Charting an Aquaculture Future for the Caribbean

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# Abstract

The development of marine aquaculture in the Caribbean has been identified as an avenue to stimulate local economies, increase employment opportunities, and improve seafood supply and food security. However, when located close to shore, aquaculture’s environmental impacts can jeopardize valuable habitats (e.g., mangroves, coral reefs, seagrass beds) and competition for coastal space can lead to conflicts with fisheries, tourism, and other uses. Farming further offshore is a possible option for alleviating these stresses. Using high-resolution environmental and economic data, we develop a spatial bio-economic model to identify suitable areas throughout the Caribbean for offshore finfish aquaculture, parameterized based on cobia (*Rachycentron canadum*), and to estimate potential outcomes in terms of yields and profits under different market scenarios. We find that Caribbean nations contain XXXX hectares of marine space technically feasible and profitable for cobia aquaculture. Accounting for spatial differences in cobia growth and production costs, we estimate the offshore cobia aquaculture production potential of the Caribbean to be XXX (MT). Areas associated with the highest relative economic potential were X, X, and X. Offshore aquaculture is a capital intensive activity mediated by socioeconomic conditions, such as foreign investment risk and XX, which were found to be factors limiting production in our analysis. The results of this research can be used to help prioritize areas for offshore cobia aquaculture development and as a framework for identifying priority areas for offshore aquaculture of other species. Additionally, we discuss the future potential of the development of offshore aquaculture in the Caribbean.

# Introduction

The global fish **supply** is expected to exceed 151 million tons by 2030 to meet growing demands, a 10% increase over current levels (Kobayashi et al. 2015; FAO 2016), and the vast majority of new production must come from aquaculture given only modest potential increases from capture fisheries (Costello et al. 2016). Aquaculture seems poised to meet this challenge as the fastest growing food production sector globally, surpassing wild fisheries production for the first time in 2014 (FAO 2016). Marine aquaculture, or mariculture, is seen as having particularly strong growth potential (Merino et al. 2012). And as mariculture technology advances, production from offshore mariculture, generally defined as occurring more than three nautical miles offshore and/or in depths of greater than 30 m (Froehlich et al. 2017), is expected to increase (FAO 2016). By moving to deeper waters further from the coast, offshore aquaculture could be a viable strategy to minimize aquaculture's adverse environmental and socioeconomic consequences (Holmer 2009; **???**), and production potential in the offshore realm far exceeds seafood demand for the foreseeable future [Kapetsky, Aguilar-Manjarrez, and Jenness (2013);Gentry, Froehlich, et al. (2017)). Despite strong arguments for offshore aquaculture development, how this growth can and should be realized requires an understanding of the sustainable and economically-viable production potential at the regional level, along with an identification of hurdles impeding development.

In recent years, there has been a growing interest in aquaculture development in the Caribbean to increase food security and economic development (Van Wyk and Davis 2006; Creswell 5AD–2007; **???**; Pérez-Ramírez 2017). Currently, the Caribbean accounts for < 0.1 % of global aquaculture production, and over 88% of seafood consumed in the region is from wild capture fisheries (FAO 2016). To meet seafood demand in the region, over 144,000 mt of seafood valued at XX $USD is imported annually (FAO 2016). Furthermore, seafood consumption per capita in the Caribbean is projected to increase rapidly (22%) over the next decade (FAO 2016). Wild fisheries production in the region is unlikely to play a meaningful role in decreasing exports and/or meeting growth in demand because of overfishing, degradation of coral ecosystems, and climate change (Burke et al. 2011; Pérez-Ramírez 2017). Aquaculture development could be an opportunity for Caribbean countries to diversify their economic activities, reduce reliance on foreign imports, provide jobs and economic security to local residents (**FAO 2002**), and to promote a seafood industry that is more resilient to the effects of climate change (Pérez-Ramírez 2017).

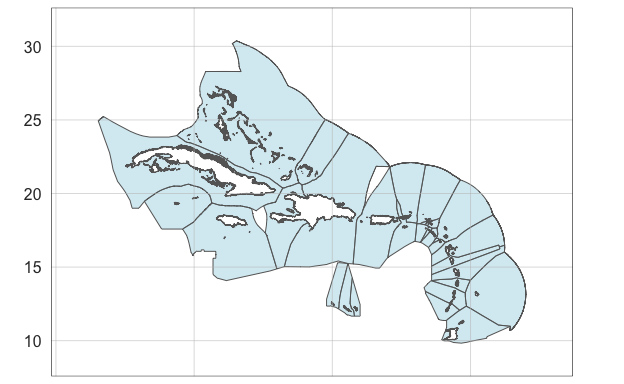
Most aquaculture efforts in the Caribbean have been directed towards land-based aquaculture of tilapia (*Oreochromis sp.*) and coastal pond aquaculture of white-legged shrimp (*Litopenaeus vannamei*) [Lovatelli et al. (2013)). However, the potential for increased production of land-based aquaculture in the Caribbean is extremely limited due to the requirements of land space, freshwater, and energy resources (**???**). Similarly, expanded development of coastal aquaculture in the region is likely not sustainable and difficult due to conflicts over space in highly utilized and ecologically sensitive coastal areas (Gentry, Lester, et al. 2017). For example, coastal aquaculture can harm mangroves and coral reefs by increasing nutrient loads and causing physical damage to the habitat from farm infrastructure (Benetti et al. 2006; Gentry, Lester, et al. 2017), with cascading effects on marine-based tourism, the backbone of many Caribbean island economies (**???**). Offshore aquaculture could be a promising alternative (D. D. Benetti, Benetti, et al. 2010; Gentry, Froehlich, et al. 2017), and recently developed submersible cages will allow aquaculture to be developed in areas that were previously considered unsuitable due to waves, depth and/or high risk of damage from large storms and hurricanes (D. D. Benetti, Benetti, et al. (2010)). Environmental conditions in the Caribbean such as relatively small seasonal fluctuations in ocean temperature and a stable water column provide ideal conditions for the offshore culture of a number of species (REF). Small-scale trials raising cobia (*Rachycentron canadum*), pompano (*Carangidae sp*), and red drum (*Sciaenops ocellatus*) in offshore environments were successful in the Bahamas and Puerto Rico (Benetti et al. 2010). Cobia in particular has been identified as an ideal candidate species for aquaculture in tropical and subtropical regions because of its relatively fast growth rates, high market value, and tolerance for variations in salinity and temperature (**???**; D. D. Benetti, O’Hanlon, et al. 2010; Estrada et al. 2016). The largest open ocean mariculture farm in the world, Open Blue, has been successfully culturing cobia off the Caribbean coast of Panama since xxxx.

Critical knowledge gaps that hinder the development of offshore aquaculture in the Caribbean include: 1) the bioeconomic production capacity of the region (CRFM 2015), 2) how that potential varies across EEZs, and 3) what factors are currently most likely to be limiting development (e.g., biophysical conditions, regulatory environment, capital investment, expertise, etc.). Using high resolution spatial data, we develop a bioeconomic model to estimate the total production potential (in terms of weight and revenue) of offshore cobia aquaculture in the Caribbean. We examine the spatial distribution of offshore aquaculture potential to identify ‘hotspot’ locations for future development. We examine the variation of individual farm profitability between and across EEZs to determine the importance of site selection in aquaculture development and to quantify the potential benefits of strategic spatial planning. We explore these results under several scenarios of cobia production using a supply and demand curve to set cobia market price. Our approach could be applied to other farmed species or applied to other regions, and our results can help to chart a course for a sustainable and economically prosperous offshore mariculture industry in the Caribbean.

# Methods

## Description of Study Region

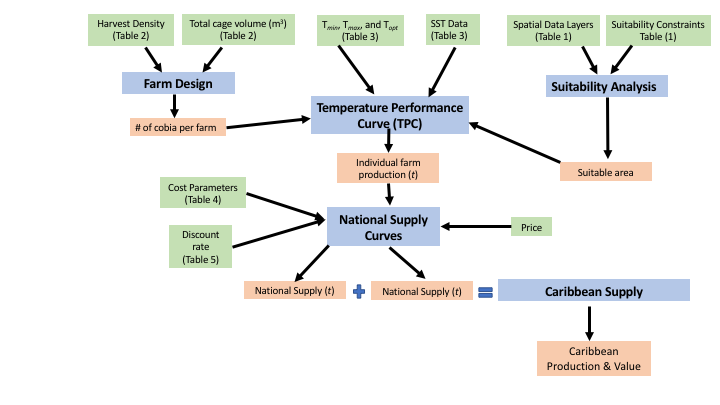
Our study domain includes the territorial waters and Exclusive Economic Zones (EEZs) surrounding the 28 island countries that comprise the Greater and Lesser Antilles of the Caribbean Sea (Figure 1). All analyses are performed at a 1 km2 spatial resolution. We do not consider the potential of offshore aquaculture development in the high seas or disputed waters. A shapefile from VLIZ (2014) is used to define the maritime boundaries for all island countries.



The study area for this project is indicated in blue. EEZ boundary data were obtained from VLIZ (2016).

## Overview

We develop a spatial bioeconomic model to estimate the production potential (in terms of biomass (*t*) and Net Present Value (NPV)) for offshore cobia mariculture in the Caribbean region (Figure 1). The first steps of our analysis are to identify 1 km2 sites throughout the study region that would be suitable for mariculture development and create a hypothetical farm design to apply to all suitable sites. Next, we apply a temperature performance curve (TPC) to predict temperature-dependent growth of cobia at each farm and we establish supply curves to determine national and Caribbean-wide cobia production that would be achieved under several scenarios of cobia price and production costs. We also consider a scenario where Caribbean production affects the global price of cobia. Finally, we use our production model and estimated economic parameters to calculate Net Present Value (*NPV*) over a 10 year time horizon. We assume that only farms that have a positive NPV will be developed.



Model schematic for estimating cobia aquaculture production potential. Green squares indicate model inputs, blue squares indicate model components, and orange squares indicate model outputs.

## Suitability Assessment

The first step in our analysis identifies areas that are potentially suitable for the development of offshore mariculture. To determine what areas are suitable, we consider six factors: depth, current speed, coral reef presence, shipping activity, oil structures, and areas designated for conservation (Table 1).

Description of spatial data layers and criteria used to identify cells suitable for development of offshore aquaculture in the Caribbean

|  |  |  |  |
| --- | --- | --- | --- |
| Layer | Year | Criteria | Source |
| Marine Protected Areas | 2016 | Not an established, designated or proposed Marine Protected Area | IUCN and UNEP-WCMC 2016 |
| Oil Rigs | 2003 | No existing benthic oil structures | Halpern et al. 2008 |
| Shipping | 2005 | Not included in the top 10% of relative shipping activity in the Caribbean | Halpern et al. 2008 |
| Coral Reefs | 2010 | No coral reefs are present in the 1 km2 area | UNEP-WCMC, WorldFish Centre,¾WRI,¾TNC¾2010 |
| Depth | 2009 | Depths >=25 and < = 100 | Kapetsky et al. 2013 |
| Current Velocity | 2005-2015 | Maximum average monthly zonal or meridional current velocity < 1 | ESR 2009 |
| Deep sea bed mining claims | 2016 | No mining claim or contract present | deepseaminingwatch.ms.ucsb.edu |

Our suitability assessment assumes the use of SeaStation cages, which are submersible, self-tensioned, single rim cages and are the most widely used offshore aquaculture cages in the U.S. [Loverich (2010); Open Blue 2016]. The minimum site depth for installation of a SeaStation cage, listed by the original manufacturer, is 25 m (OceanSpar 2013). The maximum suitable depth for cage installation for this analysis is set at 100 m because, in waters deeper than 100 m, cage installation and inspection of mooring and anchoring systems are more difficult and costly (**???**; Kapetsky, Aguilar-Manjarrez, and Jenness 2013). Using spatial bathymetry data for our study region, areas within a 25 - 100 m depth are scored as suitable for offshore mariculture development. Additionally, SeaStation cages are not recommended in areas with current velocities over 1 m/s (Loverich 2010). To identify areas with unsuitably high current velocities, we use 10 years (2005-2015) of 5 day average zonal and meridional current velocity. The absolute maximum zonal and meridional average daily velocities that occurred over the 10-year time period are extracted for each cell, and any cell with a maximum zonal or meridional velocity greater than 1 m/s are scored as unsuitable. To minimize the ecological impact of offshore mariculture development, we also identify as unsustainable any cells with coral reef habitat.

To identify areas currently designated or utilized for purposes that would preclude offshore mariculture development, we use spatial data on: shipping activity, existing benthic oil structures, areas permitted for deep sea bed mining, and areas that have been designated as Marine Protected Areas (MPAs) or conservation priority areas (Table 1). Areas that fell in the 10% of the highest relative shipping activity areas designated for conservation or deep sea bed mining purposes, and areas with existing benthic oil structures, are considered unsuitable for offshore mariculture development.

All spatial data layers listed in Table 1 are converted to raster format with a 1 km2 spatial resolution. Data files that had a resolution > 1 km2 are interpolated to the 1 km2 grid using 'nearest neighbor technique' in R's [raster](https://cran.r-project.org/web/packages/raster/index.html) package. All 1 km2 cells from each layer that fell outside of the suitable threshold are given a score of zero and cells falling within the threshold are given a score of 1. We then overlay all data layers and multiply the values of all layers in each cell. This result is a final single data layer, where cells suitable for offshore aquaculture development based on all criteria listed in Table 1 have a score of 1, and unsuitable cells a value of 0.

## Growth Potential

Temperature is one of the primary abiotic factors controlling growth in ecotherms, including cobia (Brett 1979), and is a factor that cannot be easily controlled in offshore mariculture grow-out settings (Tidwell 2012). To reflect spatial differences in productivity across farms attributed to temperature variations, we use 10 years of remotely-sensed sea surface temperature (SST) data (NASA 2014) to calculate 1 km2 resolution spatial data layers of average monthly SST. We then use a thermal performance curve (TPC) to model temperature dependent individual somatic growth (, kg per month) of cobia for each farm site (Klinger, Levin, & Watson 2017).

### Thermal Performance Curve

The TPC is a temperature-dependent piecewise linear function defined as follows:

where is sea surface temperature in C, is the optimal temperature for cobia growth in C, and and are slope parameters (kg per month per C), and , and are intercept parameters (kg per month). At temperatures below the minimum temperature for growth () and above the maximum temperature for growth (), is forced to 0 to reflect the absence of growth. Where is negative, . The following values and references for temperature-growth components of cobia were adopted from Klinger, Levin, and Watson (2017), who also used a TPC to model cobia growth.

Temperature-growth parameters and linear function constants for cobia

|  |  |
| --- | --- |
| Parameter | Value |
| Tmin | 22.0000 |
| Topt | 29.0000 |
| Tmax | 32.0000 |
| Monthly growth rate (grams per month) | 0.5000 |
| a1 | 0.0714 |
| a2 | -0.1667 |
| b1 | -1.5714 |
| b2 | 5.3333 |

Individual cobia growth at month for site () is estimated using the TPC for all 120 months in the SST timeseries. The 10 year () average individual growth (${G}\_{i,t} $) at site is then calculated for each calendar month :

## Bioeconomic Model

We model future offshore aquaculture potential in the Caribbean by coupling site specific estimates of average monthly cobia growth with a detailed farm design and economic model parameterized with values from the literature and technical reports.

### Farm Design

To estimate production, we assume a fixed farm design, per 1 km2 site, across our study region. SeaStation cages are typically configured using a mooring system that includes a grid, anchor, and mooring lines secured at varying distances from the cages (**???**; Xu, Zhu, and Miao 2015).We develop a hypothetical farm design for a 1 km2 cell that has 16 SeaStation cages (each 6,400 m3) configured in two eight-cell grid mooring systems that occupy a total space of approximately ~ 0.48 km2 and provide a total cage capacity of 102,400 m3 (Figure 2). The cages are held in position by the mooring system at depths of 15-20 m below the surface(Loverich 2010). This cage configuration is similar to a 0.4 km2 offshore mariculture farm located off the coast of Kona, Hawaii that has an eight-cage SeaStation array with a total cage volume of 64,000 m3 (Sims, n.d.).

The total cage volume per unit of total farm area for our hypothetical farm design falls within the range of total cage volume per unit farm area for the Kona farm (Sims, n.d.) and another offshore farm using SeaStation cages in the Gulf of Maine (Fredriksson et al. 2004); (DeCew et al. 2010). Additionally, the total space occupied by the farm's infrastructure (0.48 km2) follows the guidelines issued in NOAA's Fishery Management Plan (FMP) for offshore aquaculture development in the Gulf of Mexico that specifies the total mariculture farm area should be twice the size of the total area occupied by farm infrastructure.

Table 2: Farm design specification for hypothetical 1 square kilometer offshore cobia farms

|  |  |
| --- | --- |
| Farm Specification | Value |
| Cage volume (m3) | 6,400 |
| Number of cages | 16 |
| Harvest size (kg) | 5 |
| Harvest density (kg/m3) | 15 |
| Harvest desnity (# of individiuals per cage) | 16,000 |
| Natural mortality rate (M) |  |
| Stocking density (# of individuals per cage) |  |

### Growth Model

Individual cobia growth at month for site () is modeled using the previously calculated 10 year () average individual growth (${G}\_{i,t} $) at site for calendar month . Fingerlings are stocked at an initial weight of 15 grams and fish weight () in month at site is calculated as the cumulative growth since the stocking month ():

We apply an instantaneous mortality rate of 0.024, which we adopt from previous studies that have estimated a total 12 month survival rate of 75% for cobia raised in offshore cages in the Caribbean ((**???**); Huang 2011). A cage at site is harvested when individual fish have grown to a harvestable size of 5 - 6 kg.

#### Stocking Density

To maintain a steady supply of product, commercial mariculture farms typically stage the stocking of cages so that fish of a harvestable size are available year-round. We therefore assume that five cages at each site are stocked with cobia fingerlings during the first month, and that one (or more) cage is stocked with fingerlings each month thereafter. XX suggest as a target harvest density for sustainable offshore mariculture. Because growth rates vary across farm sites and all sites are assumed to experience an instantaneous mortality rate of 0.024, we investigate the following two scenarios of the initial number of stocked fingerlings ():

##### Fixed Stocking Density

The number of fingerlings stocked in each cage is fixed at the level that achieves the target harvest density of in 12 months. Given a cage volume of 6,400 m3, a total survival rate of 75%, and a target harvest density of , is set to 25,600.

##### Optimal Stocking Density

The number of fingerlings stocked in each cage is optimized at the level that achieves the target harvest density () at the time fish reach the final harvest weight of 5 kg, or 19,200 fish per cage.

The optimal stocking number () for each site is estimated using the historical SST timeseries. The number of hypothetical completed grow out cycles (), wherein a cobia is raised from an initial stocking weight of 0.15 g to a final harvest weight of 5 kg, is calculated for each site by first dividing the cumulative individual growth over the 120 month timeseries by the target harvest weight.

The average number of months per grow out cycle () is then calculated as . Given and the target harvest of 19,200 5 kg fish, the optimal number of fingerlings () to stock can be estimated for each site as follows:

For a farm site with a 12 month average harvest cycle (), is 25,600 and equivalent to the number of fingerlings stocked at all sites in the fixed stocking scenario.

#### Total Biomass

Total site biomass in each month () is a function of the number of stocked cages , initial stocking number , and the instantenous mortality rate (**???**).

Where is the number of stocked cages at site , is the weight of individual fish in cage in month , and is the initial number of fish stocked per cage at site .

### Economic Model

#### Costs

The total cost of production for each farm consists of start up costs () plus the sum of operating costs ()

Costs of aquaculture infrastructure and installation increase with depth and distance from shore(**???**). Start-up costs are therefore modeled to include initial capital expenditures () and installation costs (), both as a function of average site depth in meters , and EEZ-specific permit and/or lease cost :

Initial capital expenditures () include the cost of 16 SeaStation fish cages ($269,701 each) plus the cost of one 16-m-long support vessel and two 7-m-long motorboats. Installation costs include the labor costs for installation of the culture system. A 10% increase in cage and installation costs are assinged to sites with depths greater than 50 m (**???**).

Operating costs are organized in two main categories; farm labor and maintenance costs as a function of site depth and EEZ-specific hourly salary and fuel costs (), and costs associated with purchasing and feeding stocked fish .

Labor and maintenance costs () at site in month are modeled as follows:

Where 2,720 is the total monthly labor hours required at site (17 full time workers); is the EEZ-specific hourly salary; is distance from shore (in meters); 3,219 is average fuel efficiency (meters per gallon); 60 is the number of one-way trips required per month for running the farm; and is the per-gallon cost of fuel as a function of EEZ.

Fingerling and feed costs () at site in month include the cost of an individual fingerling ($2.58) times the number of fingerlings stocked in month (). Feed costs are calculated based on a constant feeding strategy of 2% of total biomass and a feed price of $1.68 per kg. Because our model operates at monthly, not daily, timesteps, we calculate total feed based on the average total biomass during month .

#### Revenues

Farms earn revenue by harvesting market weight (5 kg) cobia. Thus, farms only earn revenue in months where individual fish weight () reaches 5 kg. In these harvest months, farm revenue is simply a function of harvest weight (kg) and cobia price (), , otherwise :

Where is the total biomass of cobia at farm in month and is the global price of cobia in month . Cobia farms in the Caribbean are initially assumed to be price takers and thus production in month does not affect price in month .

Total farm profit () for farm is then simply the sum of revenues less total farm costs.

We then calculate the 10-year net present value (NPV) of farm using EEZ-specific discount rates () (Table 5):

#### Discount Rate

Individual discount rates are determined for each Caribbean country that incorporate the foreign investment risk associated with that country. We modify previously published methodologies to quantify a country’s relative investment risk in the Caribbean, where limited data on economic and political conditions are available. Bhalla (1983) developed the Foreign Investment Risk Matrix (FIRM) to assist investors in classifying the political and economic risks associated with investing in different countries using discrete risk categories. An expanded version of FIRM was developed by McGowan and Moeller (2009) that utilizes three political and three economic continuous risk variables that are readily available for most countries.

Limited data were available for the risk variables described by McGowan and Moeller (2009) for Caribbean island countries. Only three countries in our study have data available for the “conflict” variable and only nine have data available for all five of the other McGowan and Moeller risk variables. Therefore, to calculate risk scores for the island countries in our region, we identify comparable, substitute risk variables for each of McGowan and Moeller’s risk variables. We then calculate Pearson’s correlation coefficients and significance vales between McGowan and Moeller’s risk variables and our selected substitute variables using countries with data available for both sets to validate our substitute variables (Table XX). Although there are not enough data for the conflict variable in the Caribbean to calculate a correlation coefficient, we assume WRI’s political stability score to be a logical substitute.

Averages of political and economic variables are calculated by removing any variables for which data qre not available for that country. In some cases this means that the only data available to calculate a final relative risk score is GDP per capita. Bhalla (1983) states that GDP per capita is one of the most important variables determining both political and economic risk because income per capita reflects both the underlying economy and the effectiveness of political management. For the 14 countries with data available for all variables, we find GDP to be a significant (r = 0.88, *p*-value = < 0.001) predictor of the final risk score, providing further support for this approach (Figure 1).

For each variable, a country’s rating is determined by transforming the data for that variable to a scale of 1 (low risk) to 5 (high risk) and multiplying by the specified weight to determine the variable’s final score (R x W) (Table 3). Political and economic risk scores are calculated by taking the sum of final scores for all three variables, and the total risk score is calculated by multiplying the political and economic risk scores by the specified weight and summing the values (Table 3). The weights shown in Table 3 were arbitrarily chosen by McGowan and Moeller (2009). In practice, they recommend weighting variables according to relevance and importance to the particular project that is being assessed. For this analysis, all political and economic variables are given equal weight.

### Supply Curves

Using the cost function described in equation X, we construct national and Caribbean-wide supply curves for cobia by aggregating farm-level supply curves. For a given price, only farms with a positive 10-year NPV are considered feasible for development. We then calculate, for each EEZ () the harvested biomass (in metric tons), , and NPV () over a 10-year period produced by all profitable farms in an EEZ across a range of prices (X-XXX).

National supply curves are aggregated into a single Caribbean-wide supply curve to estimate total potential cobia production () and NPV () for the Caribbean over a 10-year period.

Lastly, feasible farms within each EEZ are ranked according to yield and profit (highest to lowest) and ranges for farm-scale yield and revenue were compared within and across EEZs.

## Production Scenarios

We apply our bioeconomic model to three production scenarios that consider different price structures:

1. Maximum production scenario: The global price required to make all suitable cells profitable is estimated and all suitable cells are developed
2. Current market scenario: Total production assuming current market price (insert value and reference) of cobia

For both scenarios we examine and compare the following:

* Total production (in terms of profit and weight) for the entire study (Caribbean) region (do economic constraints restrict things to below ecological limits (see below).... if its below then economic constraints will keep it below ecological capacity)
* Total production (in terms of profit and weight) for each EEZ
* Range of individual farm production within EEZs (to see potential gains of strategic spatial planning) and across EEZs (to determine the island countries with the greatest potential for offshore aquaculture development)

### Ecological Carrying Capacity

Determining the aquaculture production level that a given region (in this case, an EEZ) can sustain without resulting in negative impacts to the surrounding ecosystem and environment is difficult, and will depend on the specific local oceanographic conditions and ecosystem dynamics. Although models have been developed to simulate conditions of a local area and to generate impacts of given aquaculture production scenarios on the surrounding ecosystem (AquaModel; FARM), currently, limited empirical evidence exists to estimate the ecological carrying capacity for aquaculture production at a regional scale.

We examine the production estimates for each scenario and determine how they compare to two benchmarks we define as ecological capacity limits:

1. Existing practices capacity limit - Ecological production limit is determined by identifying the highest aquaculture per unit area of EEZ worldwide. At the scale of an entire EEZ, no EEZ currently has such extensive aquaculture to have resulted in a documented surpassing of the ecosystem’s capacity, so this could provide a useful point of reference.
2. Precautionary ecological capacity limit - Aquaculture production per unit area allowed in the Gulf of Mexico by the current NOAA Fishery Management Plan (FMP) for offshore aquaculture development in the region. The FMP regulations were designed with the intent to be precautionary in terms of avoiding detrimental impacts on the ecosystem, so this can be viewed as a conservative limit.

## Sensitivity analyses

Finally, to identify the current major hurdles to the development of offshore aquaculture in the Caribbean, we determine the main factors contributing to variability of farm and EEZ level aquaculture production by performing a suite of sensitivity analyses.

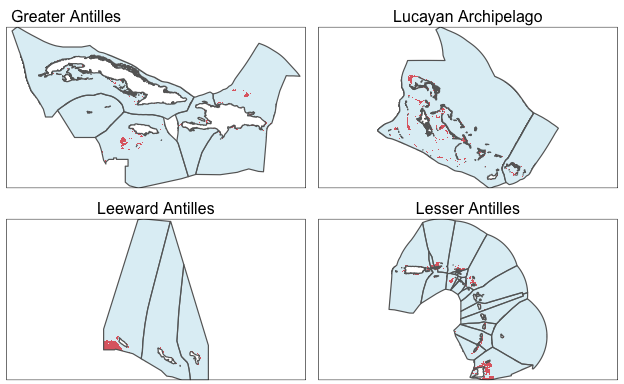
Specifically, we compare the output at both the individual farm, EEZ, and regional level by running the model under a range of values for the following parameters:

* Range of suitable depths
* Costs fingerling and feed
* Cobia price
* shift in demand curve
* Risk parameters

# Results

## Suitability Assessment

Based on the factors and criteria described in Table 1, we find a total of 50,380.6 km2, or 1.698449 % of EEZ area in the Caribbean, suitable for offshore aquaculture development (Figure 3).



The suitable area based on each of the factors considered in our analysis are listed in Table 4.

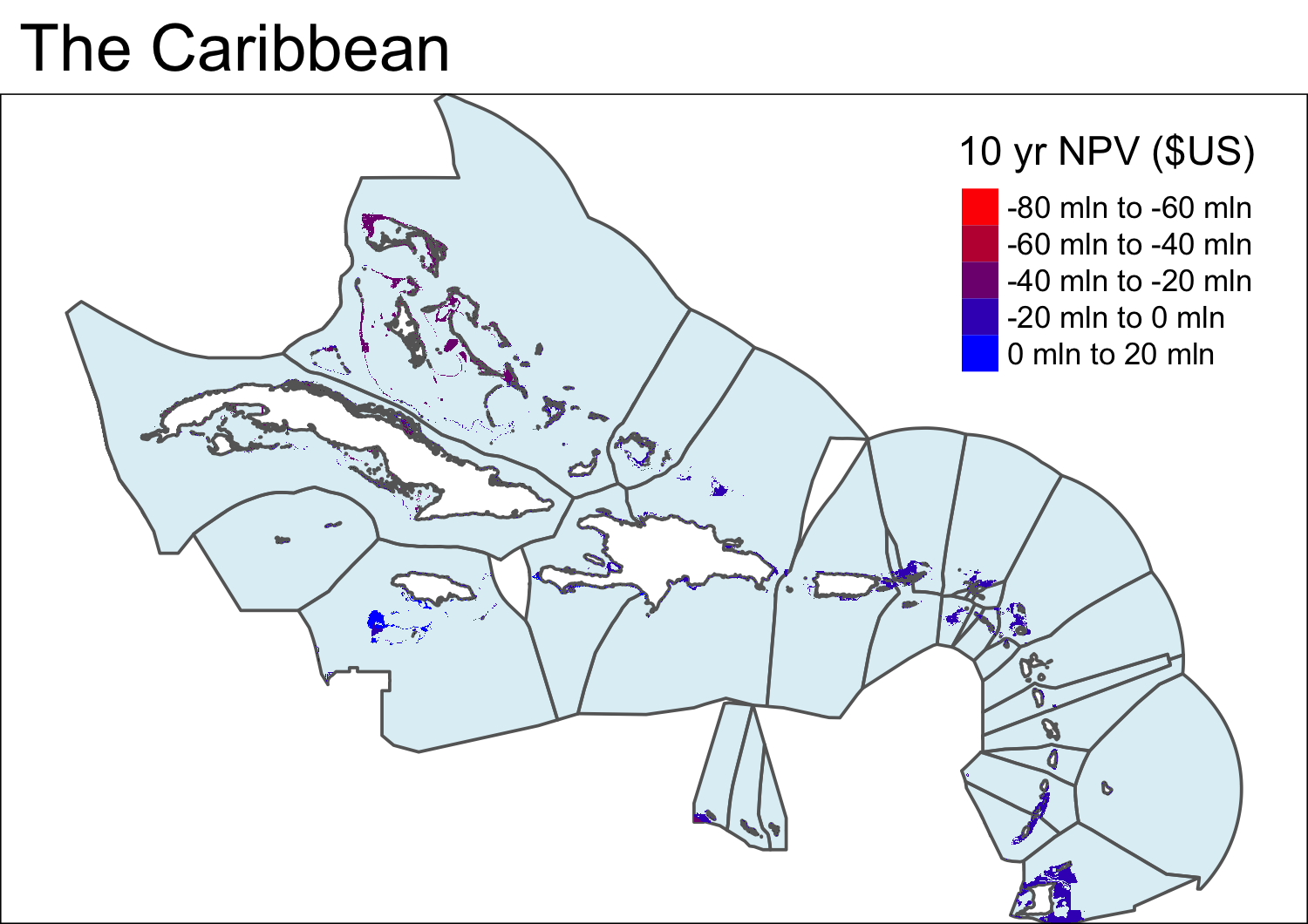
Depth is the largest constraining factor, with less than 2% of the total study area within the suitable depth range required for deployment of offshore SeaStation cages. Deep sea mining did not eliminate any areas because currently no deep sea bed mining permits have been issued in the region. However, this may be an important factor to consider in other regions or in the future in the Caribbean. .

Table XX: Estimated suitable area (km2 by EEZ)

|  |  |  |  |
| --- | --- | --- | --- |
| EEZ | Total Area | Suitable Area | Percent Suitable |
| Trinidad and Tobago Exclusive Economic Zone | 76,575 | 10,189 | 13.31 |
| Saba Exclusive Economic Zone | 9,488 | 1,050 | 11.07 |
| Grenadian Exclusive Economic Zone | 25,577 | 1,142 | 4.46 |
| Sint-Maarten Exclusive Economic Zone | 466 | 19.52 | 4.19 |
| Saint Vincent and the Grenadines Exclusive Economic Zone | 36,243 | 1,415 | 3.91 |
| Aruban Exclusive Economic Zone | 29,950 | 945.9 | 3.16 |
| Sint-Eustatius Exclusive Economic Zone | 2,175 | 65.25 | 3 |
| Saint Kitts and Nevis Exclusive Economic Zone | 9,502 | 256.3 | 2.7 |
| Bahamas Exclusive Economic Zone | 618,667 | 14,314 | 2.31 |
| Virgin Islander Exclusive Economic Zone | 38,290 | 813.9 | 2.13 |
| Saint Lucia Exclusive Economic Zone | 15,413 | 285.5 | 1.85 |
| Jamaican Exclusive Economic Zone | 257,049 | 4,720 | 1.84 |
| Antigua and Barbuda Exclusive Economic Zone | 111,560 | 1,949 | 1.75 |
| Haitian Exclusive Economic Zone | 103,498 | 1,780 | 1.72 |
| British Virgin Islands Exclusive Economic Zone | 81,583 | 1,271 | 1.56 |
| Anguilla Exclusive Economic Zone | 90,154 | 1,221 | 1.35 |
| Turks and Caicos Exclusive Economic Zone | 91,028 | 1,028 | 1.13 |
| Montserrat Exclusive Economic Zone | 7,190 | 73.67 | 1.02 |
| Puerto Rican Exclusive Economic Zone | 154,652 | 1,515 | 0.98 |
| Dominican Republic Exclusive Economic Zone | 350,698 | 3,290 | 0.94 |
| Dominican Exclusive Economic Zone | 28,590 | 242.3 | 0.85 |
| Cuban Exclusive Economic Zone | 352,266 | 2,475 | 0.7 |
| Bonaire Exclusive Economic Zone | 12,980 | 42.62 | 0.33 |
| Curaçaoan Exclusive Economic Zone | 25,397 | 71.02 | 0.28 |
| Saint-Barthélemy Exclusive Economic Zone | 4,179 | 7.32 | 0.18 |
| Cayman Islands Exclusive Economic Zone | 118,398 | 114.4 | 0.1 |
| Barbados Exclusive Economic Zone | 185,006 | 84.08 | 0.05 |
| Guadeloupean Exclusive Economic Zone | 90,859 | 0 | 0 |
| Saint-Martin Exclusive Economic Zone | 1,099 | 0 | 0 |
| Martinican Exclusive Economic Zone | 47,600 | 0 | 0 |

The identified suitable areas are not distributed evenly across EEZs (Table 5). The Bahamas Exclusive Economic Zone contains the largest amount of suitable area and Trinidad and Tobago Exclusive Economic Zone (13.3056986 %) and Saba Exclusive Economic Zone (11.0667284 %) includ the highest percentages of suitable area (>10%), while no suitable areas are identified in the EEZ's of Guadeloupe, Saint Martin or Martinique.

## Profitability



# Discussion

# References

# Appendix

## removed text (just in case we need later)

Guidelines for aquaculture development in U.S. waters of the Gulf of Mexico listed in a recent Fishery Management Plan stated that all aquaculture farms should be a minimum of 3 km apart and set a production limit of r prettyNum(Totalproduction, big.mark=",") mt for a total area of prettyNum(Totalarea,big.mark=",") km2 identified for aquaculture development, or r prettyNum(Productionrate,big.mark=",") mt/ km2. This production limit was identified as precautionary and based on historical wild fisheries capture for the region, due to lack of better methods or information on the ecological capacity of the region. To determine how this specified limit on production per unit area compared to production levels in other regions, we conducted a global assessment of production per unit of EEZ area in depths of 0 to 90 m for all EEZs. We obtained total marine aquaculture production by country, including finfish, invertebrate, and algae aquaculture production, for 2014 from FAO and calculated the total area in a depth range of 0-90 m for aquaculture by EEZ using global 1 km2 resolution bathymetry data from Becker *et al* (**???**). Total marine aquaculture production included finfish, invertebrates, and algae, thus we did not apply a minimum depth limit, because some these species are farmed in shallower water than is required for finfish cage culture. Although this does not allow for a direct comparison to production as modeled in our study, it provides another regional production level benchmark for comparison.

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