Charting an Aquaculture Future for the Caribbean

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# Abstract

The development of aquaculture in the Caribbean has been identified as an avenue to stimulate local economies, improve employment opportunities, and increase 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 users. Farming further offshore is a possible option for alleviating these stresses. Using high-resolution environmental and economic data, we developed a spatial bio-economic model to identify suitable areas for offshore finfish aquaculture, parameterized based on cobia (*Rachycentron canadum*), throughout the Caribbean and estimate potential outcomes in terms of yields and profits under different supply and demand 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 requiring considerable investment and enabling socioeconomic conditions, such as XX 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 serve 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

1. Summary and importance of global aquaculture production
   * Projected increase in seafood demand and aquaculture as the most likely means to fill this demand (i.e., limited ability of wild fisheries to increase production)
   * Brief summary of ecological, social and economic benefits of aquaculture
   * Despite strong arguments for aquaculture growth to meet increasing seafood demand at a global scale, how aquaculture development and growth can and should be realized at a regional scale requires an understanding of the sustainable and economically viable production potential of a region

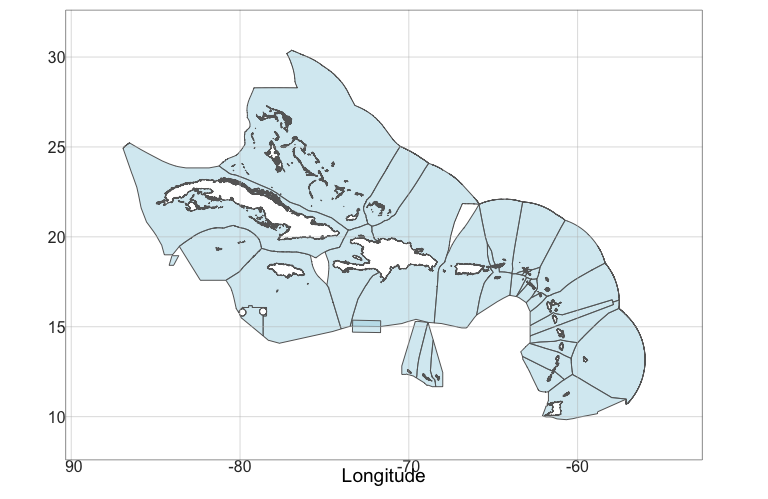
* \*Description of factors that must be considered when determining aquaculture production potential of a given region ( see (McKindsey et al. 2006); Dunn et al. 2013).
  + physical
  + ecological
  + social
  + economic

1. The Caribbean as a region where aquaculture development could be particularly beneficial
   * Caribbean seafood consumption production, and trade (include information on seafood exports and imports)
   * Describe current aquaculture production occurring in the Caribbean (minimal)
   * Recently, further development of aquaculture has been identified as a priority in the Caribbean to reduce reliance on imports and provide a new source of income and livelihoods.
   * Potential for land-based and coastal aquaculture in the Caribbean is extremely limited (explain why…..limited space on land, limited freshwater, limited energy resources(e.g. reliable electricity), , environmental concerns with coastal aquaculture), suggesting the need to look to offshore aquaculture
2. Offshore aquaculture is an emerging approach to mariculture where farms are some distance offshore
   * Overview of offshore aquaculture worldwide
   * Brief discussion of advantages of offshore aquaculture (specifically in the Caribbean)
   * Likely species/technology in the Caribbean (concluding that cobia is one of the more promising species because it is fast growing, has had demonstrated success in offshore farms, is a high value species, etc. and thus is the focus of our analysis)
3. Overview of cobia biology and cobia farming (this section should make it clear why SST was not a necessary layer in our suitability assessment , but was important to consider in our growth model).
4. Introducing our study
   * Offshore aquaculture is nearly untapped in the Caribbean, raising questions about what the actual potential is, how that potential varies across the many EEZs of the Caribbean, and what factors are currently most likely to be limiting development
   * Using high resolution spatial data, we develop a spatial bioeconomic model to estimate the total production potential (in terms of weight and revenue) of offshore cobia mariculture in the Caribbean region. We examine the spatial distribution of offshore mariculture potential to identify ‘hotspots’ locations (in terms of weight and revenue) for future offshore mariculture farm development. We examine the variation of individual farm profitability between and across EEZs to determine the importance of site selection in mariculture development and to quantify the potential benefits of strategic spatial planning. We explore these results under several scenarios of cobia proudction using a supply and demand curve to set cobia market price. We also run sensitivity analyses on fixed parameters to identify and quantify the effects of factors constrainig our model. 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

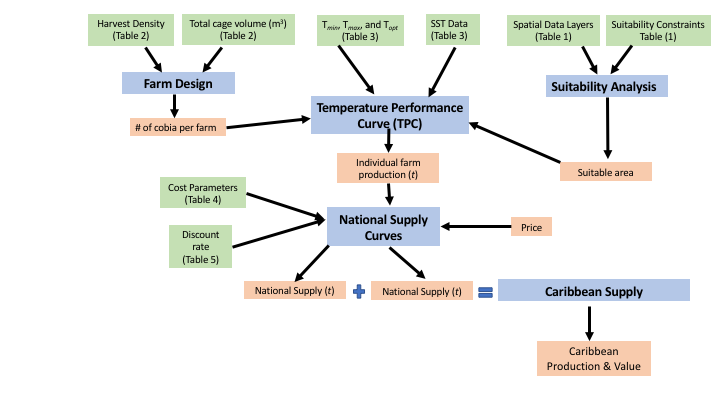
Our study domain includes the territorial waters and Exclusive Economic Zones (EEZs) surrounding the 28 island countries that comprise the Greater and Lesser Antilles of the Caribbean Sea is the area of focus for our study (Figure 1). All analyses were performed at a 1 km2 spatial resolution. We did not consider the potential of offshore aquaculture development in the high seas or disputed waters. A shapefile from VLIZ (2014) was 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 analyses were to identify 1 km2 sites throughout the study region that would be suitable for mariculture development and create a hypothetical farm design for all suitable sites. Next, we apply a temperature performance curve (TPC) to predict temperature-dependent growth of cobia at each farm and establish a supply and demand curve to set global cobia market price according to our regional production estimates. Finally, we use the estimated price and cost parameters derived from the literature to calculate Net Present Value (*NPV*) over a 10 year time horizon. We assume that only farms that have a positive NPV after 10 years 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 was to conduct an assessment to identify areas that are potentially suitable for the development of offshore mariculture. To determine what areas are suitable, we considered 6 factors: depth, current speed, coral reef presence, shipping activity, oil structures, and areas designated for conservation (Table 1).

Table 1: Description of spatial data layers and criteria used to identify cells suitable for development of offshore aquaculture in the Caribbean

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Spatial.Data.Layer | Year | Data.and.Analysis.Description | Suitability.Criteria | Data.Source |
| Marine Protected Areas | 2016 | The most comprehensive global database on conservation areas which includes marine protected areas (MPAs) and areas that achieve conservation in the long-term, referred to as other effective area-based conservation measures (OECMs). We filtered this data set to include protected areas that are located partially or completely within the marine environment. Areas classified as designated or proposed, in addition to those already established, were included to be conservative in terms of limiting aquaculture development in areas of high conservation priority. | Not an established, designated or proposed Marine Protected Area | IUCN and UNEP-WCMC 2016 |
| Oil Rigs | 2003 | Stable light flares from NOAA's National Geophysical Data Center (NGDC) with ephemeral sources of lights removed were isolated using spectra analysis to identify location of oil rigs in the ocean. | No existing benthic oil structures | Halpern et al. 2008 |
| Shipping | 2005 | Mobile data on 3,374 large (> 1000 gross tonnage) commercial and research vessels at sea in 2005 were obtained from the World Meteorological Organization Voluntary Observing Ships Scheme. Ship tracks were then created assuming ships travel in straight lines. Values ranged from 0 to 1,158 and represent the number of ship tracks recorded in a single 1 km2 cell over a one year period | Not included in the top 10% of relative shipping activity in the Caribbean | Halpern et al. 2008 |
| Coral Reefs | 2010 | Dataset on the distribution of coral reefs in tropical and subtropical regions. Data sources include the Millennium coral Reef Mapping Project (2005) and the World Atlas of Coral Reefs (Spaliding 2001). | No coral reefs are present in the 1 km2 area | UNEP-WCMC, WorldFish Centre,¾WRI,¾TNC¾2010 |
| Depth | 2009 | Global measured and estimated seafloor topography data from satellite altimetry and ship depth soundings | Depths >=25 and < = 100 | Kapetsky et al. 2013 |
| Current Velocity | 2005-2015 | OSCAR (Ocean Surface Current Analysis Real-time) contains near-surface ocean current estimates, derived using quasi-linear and steady flow momentum equations. The horizontal velocity is directly estimated from sea surface height, surface vector wind and sea surface temperature. These data were collected from the various satellites and in situ instruments. The model formulation combines geostrophic, Ekman and Stommel shear dynamics, and a complementary term from the surface buoyancy gradient. Data are on a one third degree grid with a 5 day resolution. OSCAR is generated by Earth Space Research (ESR). | Maximum average monthly zonal or meridional current velocity < 1 | ESR 2009 |
| Deep sea bed mining claims | 2016 | Worldwide spatial locations of contracts for seabed mining exploration and deep sea mining claims issued by the International Seabed Authority | No mining claim or contract present | deepseaminingwatch.ms.ucsb.edu |

We conducted our suitability assessment assuming 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 was set at 100 m because in waters deeper than 100 m, cage installation and inspection of mooring and anchoring systems is more difficult and costly (**???**; Kapetsky, Aguilar-Manjarrez, and Jenness 2013). We obtained spatial bathymetry data for our study region, and areas that fell within a 25 - 100 m depth were scored as suitable for offshore mariculture development. Additionally, SeaStation cages (or fish?) can withstand consistent current velocities up to 1 m/s (Loverich 2010). To identify areas with unsuitably high current velocities, we obtained 10 years (2005-2015) of average daily zonal and meridional current velocity. The absolute maximum zonal and meridional average daily velocities that occurred over the 10 year time period were extracted for each cell, and any cell with a maximum zonal or meridional velocity greater than 1 m/s were scored as unsuitable. To minimize the ecological impact of offshore mariculture developement, we also identified any cells with coral reef hatitat present as unsuitable.

To identify areas currently designated or utilized for purposes that would preclude offshore maruiculture development, we obtained 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 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 were considered unsuitable for offshore mariculture development.

All spatial data layers listed in Table 1 were converted to raster format with a 1 km2 spatial resolution. Data files that had a resolution > 1 km2 were 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 were given a score of zero and cells falling within the threshold were given a score of 1. We then overlaid all data layers and multiplied the values of all layers in each cell. This resulted in a final single data layer, where cells suitable for offshore aquaculture development based on all criteria listed in Table 1 had a score of 1, and unsuitable cells had a value of 0

## Farm Design

To estimate production, we assumed a fixed farm design, per 1 km2 sites, across our study region. SeaStation cages are typically configured using a grid mooring system that includes a grid, anchor, and mooring lines secured at varying distances from the cages (**???**; Xu, Zhu, and Miao 2015).We developed 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 2017). 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 area of farm area for the Kona farm (Sims 2017) and another offshore farm using SeaStation cages in the Gulf of Maine (D. W. Fredriksson et al. 2004); (J. 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.

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 (ref).Cobia take twelve months on average to grow from fingerling (~XX kg) to a harvestable size of 5 - 6 kg (Holland, n.d.) . For our cobia farms, we assume that between 1 and 5 cages at each farm are stocked with cobia fingerlings each month. The number of fingerlings stocked in each cage remained constant, and was calculated assuming constant natural mortality (*M1*)of XX (ref) and a conservative harvest density of 15 ), (or 16,000 individual fish per cage). This means that it take between 1 and 1.5 years for the cobia farms to reach their operational capacity (reach production potential), which is a reasonable assumption because most commercial farms scale production gradually [REF].

Table 3:

|  |  |
| --- | --- |
| 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) |  |

## Bioeconomic Model

### Temperature Perfomance Curve

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 used a thermal performance curve (TPC) to model temperature dependent individual growth of cobia (Dane ref). We used 10 years of satellite-based sea surface temperature (SST) data (NASA 2014) to calculate 1 km2 resolution spatial data layers of average monthly SST. Monthly biomass ()for each cage was then calculated as:

where t\_*min* is XX, t\_*max* is XX, and max growth occurs at t\_*opt*, and SST is the average monthly SST over the last 10 years for locations, , is the initial stocking density of each cage, and , the total survival rate is assumed to be 95% (Benetti et al. 2008). (Table XX)

Annual production () at each farm is then calculated as:

Where *cages* is the number of cages per farm and is the monthly total biomass per cage.

### Economic Model

#### Costs

Using cost parameters we derived from the literature for each EEZ and parameters that were fixed across all sites (Table 4), the economic model estimates total operating costs () for each farm at year as:

and for all subsequent years ( as) at each site :

where represents capital expenditure (start up costs) at each site as a function of average site depth (), distance from port (), and :

where represents materials and equipment costs as a function of depth, represent installation costs as a function of the farm's distance from shore and, base installation costs that vary by EEZ, and represents the cost of an aquaculture permit or lease as a function of EEZ (Table 4).

represents annual operating costs at each site for each year :

Where is the hours required at each site as a function of wave exposure, is the number of workers required to service a farm, and is the hourly wage per worker as a function of EEZ, is distance from shore (km), is average boat speed to farm sites, is the number of trips required per month for running the farm, is the cost of fuel as a function of EEZ, is the average fuel efficiency of the vessel, is the fixed cost of fingerlings in year for a individual farm, and is the fixed cost of feed in year for a individual farm.

#### Discount Rate

Barriers to the development of aquaculture in the Caribbean are lack of infrastructure, and political and economic stability, factors that deter private sector investors (**???**). We incorporate the foreign investment risk associated with a country into the discount rate. In general, both political and economic conditions of a country determine how much risk is associated with investing in that country, and thus how much foreign direct investment is likely to occur (Schneider and Frey 1985). Political and economic instability has been identified as a major limiting factor to aquaculture development in the Caribbean (Rojas and Wadsworth 2007), with potential investors concerned that policies affecting aquaculture business will shift before they are able to make a profit. Here, we modify previously published methodologies for quantifying country investment risk 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 (Table 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 XX). Political and economic risk scores are calculated by taking the sum of final scores for all three variable, and the total risk score is calculated by multiplying the political and economic risk scores by the specified weight and then summing the values. The weights shown in Table 1 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.

Limited data was available for the risk variables decried by McGowan and Moeller (2009)for Caribbean island countries. Only three countries in our study had data available for the “conflict” variable and only nine had 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 identified comparable, substitute risk variables for each of McGowan and Moeller’s risk variables that had data more widely available for the region. We then calculated Pearson’s correlation coefficients and significance vales between McGowan and Moeller’s risk variables and our selected substitute variables using countries that had data available for both sets to validate our substitute variables (Table XX). Although there were not enough data for the conflict variable in the Caribbean to calculate a correlation coefficient, we assumed WRI’s political stability score was a logical substitute. GDP per capita data were widely available, thus a substitute component for this variable was not necessary.

We calculated the total summed biomass (mt) over a ten year period, and the 10 year Net Present Value (NPV), and only farms that generate positive revenue are considered feasible for development. Feasible farms within each EEZ were then ranked according to: yield and profit (highest to lowest). We then examined the range of estimated yields and profits generated by farms within an EEZ, and compared the highest and lowest yield and revenue generating farms across EEZs.

#### National Supply Curves

Using the discount rate, costs, and annual cobia biomass produced at each farm, we construct a supply curve of cobia for each EEZ by summing biomass () of all profitable farms in an EEZ at every price $0.01 to xx at TR$) of each farm is calculated as:

Where is the price of cobia and is the export tax as a function of EEZ.

Annual total farm profit () for each farm at year are calculated as:

The National supply curves allow us to determine the cobia production level for each EEZ for any given price.

We then amortized annual profit at each site in relation to an economic discount rate () (Table 5) as a function of *EEZ*:

We also estimated the equivalent annual annuity () of each farm's NPV over a 10 year time horizon for each site :

#### Caribbean Supply Curve

The National supply curves are summed(?) into a single Caribbean-wide supply curve to estimate total cobia production potential for the Caribbean at any given price. For any price scenario, farms are developed in order of highest NPV.

## Production Scenarios

We estimate EEZ level and Caribbean wide cobia production under serveral scenarios: \* Maximum production scenario: All suitable cells are developed (what would the price have to be) \* Current market production scenario: Total production assuming current market price of cobia \* Price fluctuation scenarios: We estimate total production assuming an 20% (?) increase and decrease of current market price

We then examined and compared the following under each production scenario:

* Total production (in terms of profit and weight) for the entire study (Caribbean) region (does this economic contratint 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 the see potential gains of strategic spatial planning) and across EEZs (to determine the island countries with the greatest potential for offshore aquaculture development)

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 [REF], currently, limited empirical evidence exists to estimate the ecological carrying capacity for aquaculture production at a regional scale.

We examine the production estimates from the scenarios described above and determine how they compare to two within two proxies we haved defined as ecological capacity limits:

1. High ecological capacity limit- Ecological production limit is determined by identifying the highest aquaculture per unit area of EEZ worldwide e)
2. Precautionary ecologoical 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.

## Sensitivity analyses

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

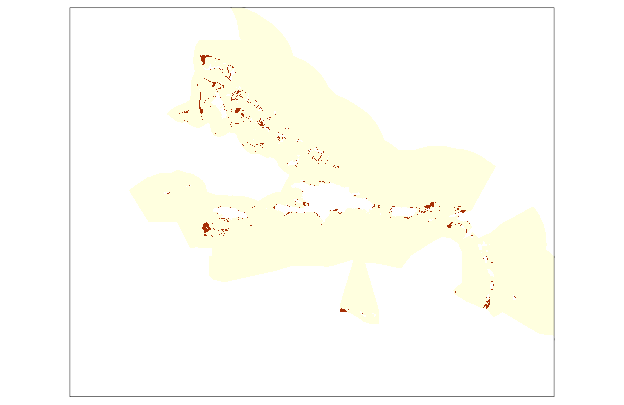
Specifically, we compared the output at both the individual farm, EEZ, and regional level by running the model under a range of values for the following parameters:

* 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 found a total of r prettyNum(final\_suitable\_area,big.mark=",") km2, or r prettyNum(percent\_total,big.mark.=",")% of EEZ area in the Caribbean, suitable for offshore aquaculture development (Figure 2).



Areas identified as suitable for the development of offshore aquaculture within each EEZ are indicated in dark red

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

Depth was 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. .

The identified suitable areas were not distributed evenly across EEZs (Table 5). The Bahamas EEZ contained the largest amount of suitable area and Trinidad and Tobago and Saba's EEZs included the highest percentages of suitable area (>10%), while no suitable areas were identified in the EEZ's of Guadeloupe, Saint Martin or Martinque.

## Bioecnomic Model

Scores for all political and economic risk components used to calculate final risk value are presented in Table 3. We then transformed the data in Table 3 to a relative scale of 1 (low risk) to 5 (high risk). All political and economic variables were given an equal weight by taking the average of the three economic and political variables, respectively. The final risk score was calculated by taking the average of the political and economic score for each country (Table 4).

Averages of political and economic variables were calculated by removing any variables for which data were not available for that country. In some cases this meant that the only data used to calculate the final relative risk score was GDP per capita. We assumed when other data were not available using only GDP per capita to determine risk was a reasonable approach because Bhalla (1983) states that this variable is one of the most important in 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 that had data available for all variables, we found 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).

# Discussion

# References

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WDPA Updates

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# 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 29,000 mt for a total area of 35,643 km2 identified for aquaculture developement, or 0.813624 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 modelled in our study, it provides another regional production level benchmark for comparison.

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