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 a species with considerable market potential, cobia (*Rachycentron canadum*). We estimate potential outcomes in terms of yields and profits under different market scenarios. We find that 50,373 km2 (1.7%) of marine space in the Caribbean is technically feasible for cobia aquaculture, with the potential to produce a total of 78.7 million metric tons (MMT) of seafood annually, an amount roughly equal to the total global production from capture fisheries (~80 MMT). Of this area, 24,046 km2 (0.81%) is economically viable given our estimates of current production costs, with the potential to produce 0.1 MMT of cobia annually. Areas associated with the highest relative economic potential were Jamaica, Trinidad and Tobago, and Haiti. The variability of farm-scale production and value, and thus the importance of site selection, differed across countries. Offshore aquaculture is a capital-intensive activity mediated by socioeconomic conditions, such as foreign investment risk and market dynamics. Accounting for these risk factors considerably lowered production in our analysis and may help explain the current lack of commercial offshore aquaculture in the Caribbean despite favorable conditions. The results of this research can be used to help prioritize areas in the Caribbean for offshore cobia aquaculture development and serve as a framework for identifying priority areas for offshore aquaculture of other species.

# Introduction

Global seafood production 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). 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; Froehlich et al. 2017). Additionally, 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 could be realized requires an understanding of the sustainable and economically-viable production potential at a 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 local seafood and economic development (Van Wyk and Davis 2006; Creswell 5AD–2007; CRFM 2014; Pérez-Ramírez 2017). In 2014, the Caribbean produced 330,704 MT of seafood, 90% of which came from capture fisheries. Currently, over 88% of seafood consumed in the Caribbean 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 over the next decade (22%)(FAO 2016). Wild fisheries production in the region is unlikely to play a meaningful role in decreasing exports 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 promote a seafood industry that is more resilient to the effects of climate change (Pérez-Ramírez 2017).

Most aquaculture efforts in the Caribbean to date 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 available land, freshwater, and energy resources (Alvarez-Lajonchère and Ibarra-Castro 2013). Similarly, expanded development of alongshore and coastal aquaculture in the region is likely unsustainable 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 (Benetti et al. 2006). 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, water depths 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. 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 (D. D. Benetti, O’Hanlon, 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 (Alvarez-Lajonchère and Ibarra-Castro 2013; 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 2007.

The global potential for aquaculutre is large in terms of suitable area (Gentry, Froehlich, et al. 2017) and careful marine spatial planning can improve outcomes across multiple economic and environmental objectives (**???**). Here, we present a framework that incorporates socioeconomic, biological, and environmental factors to estimate the potential of offshore aquaculture at a regional scale using the Caribbean, a politically and economically diverse region, as a case study. Using high resolution spatial data, we develop a bioeconomic model to: 1) estimate the offshore mariculture production capacity of the Caribbean region (in terms of amount of seafood and revenue), 2) examine the impact of farm site selection on economic outcomes across and within countries to identify potential development hotspots and determine the importance of strategic site selection, and 3) identify factors that may currently be limiting offshore mariculture development (e.g., biophysical conditions, regulatory environment, capital investment, expertise, etc.). 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

## Study Region and Overview

Our study domain includes the territorial waters and Exclusive Economic Zones (EEZs) surrounding the 28 island countries of the Caribbean Sea. We do not consider the potential for offshore aquaculture development in the high seas or disputed waters. EEZ boundaries for the 28 island countries in our study are are defined using data from Flanders Marine Institute (2011) and all analyses are performed at a 1 km2 spatial resolution. 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. The first steps of our analysis are to identify 1 km2 sites throughout the study region that may be suitable for mariculture development and create a hypothetical farm design to apply to all suitable sites. Next, we apply a thermal performance curve (TPC) to predict temperature-dependent growth and thus production of cobia at each farm. We establish supply curves to determine national and Caribbean-wide cobia production that would be achieved under several scenarios of cobia price, production costs, and investment risk. Finally, we use our production model and estimated economic parameters to calculate NPV over a 10 year time horizon and examine production and revenue outcomes under the assumption that only farms that have a positive NPV will be developed.

## Suitability Assessment

We identified areas that are potentially suitable for the development of offshore mariculture in the Caribbean by considering factors related to technical feasibility, environmental impacts, and current ocean uses (Table S1). We defined suitable thresholds for each factor and used high resolution spatial data in a Boolean overlay to identify 1 km2 areas in our study region that are potentially suitable for offshore mariculture development given the defined thresholds.

We use physical specifications listed by the original manufacture of SeaStation cages to define our thresholds for areas that are technically feasible for offshore maricuture. SeaStation cages are submersible, self-tensioned, single rim cages and are currently the most widely used offshore mariculture cages in the U.S. (Loverich 2010). The minimum site depth for installation of a SeaStation cage is 25 m and the cages are not recommended for areas that experience current velocities exceeding 1 m/s (OceanSpar 2013). We assume the maximum depth threshold for suitable areas is 100 m because cage installation and inspection of mooring and anchoring systems becomes more difficult and costly in depths > 100 (Kapetsky, Aguilar-Manjarrez, and Jenness 2013). We use spatial bathymetry data from Becker et al (2009) to identify areas within a suitable depth range and determine the absolute maximum zonal and meridional current velcocities using data on daily averages over a 10-year period (2005 - 2015) from ESR (**???**) 15to identify areas that are technically feasible for offshore maricuture development.

Offshore mariculture farms can be associated with increased nutrient levels in the water column and along the benthos from fish waste in the vicinity of the cages (REF). Nutrient pollution from fish farms can be associated with algal blooms, reduced water quality and clarity, and low oxygen conditions, all of which can be damaging to coral reef ecosystems (Ref). Using data from (2010) on locations of coral reef habitat, we excluded these areas from offshore mariculture development. Additionally, we excluded areas within designated marine protected areas (MPAs) and conservation priority areas (IUCN and UNEP-WCMC 2017).

To account for potential conflicts with other ocean uses in offshore areas, we consider shipping, structures used for oil drilling, and areas licensed for deep sea mining exploration as potential offshore activities that may conflict with aquaculture development. We exclude areas that fall within 10% of the highest relative shipping activity locations (data sources), areas with benthic oil structures (data sources), and areas permitted for deep sea bed mining exploration (data sources), assuming they are not suitable for offshore mariculture development.

## Growth Potential

Temperature is one of the primary abiotic factors controlling growth in ecotherms, including cobia (Brett 1979), and obviously cannot be easily controlled in offshore mariculture farms (Tidwell 2012). To reflect spatial differences in productivity across farms caused by temperature variations, we use 10 years of remotely-sensed sea surface temperature (SST) data (NASA Goddard Space Flight Center, Ocean Ecology Laboratory, and Ocean Biology Processing Group 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.

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

where is sea surface temperature in degrees C, is the optimal temperature for cobia growth, and and are slope parameters (kg per month per degree 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, . Our temperature-growth parameters for cobia are presented in Table SX and were adopted from (Klinger, Levin, and Watson 2017), who also used a TPC to model cobia growth.

Individual cobia growth at month for site () is estimated using the TPC for all 120 months in the SST time series. The 10 year () average individual growth () at site is then calculated for each calendar month :

We model offshore aquaculture potential in the Caribbean by coupling site specific estimates of average monthly cobia growth from the TPC model with a detailed farm design and economic model parameterized with values from the literature and technical reports. For each site, we calculate the projected net present value (NPV) over a 10 year period from the discounted stream of costs and revenues. We then limit our discussion of results to only include farms (1 km2 sites) with a positive NPV under the assumption that only profitable farm locations would be developed.

To estimate production, we assume a fixed farm design, per 1 km2 site, that we apply across the 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 (Fredriksson et al. 2004; Xu, Zhu, and Miao 2015). The cages are held in position by the mooring system at depths of 15-20 m below the surface(Loverich 2010). We develop a farm design for a 1 km2 area using the total cage volume to farm area ratio of offshore mariculture farms currently operating off the coast of Kona, Hawaii (Sims, n.d.) and the Gulf of Maine (Fredriksson et al. 2004). Our hypothetical farm has 16 SeaStation cages (each 6,400 m3) configured in two eight-cell grid mooring systems, for a total cage volume of 102,400 m3 per individual farm. The infrastructure of the farm has a footprint of ~0.48 km2, which meets 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 (GMFMC (Gulf of Mexico Fishery Management Council) and NOAA (National Oceanic and Atmospheric Administration) 2009).

### Growth Model

Individual cobia growth at month for site () is modeled using the previously calculated 10 year () average individual growth () 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 et al. 2011). A cage at site is harvested when individual fish have grown to a harvestable size of 5 - 6 kg.

D. D. Benetti, O’Hanlon, et al. (2010) 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 calculate the optimal initial number of stocked fingerlings ().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:

Total site biomass in each month () is a function of the number of stocked cages , initial stocking number , and the instantaneous 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 .

The total cost () of production for each farm consists of start up costs () plus the sum of operating costs (). Cost parameters were obtained from published literature or from personal communication with industry experts.

Some parameters were fixed across our study region (Table S3a) while others are a function of EEZ (Table S3b) and/or vary by site within an EEZ. Costs of aquaculture infrastructure and installation increase with depth and distance from shore (Nations and United 2007). Start-up costs, which include initial capital expenditures () and installation costs (), were varied as a function of average site depth in meters , and EEZ-specific permit and/or lease costs ():

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 and equitment required for installing the culture system. A 10% increase in cage and installation costs are assigned to sites with depths greater than 50 m to account for a more complex and time consuming installation procedure in deeper water (**???**). Operating costs are organized in two main categories: farm labor and maintenance costs as a function of site depth, 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, time steps, we calculate total feed based on the average total biomass during month .

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 months, farm revenue is a function of harvest biomass (, kg) and cobia price (), , otherwise . Cobia farms in the Caribbean are assumed to be price takers and thus production in month does not affect price in month . Total farm profit () is the sum of revenues less total farm costs.

Harvested biomass (in metric tons) and profit over a 10-year period are calculated for each farm across a range of prices ($1-$12 per kg).

Net present value (NPV) can be used to assess an investment’s long-term economic validity, accounting for the time value of money by discounting future cash flows at a specified discount rate that describes the present value of future cash flows. NPV for all farms that were profitable over a 10 year period was calculated as:

Where is the discount rate.

NPV is then annualized by calculating annuity:

\*insert equation for annuity calculation.

### Model Scenarios

We calculate average annual production (mt) and annual annuity ($) over a 10 year period for each farm under 2 main scenarios: 1. ‘Suitable scenario’, where farms are developed in all areas that are technically suitable for offshore mariculture development, and 2. ‘Profitable scenario’ where only farms are that profitable over a 10 year period at the current price of cobia are developed. Under the ‘profitable scenario’ are 3 sub scenarios related to the discount rate and price of feed (described in more detail below): Scenario 2a: “10% discount rate, current feed price” Scenario 2b: “10% discount rate, reduced feed price” Scenario 2c: “Country specific discount rate, current feed price’

Feed is well known to account for the largest portion of operating costs in aquaculture (REF). However, given that economic forces and technological innovation are driving promising advances in feed technology, particularly fishmeal and fish oil alternatives (refs), we chose to explore results where current feed price ($1.65/kg) are reduced by 10% in the ‘10 % discount rate, reduced feed price’.

Defining appropriate discount rates in bioeconomic models is often difficult and depends on many factors, particularly the cost of capital and project risk [REF]. As a result, we run our bioeconomic model under two different discount rate assumptions. In the first scenario, we assume a fixed discount rate of 10% across all farms, which is based on the average discount rate of 10.6% found in a meta-analysis of published bioeconomic models for aquaculture from the last 25 years (**???**). However, lack of foreign investment due to perceived financial risk has been identfied as a major barrier to aquaculture development in the Caribbean (REF). Investment risk can be represented by adjusting the discount rate accordingly when estimating returns on an investment. Therefore, our second scenario uses EEZ-specific discount rates based on the financial risk of investing in offshore aquaculture in each country.

Foreign investment risk reflects both political and economic risks in a country, which can be calculated into a single risk score using economic and socioeconomic indicators (Bhalla 1983). We applied the Foreign Investment Risk Matrix (FIRM) developed by Bhalla (1983) and modified by McGowan Jr and Moeller (2009), which utilizes three political and three economic continuous risk variables that are readily available for most countries (Table X). Risk scores were then used to scale EEZ-specific discount rates (Table 1) ranging from 10% to 25%, which aligns with the range of discount rates found in the literature of bioeconomic modelling of aquaculture (**???**).

Table 1. Investment risk scores and discount rates by country. A risk score of 1.5 (US Virgin Islands) is used as a baseline for scaling discount rates between 10%-25%

|  |  |  |
| --- | --- | --- |
| Country | Risk score | Discount rate (%) |
| Cayman Islands | 0.53 | 10 |
| Aruba | 1.2 | 10 |
| Martinique | 1.38 | 10 |
| United States Virgin Islands | 1.5 | 10 |
| Anguilla | 1.75 | 12.5 |
| Puerto Rico | 1.87 | 13.7 |
| British Virgin Islands | 1.98 | 14.8 |
| Sint-Maarten | 2.19 | 16.9 |
| Saint-Barthélemy | 2.2 | 17 |
| Bahamas | 2.21 | 17.1 |
| Barbados | 2.25 | 17.5 |
| Antigua and Barbuda | 2.27 | 17.7 |
| Sint-Eustatius | 2.29 | 17.9 |
| Trinidad and Tobago | 2.3 | 18 |
| Saba | 2.49 | 19.9 |
| Turks and Caicos Islands | 2.49 | 19.9 |
| Saint Kitts and Nevis | 2.5 | 20 |
| Guadeloupe | 2.62 | 21.2 |
| Bonaire | 2.67 | 21.7 |
| Saint Lucia | 2.69 | 21.9 |
| Dominica | 2.73 | 22.3 |
| Curaçao | 2.75 | 22.5 |
| Collectivity of Saint Martin | 2.79 | 22.9 |
| Grenada | 2.87 | 23.7 |
| Jamaica | 2.92 | 24.2 |
| Dominican Republic | 2.98 | 24.8 |
| Montserrat | 3.28 | 25 |
| Saint Vincent and the Grenadines | 3.69 | 25 |
| Cuba | 3.85 | 25 |
| Haiti | 4.03 | 25 |

# Results

## Suitability

According for some technical, environmental and use conflict constraints, we identified 50,373 km2 of ocean space (1.7% our study region) potentially suitable for the development of offshore mariculture. Depth was the largest constraining factor in the suitability analysis, as XX% of our study area fell outside the depth range (25 - 100 m) that we considered technically feasible for offshore farm infrastructure. By comparison, our second largest constraining factor was shipping activity, which only excluded XX% of our study area (Table S4).

There is considerable variability in the amount and distribution of suitable area for offshore mariculture in the Caribbean (Table 1). The Bahamas, Trinidad and Tobago, and Jamaica are the top three countries in terms of suitable area, and the spatial distribution and clustering of suitable sites differs considerably among them (Figure 1; see Figure SX for the full Caribbean suitability map).

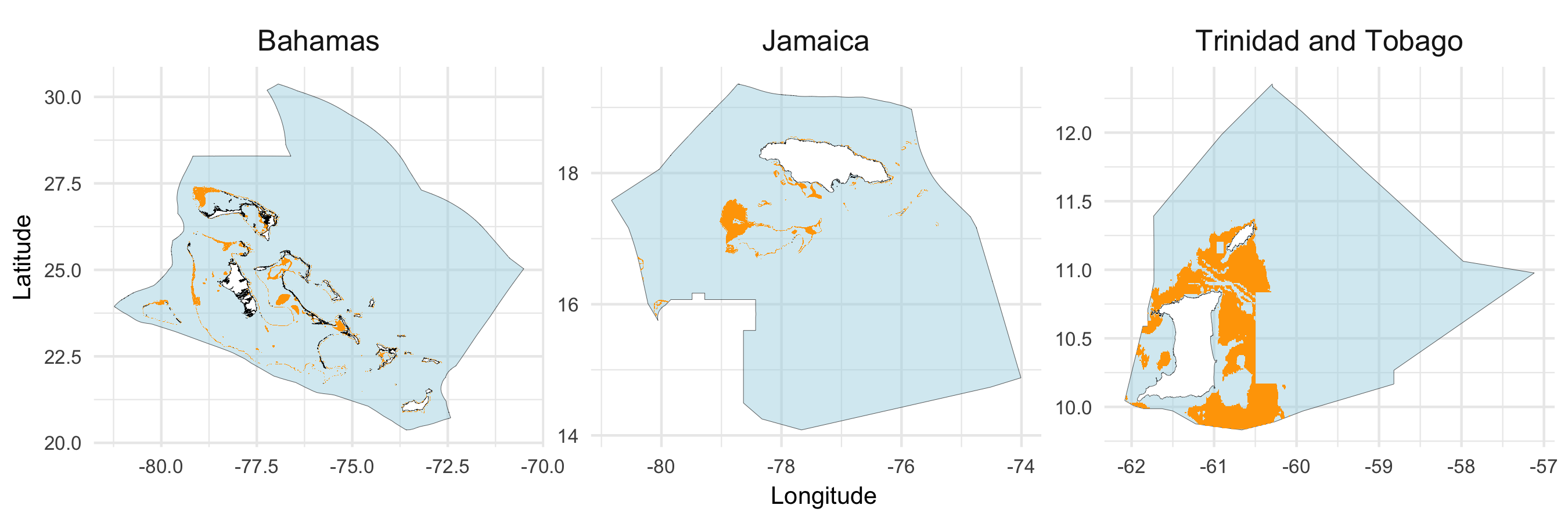


Figure 1. Results of the suitability analysis for the Bahamas, Jamaica, and Trinidad and Tobago. The orange areas represent areas that are potentially suitable for offshore mariculture

Both The Bahamas and Trinidad and Tobago have more than twice the suitable area of the country with the next largest amount of suitable area (Jamaica; Table 1). The large suitable area in the Bahamas can be attributed to its relatively large EEZ (Table 2; Figure 1). Overall, Trinidad and Tobago had the largest percentage of their EEZ identified as suitable (13.3%), followed by Saba (11.1%). Suitable areas accounted for < 5% of total EEZ area for all other Caribbean islands and no suitable areas were found in Martinque, St. Martin, and Guadeloupe because of the conservation status of otherwise suitable sites (Table 2).

Table 2. Estimated suitable area (km2 by EEZ)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Country | EEZ area (km2) | Suitable area (km2) | % suitable | Profitable area (km2) | % profitable |
| Bahamas | 615,628 | 14,311 | 2.32 | 10 | 0.00 |
| Cuba | 350,483 | 2,474 | 0.71 | 14 | 0.00 |
| Dominican Republic | 349,786 | 3,290 | 0.94 | 1,569 | 0.45 |
| Jamaica | 256,647 | 4,720 | 1.84 | 4,522 | 1.76 |
| Barbados | 184,865 | 84 | 0.05 | 79 | 0.04 |
| Puerto Rico | 154,335 | 1,515 | 0.98 | 1,495 | 0.97 |
| Cayman Islands | 118,125 | 114 | 0.10 | 0 | 0 |
| Antigua and Barbuda | 111,358 | 1,949 | 1.75 | 1,073 | 0.96 |
| Haiti | 102,801 | 1,779 | 1.73 | 1,212 | 1.18 |
| Turks and Caicos Islands | 90,765 | 1,028 | 1.13 | 0 | 0 |
| Anguilla | 90,017 | 1,221 | 1.36 | 92 | 0.10 |
| British Virgin Islands | 81,383 | 1,271 | 1.56 | 116 | 0.14 |
| Trinidad and Tobago | 76,273 | 10,186 | 13.35 | 9,333 | 12.24 |
| United States Virgin Islands | 38,130 | 814 | 2.13 | 0 | 0 |
| Saint Vincent and the Grenadines | 36,132 | 1,415 | 3.92 | 1,371 | 3.79 |
| Aruba | 29,898 | 946 | 3.16 | 0 | 0 |
| Dominica | 28,495 | 242 | 0.85 | 242 | 0.85 |
| Grenada | 25,492 | 1,142 | 4.48 | 1,142 | 4.48 |
| Curaçao | 25,315 | 71 | 0.28 | 69 | 0.27 |
| Saint Lucia | 15,354 | 285 | 1.86 | 280 | 1.83 |
| Bonaire | 12,955 | 43 | 0.33 | 38 | 0.29 |
| Saba | 9,472 | 1,050 | 11.08 | 1,050 | 11.08 |
| Saint Kitts and Nevis | 9,450 | 256 | 2.71 | 248 | 2.63 |
| Montserrat | 7,172 | 74 | 1.03 | 0 | 0 |
| Saint-Barthélemy | 4,147 | 7 | 0.18 | 7 | 0.18 |
| Sint-Eustatius | 2,166 | 65 | 3.01 | 65 | 3.01 |
| Sint-Maarten | 452 | 20 | 4.32 | 20 | 4.32 |

Ignoring economic constraints, the Caribbean’s potential to produce cobia from mariculture is extremely large, with an approximate annual production of 0.1 MMT if all suitable sites were developed with cobia farms.

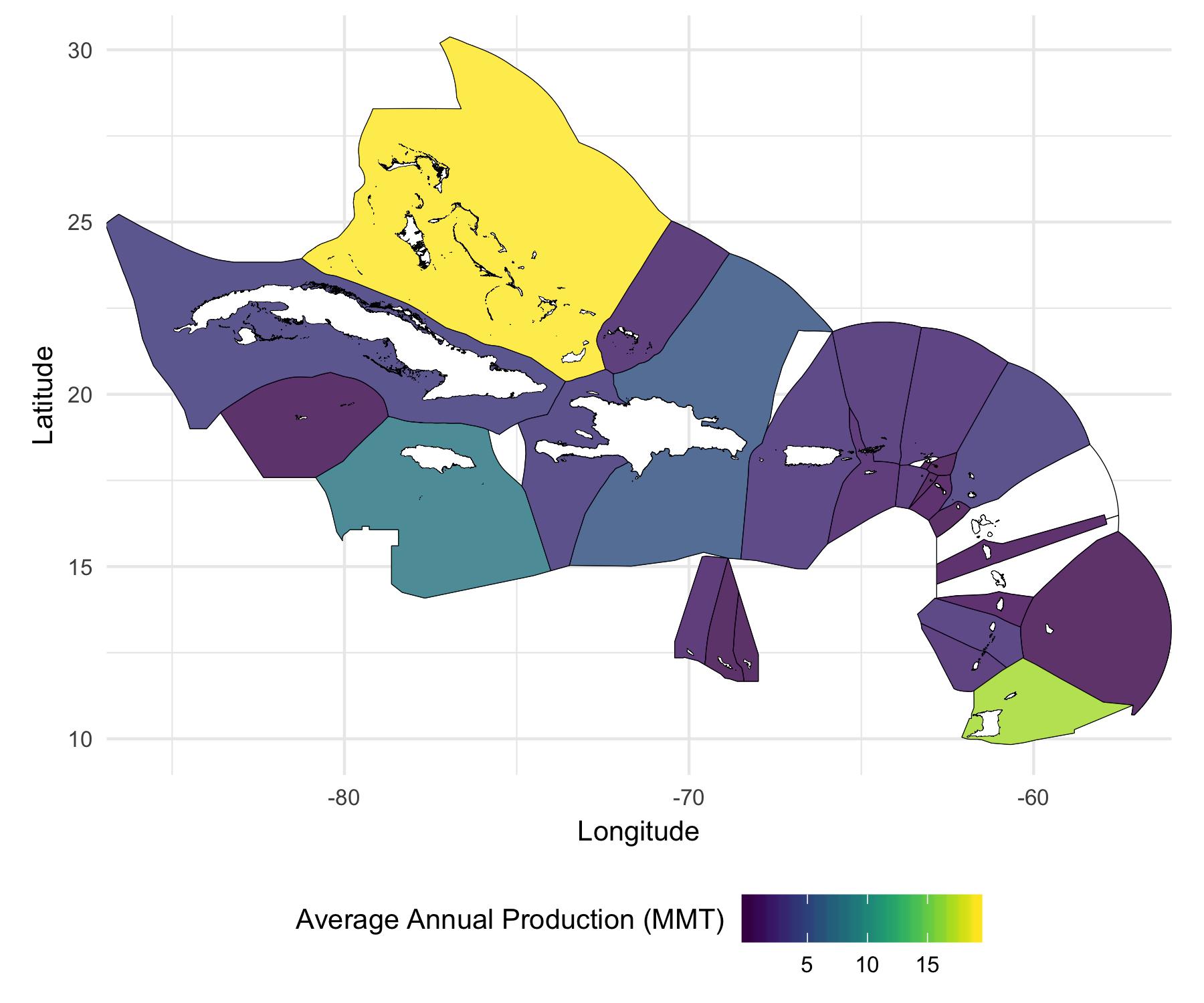


Figure 2. Estimated total production of cobia (MT) using if all suitable areas (not accounting for economic constraints) are developed as offshore mariculture farms

Variability in average annual EEZ-level production is largely driven by the amount of area that was identified as suitable within each EEZ (Table 2; Figure 2). Cobia growth is a function of temperature and, in addition to the amount of suitable area available, is a major factor for cobia production. Not surprisingly then, average cobia growth (kg/month) shows a clear seasonal trend, which varies across EEZs (Figure SX).

When economics are considered, the Caribbean’s potential for offshore cobia mariculture is considerably reduced relative to when only suitability and temperature-dependent growth are considered (Figure 2). Under the current prices and costs associated with cobia farming and assuming a 10% discount rate, none of the suitable sites in numerous countries are profitable, including Aruba, the Turks and Caicos Islands, the US Virgin Islands, Montserrat, and the Cayman Islands (Figure 3A). In the Bahamas, which has the largest amount of suitable area, average annual production declines from 19.1 MMT to just 16,379 MMT, and total annual production for the Caribbean is reduced to 0.1 MMT. The number of countries with economically viable farming areas is further reduced if the country-specific risk of investment is considered, with profitable farms remaining only in Trinidad and Tobago, Jamaica, the Dominican Republic, Haiti, and Anguilla (Figure 3B). Using EEZ-specific risk adjusted discount rates, total potential annual production for the Caribbean is 7 MMT.



Figure 3. Cobia production from profitable farms under two discount rate scenarios (10% and EEZ-specific)

At the farm level, the median cobia farm occupying a 1-km2 site in the Caribbean yields an annual supply and 10 year NPV of 158,350 MT and $14,685.9, respectively. Production and NPV are highly variable across farms in Jamaica, Haiti, and the Dominican Republic, but relatively more consistent within the other EEZs (Figure 4). EEZs with more farm to farm variability in outcomes, particularly those where some sites are highly profitable and others are unprofitable (Fig. 4), represent countries where strategic site selection is particularly important. The variability across EEZs is largely driven by temperature driven growth rates and resulting farm differences in the length of time required to raise cobia to a market size of 5 kg, with the median farm in the Caribbean completing a harvest cycle in X months but with individual farms having harvest cycles from x months to x months.

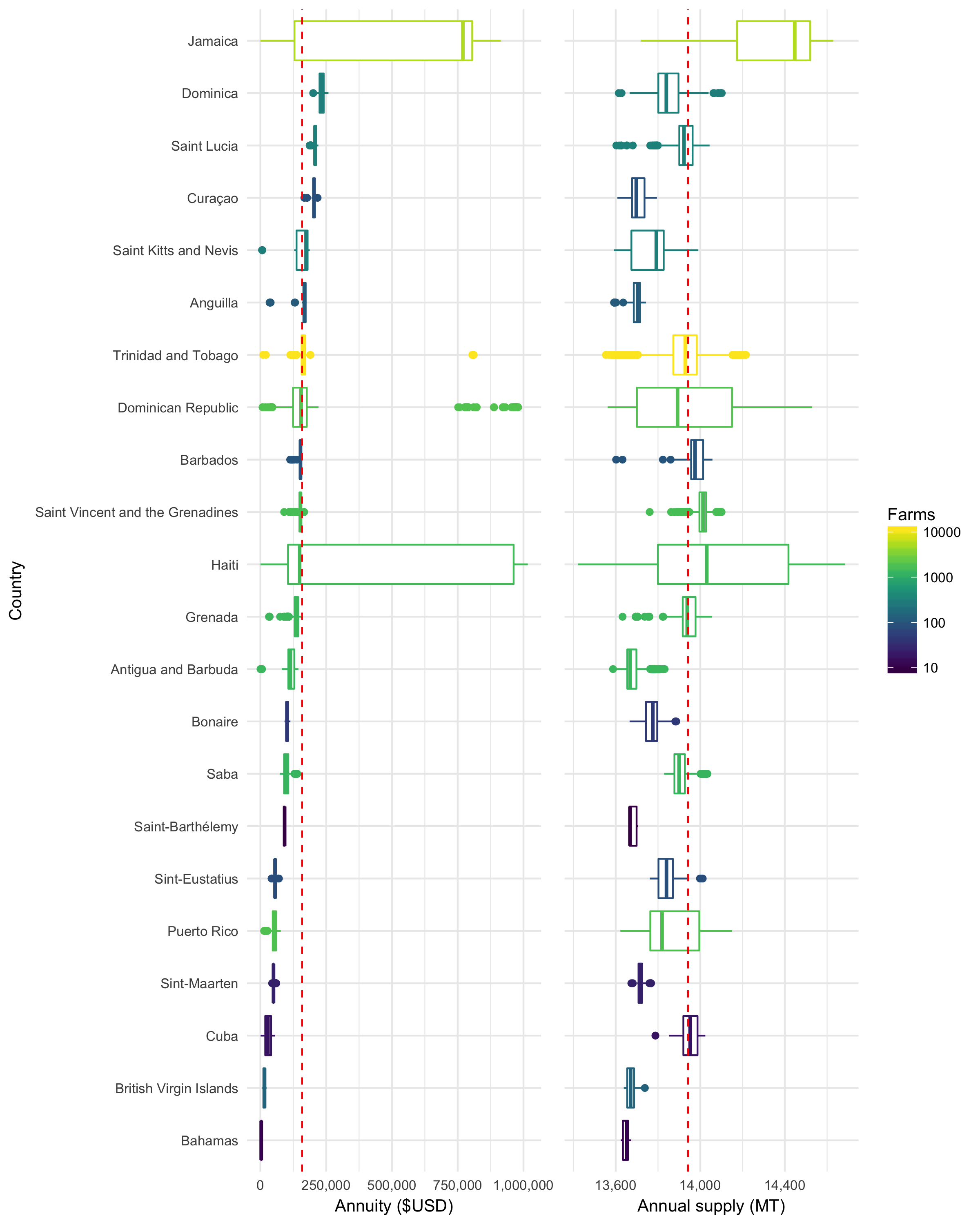


Figure 4: NPV (10% discount rate) and annual supply of cobia aquaculture per farm by Caribbean EEZ

Growth rates and harvest cycle length then impacts feed costs and the number of harvests events per 10 year period. For example, in the Bahamas, which has a large area suitable for aquaculture but a long average harvest cycle across all farms due to cooler waters, the majority of the suitable farm sites are unprofitable (Figures 2 and 3).

Our findings support the conclusion that feed accounts for the largest portion of farm operating costs, with the median farm spending 90% of operating costs on feed. We find that a 10% reduction in the price of feed could increase cobia supply by 35%. This change would increase the revenue for farms in Aruba, the Turks and Caicos Islands, the US Virgin Islands, Montserrat, and the Cayman Islands to profitable levels. Whether or not feed costs decline, no farms in the Caribbean will be profitable if the price for cobia drops below $8/kg.

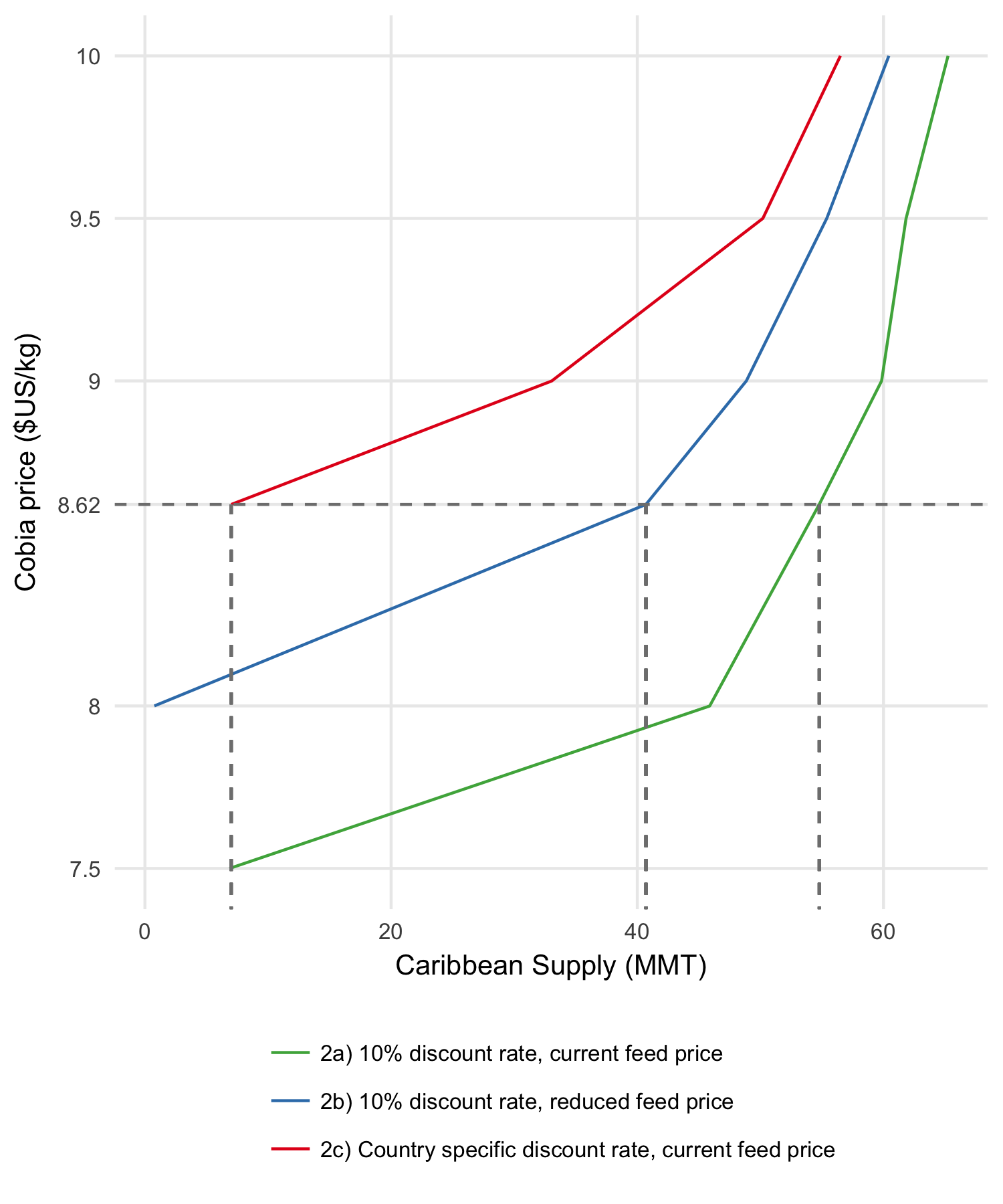


Figure 3. Cobia supply curves under current feed costs ($1.65/kg) and a 10% reduction in feed cost.

Table 4. Supply (mt) and annuity under 4 different scenarios

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| country | supply\_all | supply\_main | supply\_cntry | supply\_feed | annuity\_all | annuity\_main | annuity\_cntry | annuity\_feed |
| Bahamas | 1.9e+08 | 163790 | NA | 7285956 | -5.4e+10 | 40309 | NA | 2.6e+08 |
| Trinidad and Tobago | 1.7e+08 | 1.5e+08 | 138969 | 1.7e+08 | 1.1e+09 | 1.8e+09 | 5139447 | 1.4e+10 |
| Jamaica | 8.3e+07 | 7.9e+07 | 6e+07 | 8.3e+07 | 3.2e+09 | 3.3e+09 | 8.2e+08 | 9.3e+09 |
| Dominican Republic | 5.5e+07 | 2.7e+07 | 2117139 | 5.5e+07 | -1.1e+09 | 3.9e+08 | 4.2e+07 | 3.3e+09 |
| Cuba | 3.5e+07 | 237052 | NA | 6598515 | -7.2e+09 | 493406 | NA | 1.4e+08 |
| Antigua and Barbuda | 3.2e+07 | 1.8e+07 | NA | 3.2e+07 | -3451319 | 1.5e+08 | NA | 2.5e+09 |
| Haiti | 3e+07 | 2.1e+07 | 6913541 | 2.9e+07 | 3.5e+08 | 5.8e+08 | 1.5e+08 | 2.7e+09 |
| Puerto Rico | 2.6e+07 | 2.6e+07 | NA | 2.6e+07 | 9.4e+07 | 9.8e+07 | NA | 2.1e+09 |
| Saint Vincent and the Grenadines | 2.4e+07 | 2.3e+07 | NA | 2.4e+07 | 2.5e+08 | 2.5e+08 | NA | 2.1e+09 |
| British Virgin Islands | 2.1e+07 | 2e+06 | NA | 2.1e+07 | -6.7e+08 | 2128944 | NA | 9.9e+08 |
| Anguilla | 2e+07 | 1547466 | 1452115 | 2e+07 | -4.1e+08 | 1.8e+07 | 3434752 | 1.2e+09 |
| Grenada | 1.9e+07 | 1.9e+07 | NA | 1.9e+07 | 1.8e+08 | 1.8e+08 | NA | 1.6e+09 |
| Saba | 1.8e+07 | 1.8e+07 | NA | 1.8e+07 | 1.3e+08 | 1.3e+08 | NA | 1.5e+09 |
| Turks and Caicos Islands | 1.6e+07 | NA | NA | 3069068 | -1.5e+09 | NA | NA | 8.3e+07 |
| United States Virgin Islands | 1.4e+07 | NA | NA | 1.4e+07 | -1e+08 | NA | NA | 9.5e+08 |
| Aruba | 1.4e+07 | NA | NA | 1301730 | -1.8e+09 | NA | NA | 9815307 |
| Saint Lucia | 4782049 | 4705192 | NA | 4769870 | 6.6e+07 | 7e+07 | NA | 4.3e+08 |
| Saint Kitts and Nevis | 4322637 | 4187295 | NA | 4322637 | 4.8e+07 | 4.9e+07 | NA | 3.8e+08 |
| Dominica | 4071608 | 4071608 | NA | 4071608 | 6.8e+07 | 6.8e+07 | NA | 3.8e+08 |
| Cayman Islands | 1930112 | NA | NA | 1917220 | -2.4e+07 | NA | NA | 1.3e+08 |
| Barbados | 1406507 | 1327479 | NA | 1406507 | 1.1e+07 | 1.4e+07 | NA | 1.2e+08 |
| Montserrat | 1240034 | NA | NA | 1240034 | -939319 | NA | NA | 9.3e+07 |
| Curaçao | 1163609 | 1123581 | NA | 1163609 | 1.6e+07 | 1.7e+07 | NA | 1e+08 |
| Sint-Eustatius | 1107293 | 1107293 | NA | 1107293 | 4497454 | 4497454 | NA | 8.9e+07 |
| Bonaire | 7e+05 | 619804 | NA | 686387 | -615727 | 4583880 | NA | 5.5e+07 |
| Sint-Maarten | 329299 | 329299 | NA | 329299 | 1224083 | 1224083 | NA | 2.6e+07 |
| Saint-Barthélemy | 123106 | 123106 | NA | 123106 | 819894 | 819894 | NA | 1e+07 |

# Discussion

The total annual production of 0.1 MMT possible from all suitable areas in the Caribbean is two orders of magnitude larger than total current seafood production in the region (~300,000 MT) and approximately equal to the total annual harvest from the world’s capture fisheries (~80 MMT). Impressively, this output requires just 1.7% of the Caribbean’s marine space, a result similar to that of (2017) who estimated that current total landings could be produced from 0.015% of global ocean area. In fact, the Caribbean could match its current seafood production using just 184.2 km2 (0.006%) of its marine space.

* We should then return to the three questions posed at the end of the intro and maybe spend a paragraph talking about each, particularly in the context of “charting an aquaculture future for the Caribbean.” The last question is about barriers to development, which is where we could spend some time talking about Bess results. We still may want to consider integrating her work into the methods and results as well, unless you think the paper is better and tighter as is.
* Other topics we could cover: o Model/analysis caveats: things we could have done better; where we are most uncertain about assumptions or parameter values o Applicability of model to other species or other locations o How our results could be used to guide policy and investment in the region

# References

# Supplementary Information

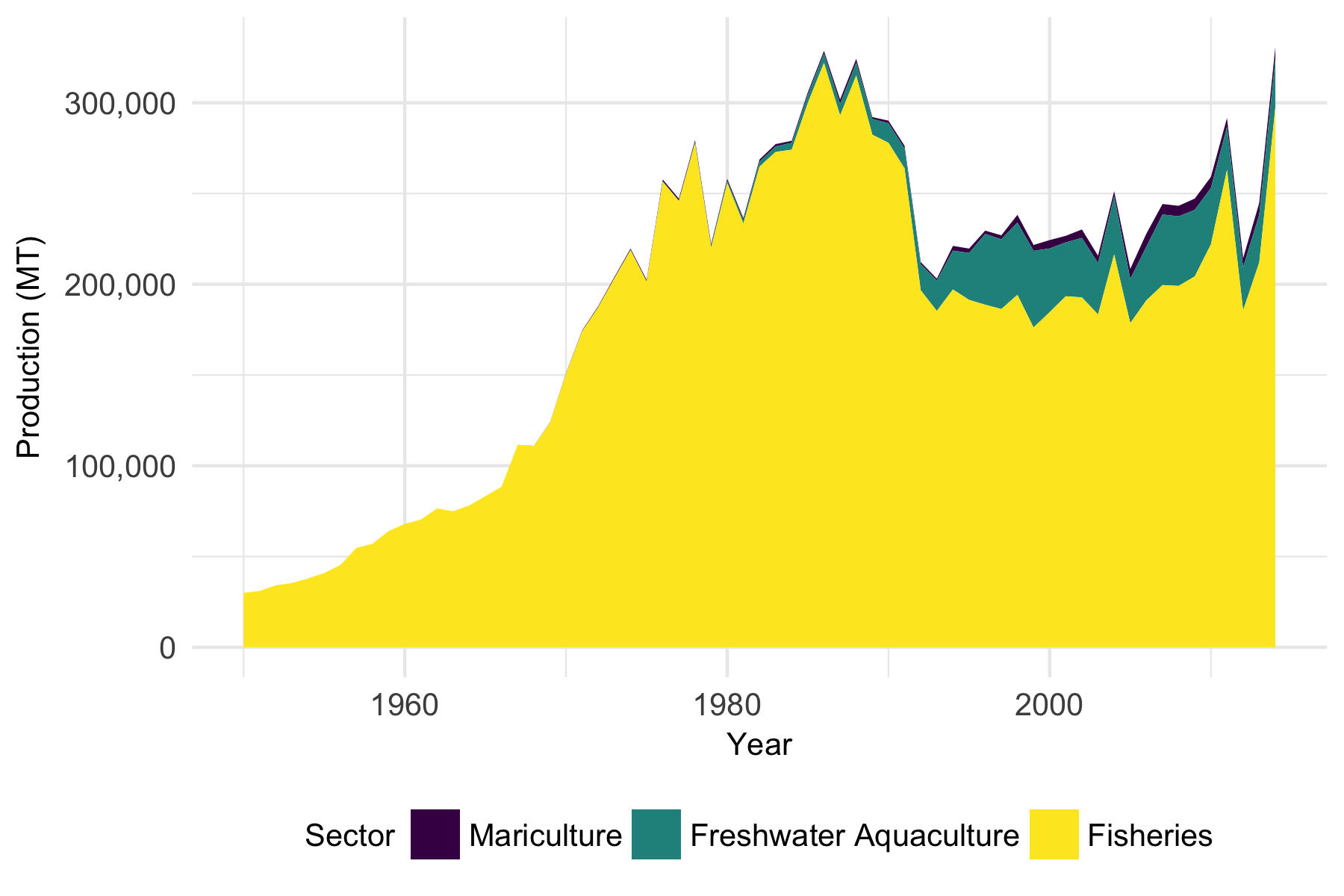
#### Risk Adjusted Discount Rate

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 are 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.



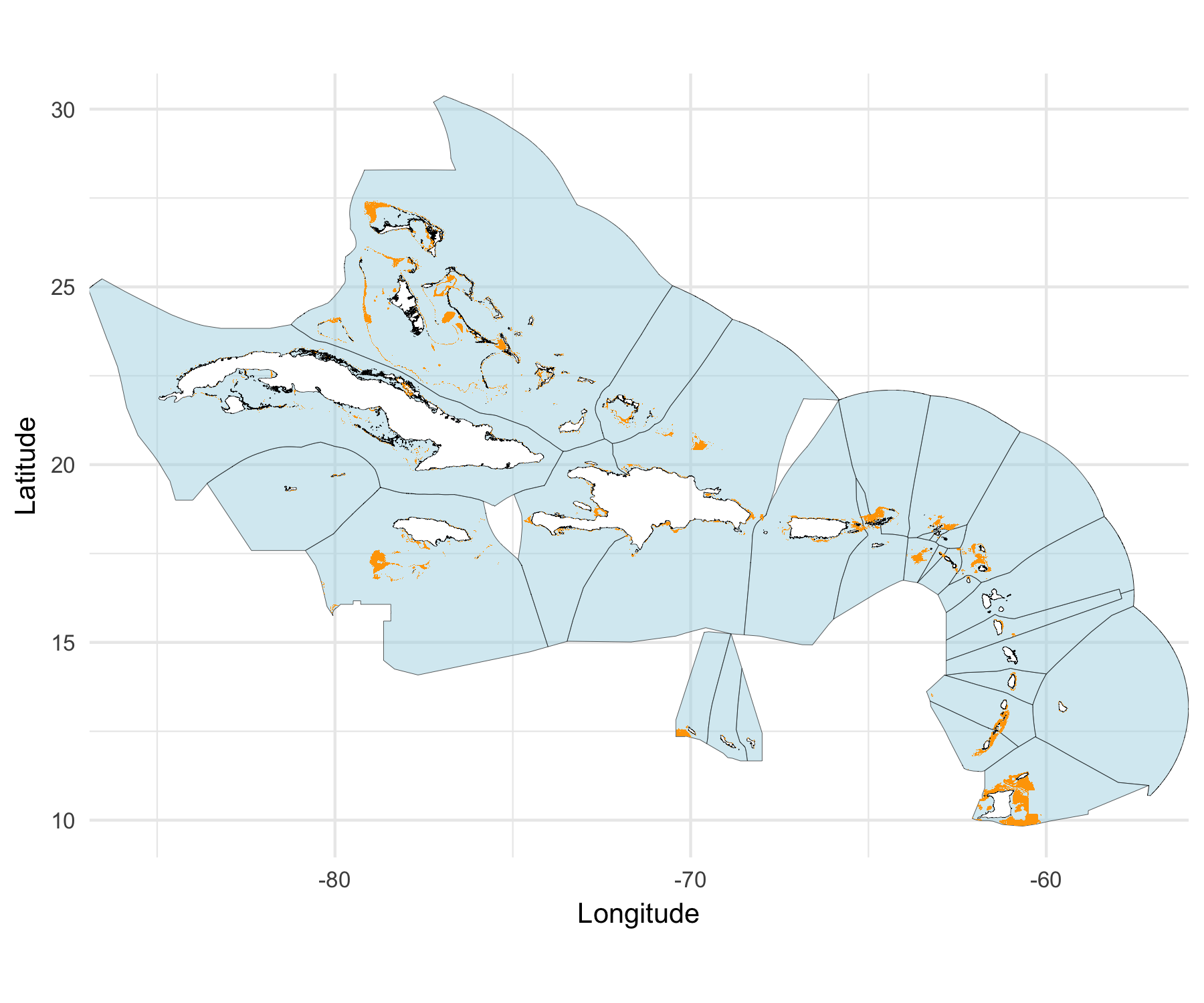


Figure S1. Areas suitable for offshore mariculture in the Caribbean

Table S1. 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 |

Table S2. Model parameters and values for the Thermal Performance Curve, Cost model, and Economic model

|  |  |  |  |
| --- | --- | --- | --- |
| Cost Parameter | Value | Unit | Reference |
| Capital Costs |  |  |  |
| Cage | 269701 | US$/cage | Bezerra et al. 2016 |
| Support vessel | 158331 | US$/vessel | Bezerra et al. 2016 |
| Farm site lease | 3265 | US$/km2 | Bezerra et al. 2016 |
| Labor installation | 52563 | US$/farm | Bezerra et al. 2016 |
| Operating Cost Parameters |  |  |  |
| fingerlings | 2.58 | US$/fingerling | Bezerra et al. 2016 |
| feed price | 1.64 | US$/kg | Bezerra et al. 2016 |
| hourly wage | varies by EEZ see Table AX | US$/hour |  |
| fuel price | varies by EEZ see Table AX |  |  |
| distance from port | varies by EEZ see Table AX | km |  |
| fuel efficiency | 3219 | m/gallon |  |
| farm workers | 17 | no. of employees operating farm/day | Bezerra et al. 2016 |
| farm days | 30 | work days at farm/month |  |
| farm hours | 8 | work hours/day |  |

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) |  |

Table XX: Cost parameters used in the bioeconomic model for cobia offshore aquaculture

|  |  |  |  |
| --- | --- | --- | --- |
| Cost Parameter | Value | Unit | Reference |
| Capital Costs |  |  |  |
| Cage | 269701 | US$/cage | Bezerra et al. 2016 |
| Support vessel | 158331 | US$/vessel | Bezerra et al. 2016 |
| Farm site lease | 3265 | US$/km2 | Bezerra et al. 2016 |
| Labor installation | 52563 | US$/farm | Bezerra et al. 2016 |
| Operating Cost Parameters |  |  |  |
| fingerlings | 2.58 | US$/fingerling | Bezerra et al. 2016 |
| feed price | 1.64 | US$/kg | Bezerra et al. 2016 |
| hourly wage | varies by EEZ see Table AX | US$/hour |  |
| fuel price | varies by EEZ see Table AX |  |  |
| distance from port | varies by EEZ see Table AX | km |  |
| fuel efficiency | 3219 | m/gallon |  |
| farm workers | 17 | no. of employees operating farm/day | Bezerra et al. 2016 |
| farm days | 30 | work days at farm/month |  |
| farm hours | 8 | work hours/day |  |

## 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* (2009). 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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