MASTER OF ENVIRONMENTAL SCIENCE
AND MANAGEMENT

SHAPING MARICULTURE DEVELOPMENT IN BRAZIL

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The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

Dr. Hunter Lenihan **Date**

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ABSTRACT

With rising human populations and declining wild fish stocks, offshore mariculture can provide an influx of seafood within the global market and assist countries in economic expansion in the coming decades. While Brazil has a large potential for mariculture development, a lack of logistical knowledge and infrastructural precedence exists to practice the cultivation strategy. In this study, we explore the spatial feasibility of mariculture development and create an interactive web-based tool to predict potential locations, yields, and profitability for offshore mariculture of cobia (*Rachycentron canadum*) in Brazil's Exclusive Economic Zone (EEZ). After analyzing spatial, infrastructural, and biological constraints of offshore mariculture, we: (1) identified that 0.25% of the study area (Brazil's EEZ) qualifies as feasible for cobia mariculture; (2) developed a model that can adjust to account for country-specific spatial conflicts, other uses of marine space, and sensitive ecosystems; (3) and determined that mariculture's profitability is extremely sensitive to feed price and market price of cobia. Our study shows productivity and profitability vary with temperature across sites within the study region and that market prices, as well as feed costs, alter the predicted profitability.

INTRODUCTION

Food systems across the globe face intense pressure to produce enough animal protein as the human population grows towards 10 billion people by 2050[1,2]. As a result, wild fish stocks, a major protein source, are overharvested and undergoing precipitous population declines[3]. Wild fishery management has improved with evidence that some wild fish stocks are increasing, but this small growth rate of wild stocks falls behind global demand for fish[4]. To meet global fish demand and human protein requirements, the mariculture (marine aquaculture) industry has been quickly expanding[5–8]. While impossible to claim a one-to-one replacement ratio between farmed and wild-caught fish, the United Nations Food and Agriculture Organization (FAO) affirms that farmed fish is the fastest-growing food sector in the world[9] . Consequently, countries may see large economic opportunities through offshore aquaculture expansion, regardless of the effects of this budding practice on the wild-capture industry. Additionally, offshore mariculture holds environmental benefits over land-based practices, as farms located further away from coastal areas better at dispersing particulates, and minimizing environmental pollution and the risk of disease to surrounding wild stocks[10].

Major constraints to offshore mariculture have prevented widespread development of offshore mariculture, including expensive infrastructure and development costs, complex permitting systems, and lack of knowledge around which ocean parcels are optimal for cultivating fish[5,11]. Without known information on ideal mariculture farm placement, in terms of biomass productivity and economic profitability, developers cannot easily determine where, or if, to establish offshore mariculture.

Brazil is one such nation with underdeveloped offshore mariculture[12]. Brazilian commercial and recreational fisheries overexploit many of their wild stocks while attempting to meet the national demand for fish. Furthermore, Brazil imports more seafood than any other Latin American country[13]. The state of Brazil's wild fisheries and the lack of mariculture development make it a prime system for investigating the potential for offshore mariculture. With the second largest coastline of all Latin American countries, Brazil offers immense potential to develop offshore mariculture.

World Wildlife Fund (WWF), an international conservation organization, is an advocate for the preservation of local fisheries, thus seeks to explore sustainable aquaculture practices in Brazil. This interest engendered the partnership between WWF and the Bren School of Environmental Science and Management to research mariculture feasibility in Brazil. Brazil's ability to develop it nascent offshore aquaculture industry hinges on understanding the potential biomass and profits from offshore farms that are crucial for mariculture investment. There have been no large feasibility studies of offshore aquaculture in Brazil to date. In this study we created a marine spatial planning web-based tool for estimating the biological and economic feasibility of offshore finfish mariculture. We used Brazil and cobia (*R. canadum*) as a model system to estimate the efficiency of our tool.

METHODS

APPROACH OVERVIEW AND STUDY AREA

The extent of this study area encompassed the boundaries of Brazil's Exclusive Economic Zone (EEZ), which lies in both the northern and southern hemispheres of the Atlantic Ocean. It occupies approximately 3 million km^2 of Brazil's coastal ocean. All analyses were performed at 123.4 km^2 (9.3 km x 13.3 km) spatial resolution to remain consistent with the resolution of available open source oceanographic data[14]. All spatial data files were transformed into the coordinate reference system SIRGAS 2000/Brazil Polyconic, or EPSG:5880.

Figure 1. Brazil's Exclusive Economic Zone highlighted in blue.

To complete our analysis, we: 1) identified potential locations for offshore cobia aquaculture by excluding incompatible areas from Brazil's EEZ; 2) estimated potential biomass productivity of the these sites using a temperature-dependent growth equation; 3) determined the potential profitability of these sites through an economic model accounting for revenues, costs, and distance to shore; and 4) developed an interactive web-based tool for the application of this analysis to other species and/or variable parameter settings.

We selected cobia (*Rachycentron canadum*) as the model species for our analysis because it is one of the most suitable candidates for offshore aquaculture in Brazil. It is a commonly studied species for offshore aquaculture globally, is native to Brazil, has high thermal tolerances, and has current fingerling availability within the country[15,16].

SITE SUITABILITY ASSESSMENT

To identify which parcels of Brazil's EEZ are suitable for marine aquaculture development, we performed a spatial analysis that considered key physical spatial conflicts, infrastructure placement, and biological tolerances. We then defined thresholds for each constraint based on previous aquaculture feasibility studies. For example, suitable depth for installing aquaculture pens was deemed to be between 25 to 100 meters. The thresholds for factors related to the technical feasibility of placing aquaculture pens were estimated assuming the use of InnovaSea SeaStation aquaculture pens (6400 m^3). These are commonly employed, submersible structures for offshore aquaculture projects[17]. See Appendix I for further description of the layers included in the suitability assessment and their respective thresholds.

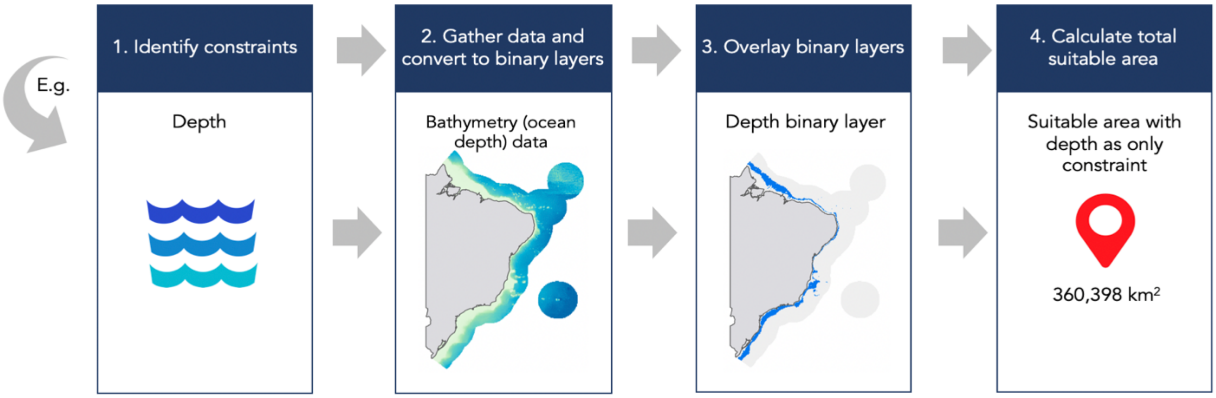

Figure 2. Example of the data processing workflow operationalized to calculate what parcels of the ocean are available for aquaculture*. Individual constraint layers were converted into binary data based on the thresholds (Appendix I), and then multiplied together resulting in a raster only showing suitable parcels. Lastly, we calculated the total potential available area*

PRODUCTIVITY ASSESSMENT

It is crucial to understand how much biomass could be produced, when seeking investment for the development of offshore mariculture. We estimated potential cobia biomass production from contemporary offshore farms in our analysis. We utilized the subset of suitable marine parcels generated from the site suitability analysis to estimate the biomass at harvest for cobia. We derived a linear model using growth rate information established in Benetti et al. (2010) to estimate how cobia's growth rate (K) varies spatially with temperature:

$$K = A \times T + B \qquad \text{(Equation 1)}$$

where A and B are the slope (0.0714) and intercept (-1.5714) established in Benetti et al. (2010) both multiplied by 12 to convert the units into years. Using the assumption that the maximum mass one cobia can grow to in one year at 27.8 °C is 6.066kg, we were then able to create a scalar to compare the growth of cobia at any other temperature. This weight was called optimal weight at harvest (OW_h). When we divided the yearly K values that we estimated using the linear model by OW_h we normalized them between 0-1 effectively making a unitless scalar ():

$$= K \times OW_h \qquad \text{(Equation 2)}$$

We estimated the final biomass at harvest by multiplying the OW_h (6.066kg) by the scalar, the stocking density (S_d), cage volume (C_v), number of cages (N_c), and the mortality rate (m_r):

$$Biomass = OWh \times \Omega \times Sd \times Cv \times Nc \times mr \qquad \text{(Equation 3)}$$

PROFITABILITY ASSESSMENT

To assess the potential profitability of Brazilian offshore mariculture, we first calculated the costs associated with production followed by the potential revenues; we then subtracted costs from profits; and finally, we calculated the Net Present Value (NPV) for each cell in which mariculture was found to be feasible.

Costs

Our cost model for offshore aquaculture in Brazil calculated total expenses (C_{total}) for each farm, including fixed one-time initial capital costs and annual operating costs, over a 10-year period:

$$C_{total} = C_{labor} + C_{fuel} + C_{capital} + C_{operations} \qquad \text{(Equation 4)}$$

Cost parameters values, listed in Appendix IV, were obtained from either published literature or personal communication with industry experts. Some parameters were fixed Appendix IV, while others were a function of distance to shore, based on the farm location.

Annual farm labor costs (C_{labor}) were calculated using the following equation:

$$C_{labor} = S_{labor} + O_{labor} \qquad \text{(Equation 5)}$$

where S_{labor} represents the cost of labor for onshore-only employees and O_{labor} the cost of labor for offshore employees.

Onshore labor cost was calculated as:

$$S_{labor} = W_{hours} + SW_{number} + W_{wages} \qquad \text{(Equation 6)}$$

where W_{hours} is the number of hours worked annually for a single employee assuming 40 hour/week shifts; SW_{number} is the number of full-time employees onshore for each farm; W_{wages} is the average wage of an onshore full-time employee on a industrial scale offshore aquaculture of Cobia in Brazil[18].

The cost of offshore workers (O_{labor}) was calculated with the equation:

$$O_{labor} = OW_{number} \times W_{wages} \times [((D_{shore}/V_{speed}) \times V_{trips}) + W_{hours}] \qquad \text{(Equation 7)}$$

where OW_{number} is the number of full-time employees offshore for each farm; W_{wages} is the average annual wage of a full-time employee on an industrial scale offshore aquaculture farm in Brazil[18]; D_{shore} is the distance of the farm to shore (km); V_{speed} is the average vessel speed (Appendix III); V_{trips} is the number of one way trips per year to the farm, assuming two boats combined make 8 round-trips per week (Appendix III); and W_{hours} is the number of hours worked annually for a single employee assuming 40 hour/week shifts.

The cost of fuel (C_{fuel}) was calculated as:

$$C_{fuel} = (D_{shore}/V_{speed}) \times V_{consumption} + F_{price} + V_{one\ way\ trips} \qquad \text{(Equation 8)}$$

where D_{shore} is the distance of the farm to shore (km); V_{speed} is the average vessel speed; $V_{consumption}$ is the average fuel efficiency of the vessel (L/h); F_{price} is the diesel price in Brazil as of January 24th, 2020; and V_{trips} is the number of one way trips per year to the farm, assuming two boats combined make 8 round-trips a week.

Profits

According to our model, farms earned revenue R_{total} by harvesting cobia when it reached the defined OW_h. Thus, for each harvest cycle (12-month time period), farms earned revenue only when fish reached the target weight; otherwise, $R_{total} = 0$. Revenue was a function of harvested farm biomass (kg) and cobia price (P_{fish}), as shown in Equation 9 . We assumed an average farm gate price of US$8.00 kg based on personal communication with industry in Brazil[19].

$$R_{total} = P_{fish} \text{ x } T_{biomass} \qquad \text{(Equation 9)}$$

We then calculated total farm profit (π_{farm}) as the sum of revenues minus the sum of costs:

$$\pi_{farm} = R_{total} - C_{total} \qquad \text{(Equation 10)}$$

Net present value can be used to assess an investment's long-term economic profitability, accounting for the time value of money by discounting future cash flows at a specified discount rate. We calculated the NPV for all farms over a 10-year period as:

$$NPV = T,\ t = 0 \sum((\pi_{farm}/(1+\ \delta)^t) \qquad \text{(Equation 11)}$$

where δ is the discount rate, which we set as the average value for an industrial aquaculture farm in Brazil (15%)[18].

Sensitivity Analyses

The use of an average price for Cobia on the Brazilian market is a large assumption in our model, as market dynamics in this rapidly developing industry are difficult to predict. Therefore, we evaluated the sensitivity of our economic results by varying cobia prices between US$7.00 to $12.00 per kg of fish, which is a reasonable range according to local experts[19] (Appendix IV).

Previous studies have used an exceedingly higher density of farms per unit area to estimate potential for offshore aquaculture on a global and country level scale[17,20,21] . However, we performed our analysis using a farm density of 1 farm per cell. We generated 3 different scenarios, varying the density of farms per cell. Our group examined farm densities of 12 farms per cell (~0.1 farm/km^2), 60 farms per cell (~0.5 farm/km^2) and 120 farms per cell (~1 farm/km^2) (Appendix IV).

Lastly, the cost of feed typically represents the main component of aquaculture operating costs. As demand for farmed fish increases rapidly, we expect the demand for high-quality feeds to also increase, increasing feed prices[23]. Thus we additionally performed a sensitivity analysis by altering feed price[18,22,17].

TOOL DEVELOPMENT

We built an interactive web application that can guide planning efforts for aquaculture development. First, we defined input and output parameters for the app. Then, we integrated these parameters to our three suitability models (site suitability, productivity, and profitability). Finally, we published the tool using shiny-io server and created a user guide. The interface of the app was created with Shiny using R version 3.6.1.

Inputs

All the constraints used in the site suitability analysis were transformed into inputs that can be modified by the app users, as well as the life history parameters in the productivity assessment, and the costs in the profitability assessment. The app will run all the suitability models based on the inputs provided by the user.

Outputs

The main outputs created by the app are three maps, one for each model. The site suitability map shows parcels identified as suitable for aquaculture, the productivity map shows biomass (MT/cell), and the profitability map shows profits (USD/cell). All maps can be downloaded in TIFF grid format for further analysis. Two additional outputs are a total suitable area chart and percentage exclusion chart.

RESULTS

SITE SUITABILITY

When factoring in spatial and infrastructural constraints, we determined 9,380 km^2 availability for offshore marine aquaculture. The northernmost parcel was located at 50°45′30″W,3°50′39″N, while the parcel located at 37°47′08″W,12°30′14″S limited the southern bounds of the total suitable area. Above 98% of suitable parcels were located in the Northeast region of Brazil, one of the five political regions of the country (*Figure 1*). The fixed and variable spatial barriers collectively excluded 99.75% of Brazil's EEZ. The largest factor limiting site suitability was depth, which limits the anchoring feasibility of offshore marine net pens. A factor that did not limit site suitability was maximum current velocity. When utilizing the model species cobia to test the availability sites within the bounds of biological thresholds, the total area available for mariculture development did not differ. Out of the three biological limitations considered for cobia, minimum sea surface temperature was found to be the most constraining factor, while dissolved oxygen and maximum sea surface temperature did not limit site suitability. Individual contributions to EEZ exclusion are reported in Figure 4. We then analyzed the feasibility of cultivating Atlantic salmon (*Salmo salar*) off the coast of Brazil and found it was not possible at any location due to Atlantic salmon's temperature requirements.

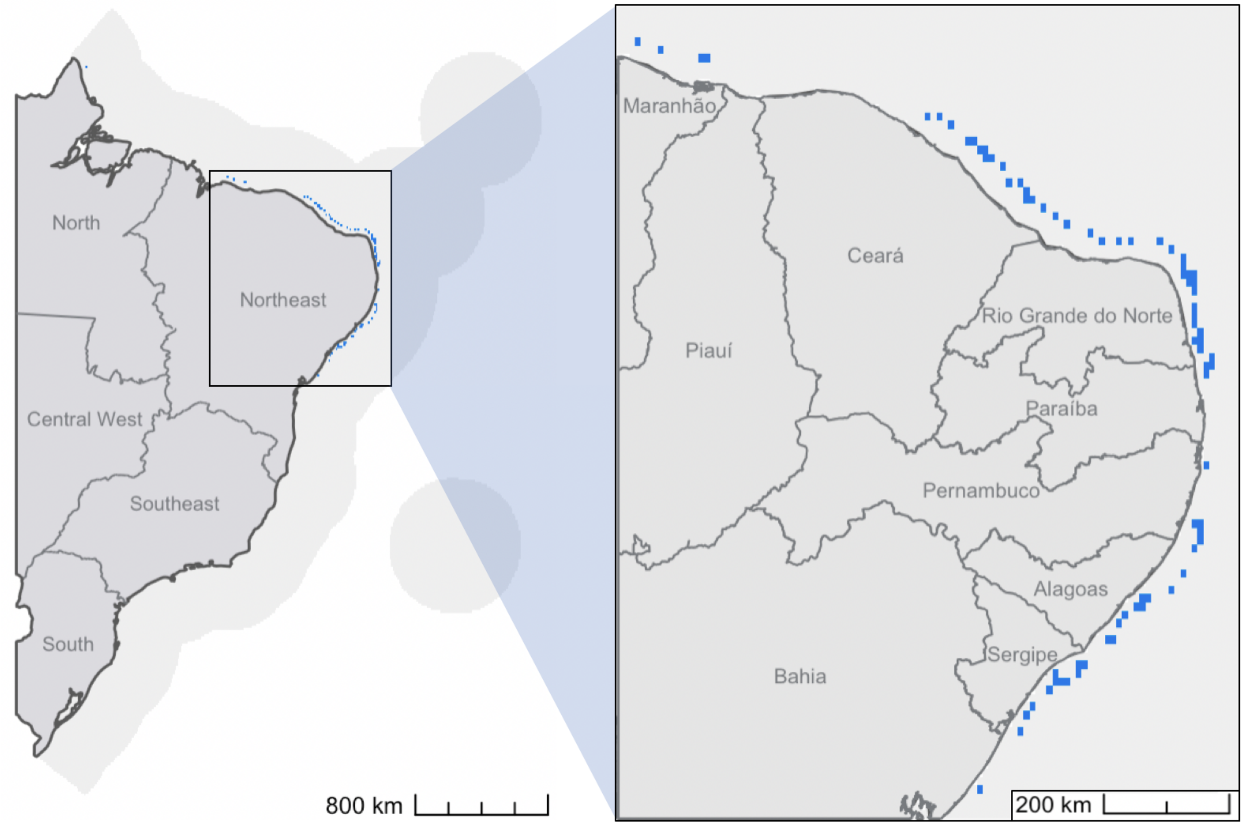

Figure 3. Suitable sites for offshore aquaculture development in Brazil. *Blue areas depict the location of available sites. Zoomed-in area for suitable parcels located in the Northeast political region of Brazil is indicated by a black rectangle. Coastal light grey represents the marine area encompassed in Brazil's EEZ.*

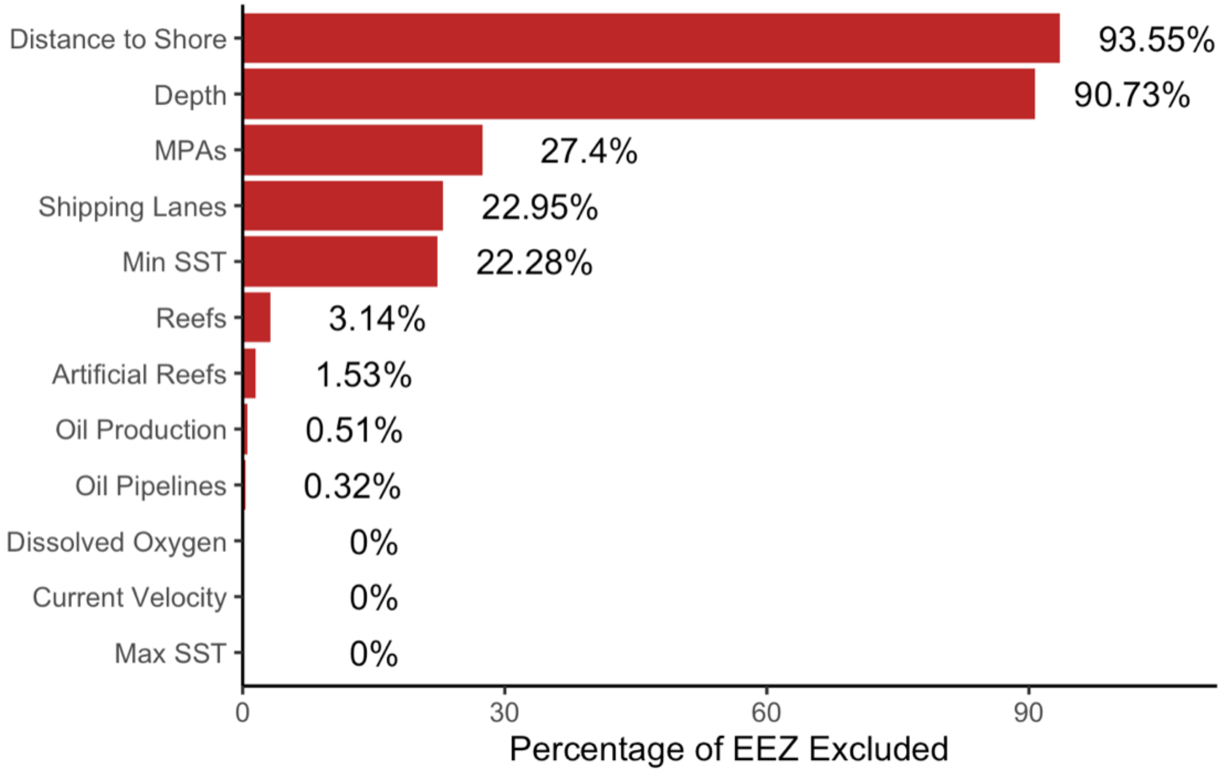

***Figure 4. Percentage of Brazil's EEZ excluded by each constraining factor**. Percentages represent the individual contribution of each constraint to eliminating the available area of the EEZ.*

PRODUCTIVITY

Projected site biomass production of Cobia ranged from 1,100 MT/cell to 1,400 MT/cell when the initial stocking density was 3 fish/m^3 and the number of cages per cell was 16. The most productive cells were located in the northern extent of the suitable sites, where temperatures were closest to Cobia's optimal growth temperature (*Figure 3*). The total productivity considering all suitable sites was approximately 94,000 tons/year.

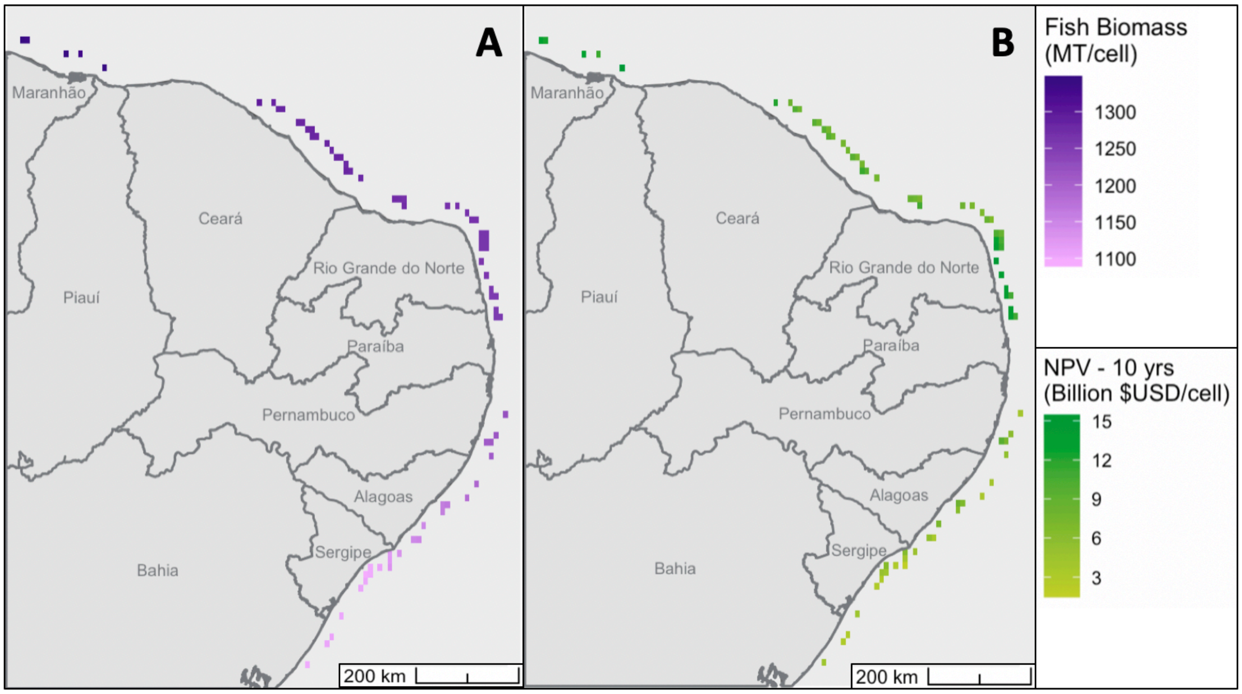

*Figure 5. **Estimated productivity and profitability in the Northeast Region.** (A) Annual estimates of Cobia biomass production in calls identified at suitable. (B) Net Present Value (NPV) calculated over a 10-year period for Cobia aquaculture in suitable cells.*

PROFITABILITY

Brazil's potential to produce cobia from offshore mariculture was approximated at a total of 94,000 metric tons of annual production from suitable sites. The average cobia farm yielded an annual biomass of 1,235,633 kg. Farm profitability varied based on two main factors: sea surface temperature and distance to shore. In our model, cobia growth solely relied on temperature, and therefore, growth rates varied across Brazil's EEZ according to water temperature, with the most productive farms located in the regions of Brazil where the water temperature is closer to cobia's optimal temperature (T_0). Since revenue is a direct function of biomass produced in the farm, farms that presented the highest revenues also produced the highest annual yield. Similarly, farms located further away from shore, presented lower profits when compared to farms closer to shore, holding all other parameters constant and accounting for labor and vessel expenses.

The southeast and south portions of Brazil's EEZ were not within the suitable temperature range of Cobia and thus showed no profitability for cobia production (*Figure 1*). We utilized a fixed feed-conversion ratio (FCR) of 3.0 for the entire study region, which is a conservative estimate based on our findings on literature[24]. Our results demonstrated that feed comprises a substantial portion of farm annual costs, accounting for an average of 90.9% of all operational costs.

Tool Outcomes

To improve sharing, reproducibility, and sensitivity of results, we developed an interactive web-based aquaculture planning tool. The tool utilizes site suitability, productivity, and profitability metrics to identify the available, productive, and most profitable parcels of EEZ for a particular species of interest.

Link: https://maricultura-gp.shinyapps.io/maricultura-app/

DISCUSSION

Overall, we found a biologically and economically compelling conceptual basis for advancing offshore finfish mariculture in Brazil. Until now, the possibility of offshore mariculture in Brazil has been largely unexplored. We hope our analysis will help to lay the foundation for developing the nascent, but growing, mariculture industry in this country. We found that there is an abundance of sites available for mariculture development within 25 nautical miles. While the overall suitable site area generated is a small fraction of Brazil's EEZ, the space is actually expansive, approximately 7 times larger than Los Angeles county in the United States. Furthermore, we not only identified how much marine space is suitable for the implementation of marine farms, but we know which specific parcels of marine space can be utilized. When deciding which cells might be the most desirable to target, aquaculture entrepreneurs and conservation organizations like the World Wildlife Fund will be able to utilize the productivity and profitability outcomes of our analyses. Understanding which areas have the highest potential profit might make an otherwise risky financial investment more reasonable and feasible in Brazil.

Despite the headway our project has made in terms of reducing the barriers to offshore aquaculture in Brazil, our analysis does not come without its limitations and assumptions. On one hand, it is important to acknowledge that the magnitude of suitable area we generated is conservative, due to our choice in a conservative projection; cell resolution for our analysis was large at about 123.42 km^2, and only accounted for 1 farm per cell. Additionally, the criteria utilized for suitability was a binary approach; therefore, if a barrier, such as a shipping lane, passed through even 1 km^2 of a cell, the parcel was considered unsuitable for mariculture development. In reality it would be possible to place a single 16-cage farm within a parcel of these dimensions if it contained a shipping lane passing through a corner of it. Our tool accounted for these assumptions by enabling the user to determine which fixed barriers they would like to exclude. For example, the tool omits shipping lanes as a barrier to mariculture development if the user unclicks this option. We also applied uniform fingerling costs instead of tapering these for larger quantities purchased. While this method holds constant with prior studies assessing the aquaculture potential of cobia[17], it may have inflated our costs. Finally, ground transportation costs were not considered for this analysis. Our economic model considered farm distances to shore but a more accurate estimate would require calculations of distances to port, since cobia are often distributed and sold at ports. There are 108 ports in Brazil, 20 of which are major ports in the country[26].

Brazil must also overcome certain internal limitations to develop offshore cobia mariculture. The biggest limitation we found was domestic feed availability. Presently, only one facility in Brazil produces cobia feed, and this operation sells feed exclusively by the batch[19]. Regardless of farm size, a prospective aquaculture entrepreneur would be required to purchase a certain quantity of feed from this producer, or import it, both costly approaches. Another consideration is fingerling availability and hatchery location. While cobia is an ideal species for production in Brazil, with fingerlings produced domestically, the costs we devised for fingerlings did not include transportation from hatchery to farm locations. Maybe the largest limitation is the assumption that large scale offshore aquaculture will have a market in Brazil. The average Brazilian consumes only 10 kg of seafood per year [25], while the global per capita consumption of seafood reached 20.3 kg in 2016[9]. Additionally, If we only consider the consumption of fish produced in land based aquaculture, Brazil's per capita average drops to 3 kg per year[25]. Due to the smaller than average amount of fish people eat per capita, and the lack of market for cobia, it is possible to flood the market easily with large scale production. Due to salmon being the most abundantly imported species into Brazil, and salmon not being able to be produced off the coast of Brazil, imports are likely to not decrease much even if offshore mariculture development were to increase. Brazil must establish local fish markets to ensure that offshore mariculture is profitable.

A challenge in planning for aquaculture development is that one strategy does not fit all situations. Our tool addresses this challenge by allowing for the consideration of various scenarios. For instance, it can be used to simulate scenarios with different farmed species and cage specifications. In addition, strategic planning needs to be adaptive to be able to survive changing conditions. Our tool makes it possible to explore how varying different parameters affects the overall suitability of a location. For example, it can estimate how changes in the market price of a species can affect the profitability of farming it. Our tool was designed to be easily adaptable to other regions and to include additional input parameters. The code used to build the tool is open source and can be used as a starting point for the creation of new tools that expand upon our analysis to include other locations. This can contribute to overall development and planning efforts of the nascent offshore aquaculture industry in many coastal countries.

Our project not only decreased some of the major challenges to development to offshore aquaculture by estimating where it should be done, but also has signifcant implications for global cultured fish availability within the seafood market. The information we discovered effectively decreases barriers to entry for offshore mariculture in Brazil, and can reduce barriers for other countries if the marine spatial planning tool is adapted by users across the globe.

APPENDIX

I. Assumptions/Rationale for Physical/Infrastructural Constraints

Distance to Shore	Mariculture development is not economically feasible at distances greater than 25 nautical miles from shore. Beyond this distance, travel time and transportation costs become overly expensive.
Depth	The manufacturer specifications for cages designed for offshore aquaculture restrict the depth at which they can be used. For this study, we used the depth threshold for the most widely used cages, the SeaStation fish pens.
Sea Surface Temperature (SST)	Sea Surface Temperature is critical for understanding which species can be cultured within a given parcel, as well as where they can be most efficiently produced. For this study, the average (2002-2009) temperature of the topmost meter of the water column was obtained.
Dissolved Oxygen (DO)	Dissolved Oxygen is also an important consideration for where species can be cultureds critical for understanding which species can be cultured within a given parcel. For this study, the long term (2000-2014) minimum mole concentration of dissolved molecular oxygen in sea water at the surface was obtained from Bio-Oracle, a database of geophysical, biotic, and environmental GIS layers.
Maximum Current Velocity	It is crucial to understand if a moored cage can withstand heavy ocean currents. The maximum sea water velocity at the surface from the years (2000-2014) was used.
Marine Protected Areas	Protected areas in Brazil have varying degrees of protection and may allow economic activities. Although regulated fishing activities are allowed in some MPAs, for the purpose of this study, we excluded all MPAs.
Reefs and Artificial Reefs	Following Henriques et al., we excluded reefs and artificial reefs because of their great ecological importance. Coral reefs support a variety of marine species comparable in number to species supported by tropical rainforests. Coral reefs are currently suffering from habitat loss from human pressure.
Oil Pipelines and Oil Production	Over half of the global oil production comes from the oceans[26], making oil infrastructure an important conflicting use of marine space. Areas where infrastructure is placed are likely to experience heavy marine traffic, making them less compatible with aquaculture activities

II. Parameters for Productivity Analysis

Species	a	b	Optimal °C
Cobia	0.8568	-18.86	29

III. Parameters for Economic Analysis

Parameter	Cost Section	Description	Value	Source
C_v	--	Cage volume	6,400 m^3	SeaStation
F_v	--	Farm volume	102,400 m^3	Calculated in study
N_c	$C_{capital}$	Number of cages per farm	16	Thomas et al, 2019
Cc	$C_{capital}$	Cost per SeaStation cage and moorings	US$ 321,000	Lipton and Kim, 2007
C_{vessel}	$C_{capital}$	Cost of vessel	US$420,376.8	Scaled from Bezerra et al. 2016
Bl	$C_{capital}$	Base labor installation cost per farm	US$139,555	Scaled from Bezerra et al. 2016
Fl	$C_{capital}$	Farm lease	US$8,668.4	Scaled from Bezerra et al. 2016
Ss	$C_{capital}$	Signaling system	US$28,021.4	Scaled from Bezerra et al. 2016
Pd	$C_{capital}$	Project development	US$53,403.7	Scaled from Bezerra et al. 2016
Misc	$C_{capital}$	Miscellaneous	US$123,685.5	Scaled from Bezerra et al. 2016
P_{fing}	$C_{capital}$	Fingerling price	US$1,50	personal communication with industry
P_{feed}	$C_{capital}$	Feed price	US$2,10	personal communication with industry
TW_{number}	C_{labor}	Total number of full-time employees	40	Thomas et al, 2019 and Bezerra et al
OW_{number}	C_{labor}	Number of full-time offshore workers	35	Thomas et al, 2019

Parameter	Cost Section	Description	Value	Source
SW_{number}	C_{labor}	Number of full-time onshore workers	5	Thomas et al, 2019
W_{wages}	C_{labor}	Hourly wage of farm workers	US$4,50	Scaled from Bezerra et al. 2016
W_{weekly}	C_{labor}	Hour worked per week	40 hours	
W_{hours}	C_{labor}	Hours worked annually for 1 full-time employee	2,080 hours	
S_{labor}	C_{labor}	Cost of labor for onshore-only employees	Variable	Calculated in study
O_{labor}	C_{labor}	Cost of labor for offshore-only employees	Variable	Calculated in study
Ep	$C_{operations}$	Electric power	US$3,661.3	Scaled from Bezerra et al. 2016
Mm	$C_{operations}$	Mooring maintenance	US$53,191.3	Scaled from Bezerra et al. 2016
Dm	$C_{operations}$	Diving maintenance	US$8,427.1	Scaled from Bezerra et al. 2016
Or	$C_{operations}$	Office rent	US$36,626.4	Scaled from Bezerra et al. 2016
Em	$C_{operations}$	Environmental monitoring	US$45,781	Scaled from Bezerra et al. 2016
Bm	$C_{operations}$	Boat maintenance	US$30,000	Costello et al, 2020
Vd	$C_{operations}$	Vessel dockage	US$20,000	Costello et al, 2020
I	$C_{operations}$	Insurance	US$50,000	Costello et al, 2020
N_{boats}	C_{fuel}	Number of boats	2	Bezerra et al. 2016 and Thomas et al, 2019

Parameter	Cost Section	Description	Value	Source
V_{speed}	C_{fuel}	Average Vessel Speed	15 km/h	Costello et al, 2020
F_{price}	C_{fuel}	Fuel price	US$0.92/L	Global Petrol Prices, January 2020
D_{shore}	C_{fuel}	Farm distance from shore	variable	Calculated in study
P_{fish}	R_{total}	Cobia price	variable	personal communication with industry
δ	NPV	Discount rate	15%	Bezerra et al. 2016
$C_{capital}$	--	One-time capital cost		Calculated in study
$C_{operations}$	--	Annual operation cost		Calculated in study
C_{fuel}	--	Annual cost of fuel	Variable	Calculated in study
C_{labor}	--	Annual cost of labor	Variable	Calculated in study
R_{total}	--	Total revenue	Variable	Calculated in study
C_{total}	--	Total farm costs	Variable	Calculated in study
π_{farm}	--	Total farm profit	Variable	Calculated in study
NPV	--	Net Present Value	Variable	Calculated in study

IV. Sensitivity Analysis

A. Fluctuation of Price (P_{fish})

Price ($USD/kg)	Minimum NPV (Billion $USD)	Mean NPV (Billion $USD)	Maximum NPV (Billion $USD)
$7.00	-49.17	-45.19	-40.36
$8.60	1.79	8.58	16.93
$10.00	44.77	55.63	70.30
$12.00	105.22	122.83	146.54

B. Fluctuation of Number of Farms per Cell (Nf per cell)

Density of Farms (# farms/cell)	Minimum NPV (Billion $USD)	Mean NPV (Billion $USD)	Maximum NPV ($USD)
1	1.79	8.58	16.93
12	322.87	423.35	546.01
60	1,710.28	2,233.28	2,854.71
120	3,444.55	4,495.68	5,740.60

C. Fluctuation of Feed Price (P_{feed})

Price ($USD/kg)	Minimum NPV (Billion $USD)	Mean NPV (Billion $USD)	Maximum NPV (Billion $USD)
$2.10	1.79	8.58	16.93
$2.52	-37.85	-33.76	-28.70

References

1. *The World Population Prospects: 2015 Revision*. (United Nations, 2015).
2. Tilman, D. & Clark, M. Global diets link environmental sustainability and human health. *Nature* **515,** 518–522 (2014).
3. Tacon, A. G. J. & Metian, M. Fish Matters: Importance of Aquatic Foods in Human Nutrition and Global Food Supply. *Reviews in Fisheries Science* **21,** 22–38 (2013).
4. Costello, C. *et al.* Global fishery prospects under contrasting management regimes. *Proc Natl Acad Sci USA* **113,** 5125–5129 (2016).
5. Campbell, B. & Pauly, D. Mariculture: A global analysis of production trends since 1950. *Marine Policy* **39,** 94–100 (2013).
6. Gentry, R. R. *et al.* Exploring the potential for marine aquaculture to contribute to ecosystem services. *Rev. Aquacult.* (2019). doi:10.1111/raq.12328
7. Clavelle, T., Lester, S. E., Gentry, R. & Froehlich, H. E. Interactions and management for the future of marine aquaculture and capture fisheries. *Fish Fish.* (2019). doi:10.1111/faf.12351
8. Merino, G. *et al.* Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate? *Global Environmental Change* **22,** 795–806 (2012).
9. FAO. *The State of World Fisheries and Aquaculture 2018 - Meeting the sustainable development goals*. 210 (Food and Agriculture Organization of the United Nations, 2018).
10. Holmer, M. Environmental issues of fish farming in offshore waters: perspectives, concerns and research needs. *Aquac. Environ. Interact.* **1,** 57–70 (2010).
11. Liu, O. R., Molina, R., Wilson, M. & Halpern, B. S. Global opportunities for mariculture development to promote human nutrition. *PeerJ* **6,** e4733 (2018).
12. Suplicy, F. M. *et al.* Planning and management for sustainable coastal aquaculture development in Santa Catarina State, south Brazil. *Rev. Aquacult.* **9,** 107–124 (2017).
13. PeixeBR. 2018 Anuário PeixeBR da Piscicultura 2018. (2018).
14. Tyberghein, L. *et al.* Bio-ORACLE: a global environmental dataset for marine species distribution modelling. *Global Ecology and Biogeography* **21,** 272–281 (2012).
15. Kerber, C. Personal Interview (Redemar Alevinos). (2020). at <http://buscatextual.cnpq.br/buscatextual/visualizacv.do?id=K4321618J6>
16. Benetti, D. D. *et al.* Growth rates of cobia (Rachycentron canadum) cultured in open ocean submerged cages in the Caribbean. *Aquaculture* **302,** 195–201 (2010).
17. Thomas, L. R., Clavelle, T., Klinger, D. H. & Lester, S. E. The ecological and economic potential for offshore mariculture in the Caribbean. *Nat. Sustain.* **2,** 62–70 (2019).

18. de Bezerra, T. R. Q. *et al*. Economic analysis of cobia (Rachycentron canadum) cage culture in large- and small-scale production systems in Brazil. *Aquacult. Int.* **24,** 609–622 (2016).
19. Gentry, R. R. *et al*. Mapping the global potential for marine aquaculture. *Nat. Ecol. Evol.* **1,** 1317–1324 (2017).
20. Costello, C., Cao, L. & Gelcich, S. *The Future of Food from the Sea*. (World Resources Institute, 2020).
21. Huang, C.-T., Miao, S., Nan, F.-H. & Jung, S.-M. Study on regional production and economy of cobia Rachycentron canadum commercial cage culture. *Aquacult. Int.* **19,** 649–664 (2011).
22. Pelletier, N., Klinger, D. H., Sims, N. A., Yoshioka, J.-R. & Kittinger, J. N. Nutritional Attributes, Substitutability, Scalability, and Environmental Intensity of an Illustrative Subset of Current and Future Protein Sources for Aquaculture Feeds: Joint Consideration of Potential Synergies and Trade-offs. *Environ. Sci. Technol.* **52,** 5532–5544 (2018).
23. Sun, L. & Chen, H. Effects of water temperature and fish size on growth and bioenergetics of cobia (Rachycentron canadum). *Aquaculture* **426–427,** 172–180 (2014).
24. ANTAQ. *Anuário Estatístico 2019 - ANTAQ*. (Agencia Nacional de Transportes Aquaviarios, 2019).
25. Medeiros, F. *Anuario 2020 Peixe BR da Piscicultura*. 48–52 (Texto Comunicação Corporativa, 2020).
26. US Energy Infomation Administration. Offshore production nearly 30% of global crude oil output in 2015 - Today in Energy - U.S. Energy Information Administration (EIA). (2016). at <https://www.eia.gov/todayinenergy/detail.php?id=28492>