SUPPLEMENTARY MATERIALS FOR

TRANSFORMING THE FUTURE OF MARINE AQUACULTURE

A CIRCULAR ECONOMY APPROACH

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ENVIRONMENTAL SUSTAINABILITY ADVANTAGES OF MARINE MICROALGAE-BASED AQUACULTURE

A. EXAMPLES OF DIRECT ENVIRONMENTAL SUSTAINABILITY ADVANTAGES

The 2020 global production of soybeans was 353 Mt/yr from a harvestable cropland area of 1.3 million km^2 (FAO, 2021). Assuming a 13% protein content in wet weight biomass (USDA, 2018), this converts to a 2020 global soy protein production of 46.0 Mt/yr. Assuming an algal protein productivity value of 3.36×10^{-3} Mt/km^2/yr (Huntley et al., 2015; DOE, 2016b; Wang et al., 2021), the microalgae cultivation area required to produce a similar amount of protein would be approximately 13,700 km^2, saving 95 times as much cropland.

Assuming a globally averaged, blue-water irrigation demand for soybean production of 123,000 m^3/km^2/yr, the amount of freshwater saved annually could approach 160 billion cubic meters. This is comparable to the current annual blue-water irrigation demand of the United States for all crops (FAO, 2022).

Assuming that soybean production requires 5.5 t/km^2/yr of phosphate fertilizer and that 2.3% of this fertilizer runs off (Alexander et al., 2008), then the amount of phosphate saved from fertilizer runoff annually would be ~164,000 t. This corresponds to ~3.2% of the annual North American phosphate fertilizer demand (FAO, 2019).

Corresponding Calculations

1. MICROALGAE BIOMASS PRODUCTION (DRY WEIGHT BIOMASS)

Assuming mean daily value from DOE (2016) scaled up to a year with 92% operational capacity over the year,

$25\ \text{g/m}^2/\text{d} \times 1\ \text{kg}/1000\ \text{g} \times 10^6\ \text{m}^2/1\ \text{km}^2 \times 336\ \text{d/yr} = 8.40\ \text{million kg/km}^2/\text{yr} = 8.40 \times 10^{-3}\ \text{Mt/km}^2/\text{yr}$.

2. MICROALGAE PROTEIN PRODUCTION

Assuming protein content of 40% of dry weight biomass (Wang et al., 2021),

$8.40 \times 10^{-3}\ \text{Mt/km}^2/\text{yr} \times 0.40 = 3.36 \times 10^{-3}\ \text{Mt/km}^2/\text{yr}$.

3. GLOBAL SOYBEAN PRODUCTION

Assuming 2020 soybean biomass production of 353 Mt/yr from 1.3 million km^2 (FAO, 2021),
2020 soybean biomass yield would be

353 Mt/yr/1.3 million km^2 = 271 t /km^2/yr.

4. GLOBAL SOY PROTEIN PRODUCTION

Assuming a protein content of 13% of wet weight biomass (USDA, 2018)

2020 soy protein production: 353 Mt/yr × 0.13 = 45.9 Mt/yr

2020 soy protein yield: 271 t/km^2/yr × 0.13 = 35.2 t/km^2/yr

5. LAND-USE EXAMPLE

Microalgae cultivation area required to produce the same amount of protein as global soy protein production:

Global Soy Protein Production		Mean Microalgae Protein Yield		Required Microalgae Cultivation Area
46.0 Mt/yr	/	3.36×10^{-3} Mt/km^2/yr	=	13,700 km^2

Soy Cropland Area / Microalgae Cultivation Area = 1.3 million km^2/13,700 km^2 = 95.0

6. FRESHWATER USE EXAMPLE

Assuming globally averaged, blue-water irrigation demand for soybean production of 123,000 m^3/km^2/yr (FAO, 2022), potential savings in blue-water irrigation demand would be:

Global Soybean Harvested Cropland		Global Soy Irrigation Demand		Global Blue-Water Irrigation Savings
1.3 million km^2	×	123,000 m^3/km^2/yr	=	160 billion m^3

7. FERTILIZER USE EXAMPLE

Assuming that soy production requires 5.5 t/km^2/yr of phosphate fertilizer and that 2.3% of this fertilizer runs off (Alexander et al., 2008), the amount of phosphate saved from fertilizer runoff annually would be:

Global Soybean Harvested Cropland		Phosphate Requirement		Percent Runoff		Phosphate Saved
1.3 million km^2	×	5.5t/km^2	×	0.023	=	164,000 t

Phosphate saved / global phosphate demand = 164,000 t/49,096,000 t = 0.33%

Phosphate saved / North American phosphate demand = 164,000 t/5, 187,000 t = 3.2%

B. EXAMPLES OF LESS DIRECT ENVIRONMENTAL SUSTAINABILITY ADVANTAGES

The 2020 production of soybeans in Brazil was 128 Mt/yr from a harvestable area of 372,000 km^2 (FAO, 2021). Assuming a 13% protein content in wet weight biomass (USDA, 2018), this converts to a Brazilian soy protein production of 16.6 Mt/yr. Assuming an algal protein productivity value of 3.36×10^{-3} Mt/km^2/yr, the microalgae cultivation area required to produce a similar amount of protein would be approximately 4,940 km^2, providing a potential savings of 75 times as much cropland.

The average 2018–2020 production of beef (equivalent carcass weight) in Brazil was 10.0 Mt/yr from a grazing area of 1.65 million km^2 (FAO, 2021). Assuming a 15% protein content in equivalent carcass weight, this converts to a Brazilian beef protein production of 1.5 Mt/yr. Assuming an algal protein productivity value of 3.36×10^{-3} Mt/km^2/yr, the microalgae cultivation area required to produce a similar amount of protein would be approximately 446 km^2, providing a potential savings of 3,700 times as much grazing pastureland.

Corresponding Calculations

1. BRAZILIAN SOY PROTEIN PRODUCTION

2020 Brazilian soybean biomass production: 128 Mt/yr from 372,000 km^2 (FAO, 2021)

2020 Brazilian soybean biomass yield: 128 Mt/yr/372,000 km^2 = 344 t/km^2/yr

Assuming a 13% protein content in wet weight biomass (USDA, 2018)

2020 Brazilian soy protein production: 128 Mt/yr × 0.13 = 16.6 Mt/yr

2. LAND-USE EXAMPLE TO REPLACE SOYBEAN CROPLAND

Microalgae cultivation area required to produce the same amount of protein as Brazilian soy protein production:

Brazilian Soy Protein Production		**Mean Microalgae Protein Yield**		**Required Microalgae Cultivation Area**
16.6 Mt/yr	/	3.36×10^{-3} Mt/km^2/yr	=	4,940 km^2

372,000 km^2/4,940 km^2 = 75.3

3. BRAZILIAN BEEF PROTEIN PRODUCTION

Average 2018–2020 Brazilian Beef Production (equivalent carcass weight): 10.0 Mt/yr from 1.65 million km^2 (FAO, 2021)

Assuming a 15% protein content in equivalent carcass weight, the conversion from equivalent carcass weight to protein content is determined as follows:

Deboned and trimmed beef: 65% of equivalent carcass weight: 10 Mt/yr × 0.65 = 6.5 Mt/yr
(Saner and Busemen, 2020)

Beef protein: 23% of deboned and trimmed beef: 6.5 Mt/yr × 0.23 = 1.5 Mt/yr
(Williams, 2007)

Conversion Factor: Beef carcass weight production to beef protein production: 0.65 × 0.23 = 0.15 or 15%

4. LAND-USE EXAMPLE TO REPLACE BEEF PASTURELAND

Microalgae cultivation area required to produce the same amount of protein as Brazilian beef protein production:

Brazilian Beef Protein Production		**Mean Microalgae Protein Yield**		**Required Microalgae Cultivation Area**
1.5 Mt/yr	/	$3.36 \text{ x } 10^{-3}$ Mt/km^2/yr	=	446 km^2

1.65 million km^2/446 km^2 = 3700

C. GLOBAL MARINE MICROALGAE PRODUCTION POTENTIAL

Our estimates of global marine microalgae production potential are based on a modified version (Scott-Buechler, 2021) of the geospatial model developed by Moody et al. (2014). In both models, microalgae production was estimated initially using local annual incoming solar radiation data and a validated growth model based on reported values in the scientific literature. Geostatistical methods were then used in ArcGIS to interpolate local values to create a global map of marine microalgae production potential. Moody et al. (2014) assumed the maximum daily productivity to be 14.8 $g/m^2/d$. Scott-Buechler (2021) used a maximum daily productivity of 25 $g/m^2/d$ based on projected values reported by the DOE (2016) and consistent with the values reported by Huntley et al. (2015). It was assumed that 80% of a given area was put towards microalgae cultivation, with the remaining 20% set aside for necessary infrastructure.

To convert from biomass production to protein production, protein content was assumed to be 55%, consistent with values for *Chlorella* spp. and *Spirulina* spp., the two groups of microalgae species that currently show the greatest promise for commercial-scale human nutrition. An extraction efficiency of 90% was assumed.

Once the global map of marine microalgae production potential was created, the GIS-based multiple-criteria decision analysis model developed by Scott-Buechler (2021), which built on the model presented in Correa et al. (2019), was used to select environmentally and financially suitable areas for large-scale marine microalgae cultivation. One major constraint was to limit cultivation areas to within 20 km of the coast. This constraint was selected to limit the cost of transporting seawater inland.

Using only the top 5% of suitable areas for marine microalgae cultivation within 20 km of the coast, global marine microalgae production potential was estimated to be 587.9 Mt/yr. This is more than double the projected global protein demand for 2050 reported by Henchion et al. (2017), which ranges from 263.85 Mt/yr to 286.5 Mt/yr.

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