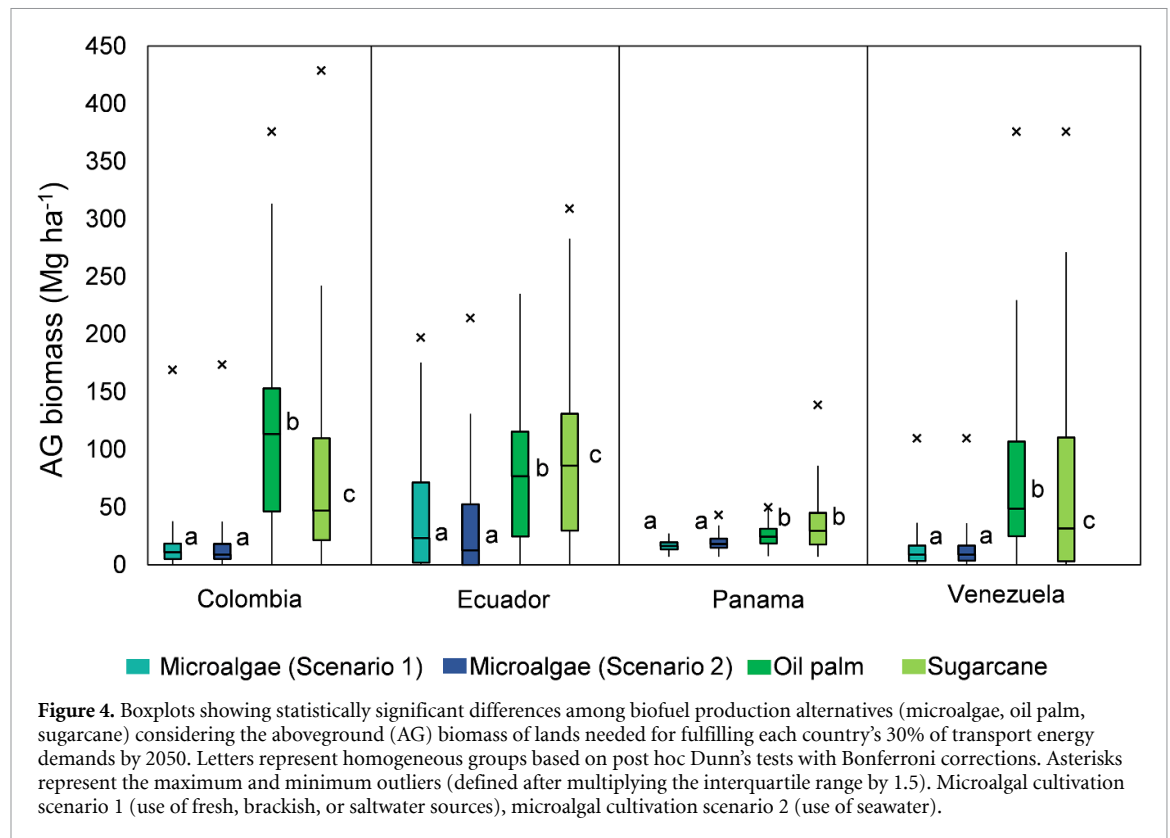
Microalgal cultivation would lead to lower competition with high-value agricultural lands in Ecuador (compared to sugarcane), Panama and Venezuela (compared to oil palm and sugarcane) (figure 2). Microalgal cultivation would consistently lead to lower competition with biodiversity and aboveground biomass (figures 3, 4). Higher targets in biofuel demands would increase competition with areas of higher agricultural and biodiversity value and larger aboveground biomass within countries (figures 5, 6, 7).



4. Discussion

Based on our analysis, microalgal biofuel production systems would require between 48% and 33% of the land area compared to oil palm and sugarcane, respectively, to fulfill 30% of transport energy demands by 2050. This arises because of the higher

microalgal biofuel production efficiencies per unit area, compared to any other biofuel crop (Carneiro *et al* 2017, Correa *et al* 2017, 2019a). Even if future oil palm and sugarcane biofuel productivities increase as a result of better management practices and the development of more productive varieties (Murphy 2009, Jaiswal *et al* 2017), they are unlikely



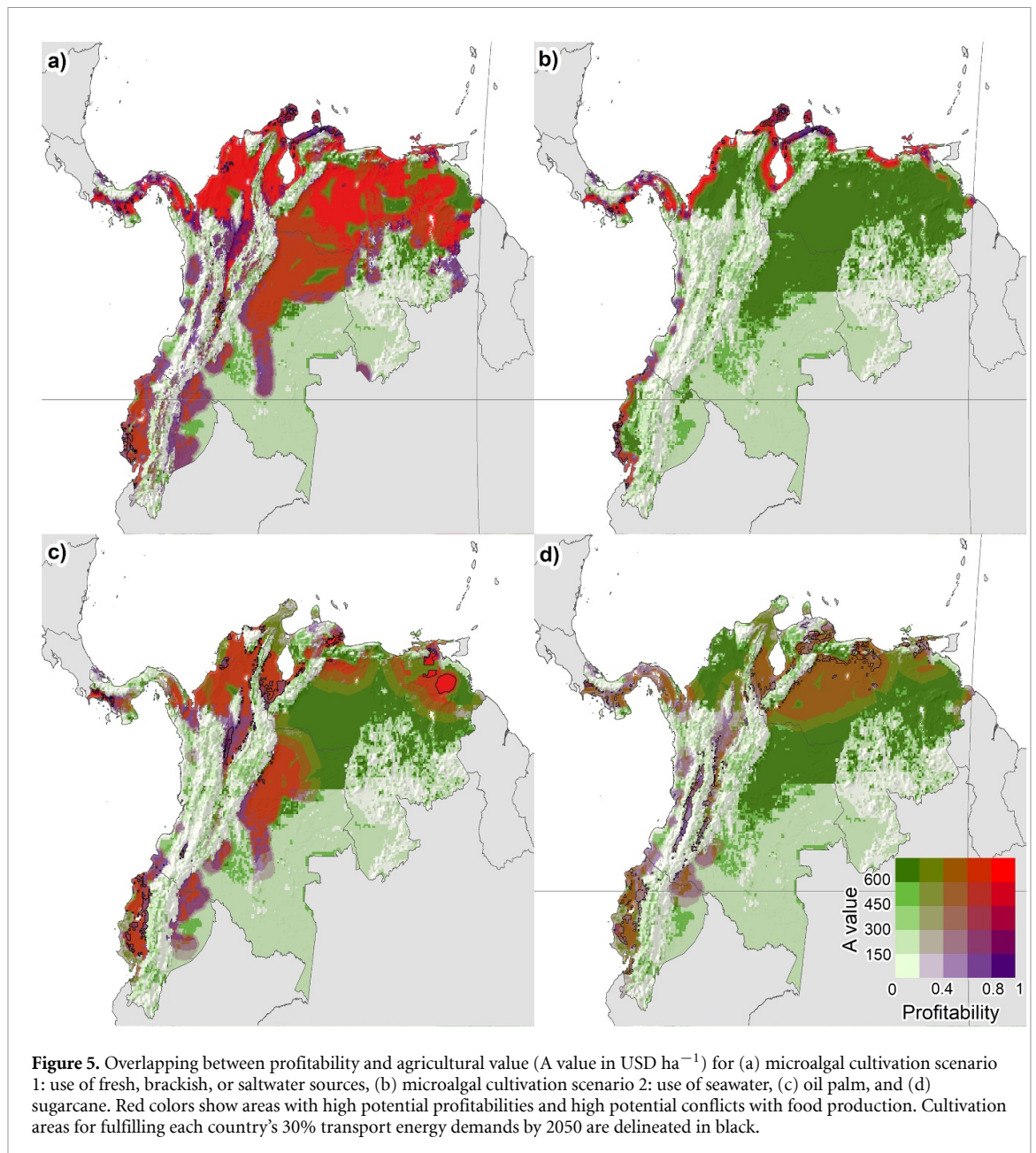
to approach the production efficiency of microalgal production systems, with estimated maximum oil yields at $136\,900\text{ l ha}^{-1}$ (Chisti 2007). Furthermore, an increase in microalgal productivity can be achieved through technological improvements that maximize biomass and lipid production, including the use of photobioreactors, nutrient starvation techniques (Leong *et al* 2018, Anto *et al* 2019), and control in pH and salinity conditions (Sharma *et al* 2018) coupled with the selection of highly productive microalgal strains (Sharma *et al* 2019).

Microalgal production systems would additionally offer a more adaptable alternative for maintaining biofuel productivity while coping with increasing temperatures and changes in rainfall patterns in the Neotropics. This is because many microalgal strains thrive in areas with higher mean annual temperatures (Moody *et al* 2014), microalgal cultivation does not depend on rainfall (particularly if cultivating seawater species) (Ishika *et al* 2017), and there are a wide range of microalgal strains that could be rapidly developed to cope with evolving cultivation conditions (Aslam *et al* 2017, Lim and Schenk 2017). Thus, increases in mean annual temperature and changes in precipitation patterns within the study region would not significantly alter best areas for siting microalgal production farms. In contrast, oil palm and sugarcane can be cultivated within a more limited temperature range and as rainfall is usually required for their production, the best areas for microalgal cultivation are expected to change with global warming. Unless new varieties tolerant to higher mean annual temperatures

and drought are developed in the near future (Paterson *et al* 2015, Linnenluecke *et al* 2018), oil palm and sugarcane cultivation will likely shift to higher altitudes (IIASA/FAO 2012), competing with areas of high agricultural and biodiversity value in inter-Andean valleys and mid-altitude areas.

4.1. Competition with high-value agricultural lands, biodiversity, and aboveground biomass among biofuel production systems

As in Correa *et al* (2019b) our analyses indicate that microalgal cultivation should be prioritized in dry lowlands (i.e. areas with median rainfall values equal than 547 and 498 mm for Scenarios 1 and 2 in the present study, respectively, which correspond to semi-arid lands) while oil palm and sugarcane would require humid areas (i.e. areas with median rainfall values equal to 1607 and 1382 mm for oil palm and sugarcane, respectively). In general, dry lands are considered less suited for agriculture (Li *et al* 2017, Taylor 2018), and additionally hold lower biodiversity values (Neves *et al* 2020) and lower aboveground biomass contents (Álvarez-Dávila *et al* 2017) than more humid areas. As a result, competition with food production, biodiversity, and aboveground biomass among countries would, in general, decrease if biofuel production is based on microalgae, compared to oil palm and sugarcane. Notwithstanding, dry ecosystems hold unique species (Brito *et al* 2014), provide valuable ecosystem services (e.g. tourism and desertification control) (Dudley *et al* 2014), and are considered at risk in the Neotropics (Etter

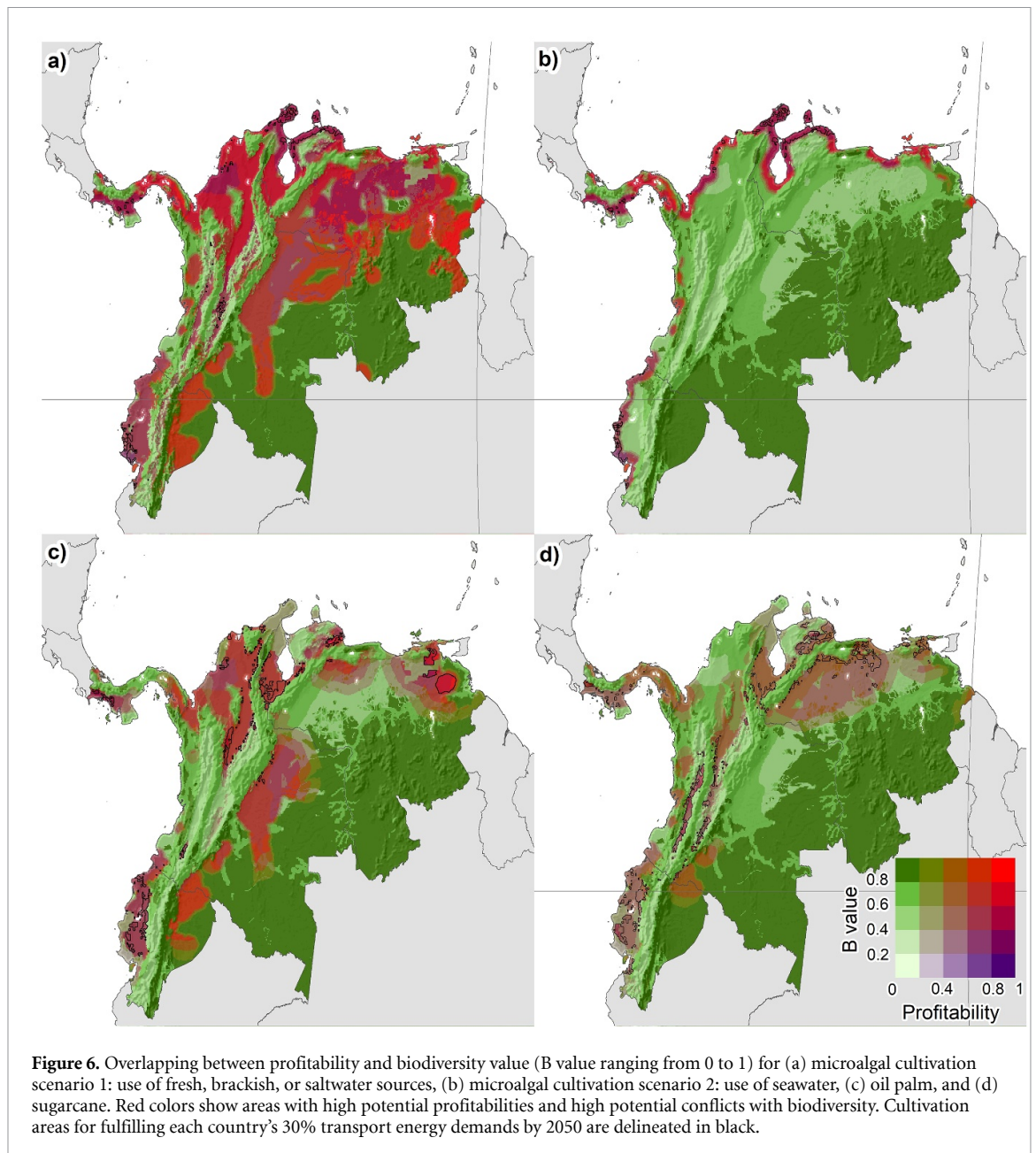


et al 2017). Our analyses limited microalgal cultivation to human-transformed dry areas (Venter *et al* 2016), however, even in these lands microalgal cultivation should reduce impacts on biodiversity and ecosystem services by limiting the removal of habitat patches for native species (Correa *et al* 2019b) and by avoiding pollution (e.g. through the recycling of microalgal cultivation effluents) (González-González *et al* 2018).

Furthermore, less than 5.3% of microalgal production areas (i.e. around 1267 km²) would occur within the highly biodiverse and carbon-rich rainforests, in contrast to oil palm and sugarcane that would occur within rainforests in between 30.5–32.4% of their estimated cultivation areas (i.e. 16 373 and 22 017 km², respectively). Zoning the cultivation in areas of lower biodiversity value and lower carbon contents, such as pastures and

transformed/degraded lands for oil palm (García-Ulloa *et al* 2012, Castiblanco *et al* 2013, Ocampo-Peñuela *et al* 2018) and sugarcane (Gilroy *et al* 2015, Rueda Ordoñez *et al* 2018), could reduce potential deforestation if expanding food crops for biofuel production. However, in doing so biofuel productivities per unit area would also be reduced (as pixels with lower potential productivities would need to be selected), thereby increasing the land footprint required to meet energy targets.

The use of seawater for microalgal cultivation could reduce competition with freshwater—provided that microalgal strains that tolerate a wide range of salinity conditions are cultivated (Ishika *et al* 2017)—and become the best alternative in dry areas with compromised water security (Vorosmarty *et al* 2010). However, a trade-off among seawater availability, agricultural value, and biodiversity value, would



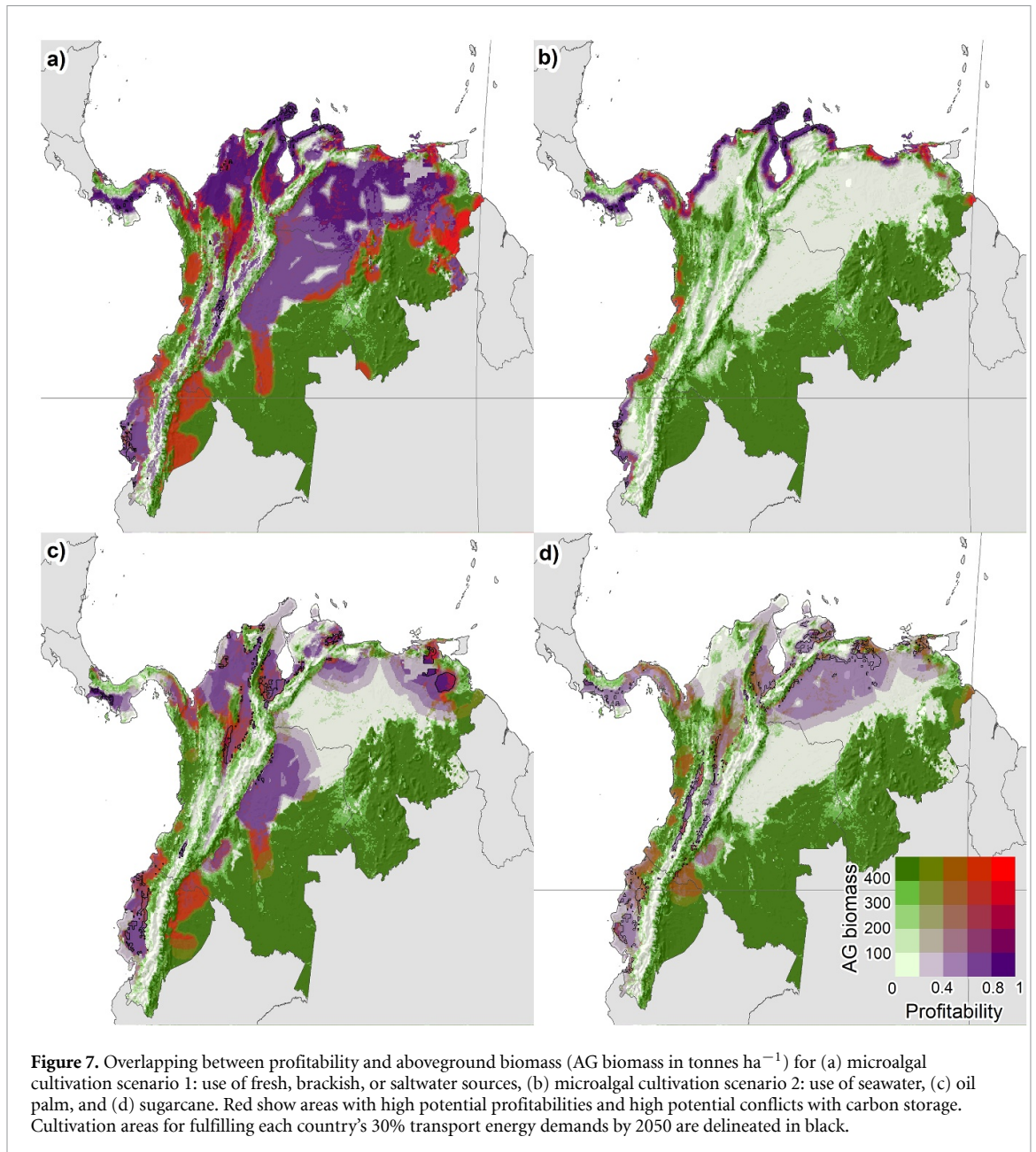
occur in the Colombian Caribbean region, where suitable areas for food production and with high biodiversity are located near the coasts. Reducing future targets in microalgal biofuel production (e.g. from 30% to 20% of total transport energy demands) would become a more sustainable option to limit potential direct land-use change of high-value lands for agriculture or biodiversity conservation in the Colombian Caribbean.

While microalgal cultivation would be the preferable alternative for biofuel production within the study region, the co-location of microalgal production systems with existing oil palm (Cheah *et al* 2018) and sugarcane crops (Santana *et al* 2017) has been recently explored as a mean to increase the overall sustainability and profitability of biofuel production. Oil palm and sugarcane industrial operations can offer CO₂ and nutrients that facilitate microalgal

productivity, as well as electrical energy that can be used during microalgal cultivation and harvesting (Klein *et al* 2018).

4.2. Increases in transport energy demands

Following the success of Brazil in bioethanol production from sugarcane, several Neotropical countries aim to increase mandatory biofuel blends (Gonzalez-Salazar *et al* 2017, Cutz and Nogueira 2018). Furthermore, high demands for biofuels in developed economies can promote biofuel's exports from Neotropical countries (Acharya and Perez-Pena 2020). Increasing targets in biofuel production, either for the domestic production of biofuel blends or for exports, would intensify conflicts with food production, biodiversity, and carbon storage in the region. Even for microalgal production systems, environmental impacts would increase as areas with lower



productivity per unit area, or with higher agricultural, biodiversity, and aboveground biomass values are considered suitable to reach higher biofuel production targets. Limiting targets in biofuel production could thus reduce environmental impacts in the Neotropical region.

Encouraging biofuel production outside priority areas for biodiversity and carbon storage (e.g. tropical rainforests) can reduce the overall environmental impacts of biofuel production in the Neotropical region. This could be achieved through the implementation of policies and frameworks (e.g. sustainability certification schemes) that prevent deforestation and promote sustainable biofuel production practices (De Man and German 2017). The implementation of microalgal production systems can derive from the development of taxation schemes that discourage less sustainable alternatives while subsidies and technological improvements increase their profitability

(Saravanan *et al* 2018, Correa *et al* 2019a). These technological improvements include the development of biorefinery systems in which high-value co-products such as protein and pigments (Su *et al* 2017, Mathmani and Pugazhendhi 2019) are extracted along with biofuels (Moreno-Garcia *et al* 2017, Chia *et al* 2018), the recycling of water and nutrients from cultivation (e.g. through anaerobic digestion) (González-González *et al* 2018), the development of more efficient harvesting techniques (Fasaei *et al* 2018, Singh and Patidar 2018), and the co-location with free sources of nutrients or CO₂ from industries (Judd *et al* 2017).

5. Conclusions

Even in countries with large fossil fuel reserves (e.g. Venezuela), biofuel production is projected to increase to fulfill future transport demands,

decreasing the uncertainties associated with future fossil fuel markets (Ansari and Holz 2020) while climate change is mitigated (Binsted *et al* 2019). Microalgal production systems offer the most sustainable alternative for future biofuel production within the Neotropical region. Compared to oil palm and sugarcane, microalgal production systems can be implemented in areas with lower value for food production, biodiversity, and carbon storage, as they can overlap drier lowlands within countries. Furthermore, to fulfill 30% of each country's transport energy demands, less than 5.3% of their estimated cultivation areas would overlap rainforests, in contrast to oil palm and sugarcane, which would overlap rainforests in at least 30% of their estimated cultivation areas. Additionally, microalgal production systems could reduce land area requirements by at least 52% compared to oil palm and 67% compared to sugarcane. Decreasing targets in biofuel production (either for domestic production or for exports) would further limit potential environmental impacts associated with the expansion of microalgal biofuels.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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