Charting an Aquaculture Future for the Caribbean

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fig\_width <- 8  
fig\_asp <- .65  
knitr::opts\_chunk$set(echo = FALSE, message = F, warning = F,  
 fig.asp = fig\_asp, fig.width = fig\_width  
   
 )

# 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

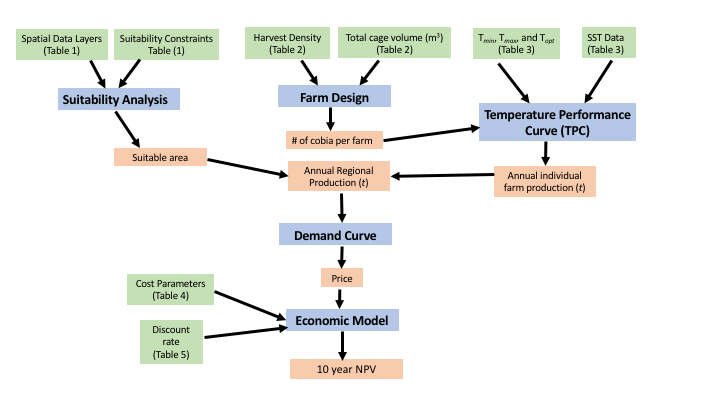
* \*Description of factors that must be considered when determining aquaculture production potential of a given region ( see McKindsey et al. 2006; Dunn et al. 2013).
  + physical
  + ecological
  + social
  + economic

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 profit) of offshore aquaculture in the Caribbean, using cobia as a case study. We examine the spatial distribution of offshore aquaculture potential to identify ‘hotspots’ for potential future offshore aquaculture development, and how it is distributed across space. Additionally, 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 regionally scaled production capacity scenarios, and identify the main parameters constraining production in 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 aquaculture industry in the Caribbean.

# Methods

## 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 perfomance curve (TPC) to predict temperature-dependent growth of cobia at each farm and create a supply curve to estimate cobia price, based on the 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 postive NPV after 10 years will be developed.

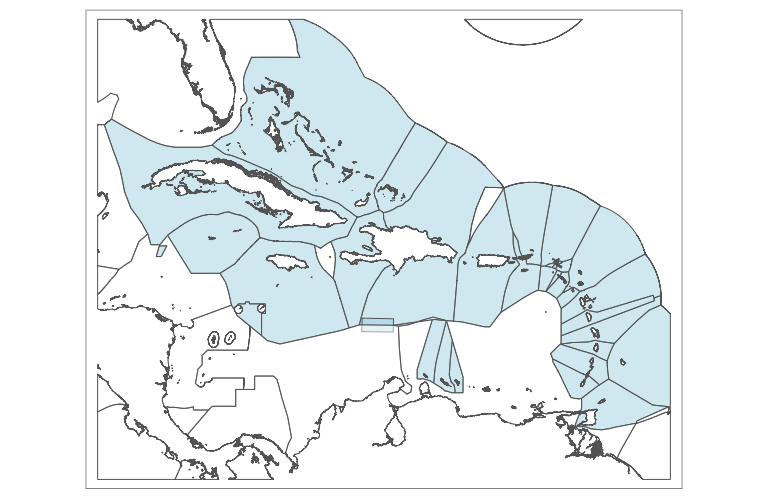


Model schematic for estimating cobia aquaculture production potential. Green squares indicate model inputs, blue squares indicate model components, and orange squares indicate model outputs.

## 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 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.

## OGR data source with driver: ESRI Shapefile   
## Source: "/Users/lennonthomas/Box Sync/Waitt Institute/Blue Halo 2016/Carib\_aqua\_16/Suitability/tmp", layer: "carib\_eez\_shape"  
## with 54 features  
## It has 23 fields



The study area for this project is indicated in blue. EEZ boundary data were obtained from VLIZ (2014).

## 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 six factors: depth, current speed, coral reef presence, shipping activity, oil structures, and areas designated for conservation (Table 1).

## \*\*Spatial Data Layer\*\* \*\*Year\*\*  
## 1 Marine Protected Areas 2016  
## 2 Oil Rigs 2003  
## 3 Shipping 2005  
## 4 Coral Reefs 2010  
## 5 Depth 2009  
## 6 Current Velocity 2005-2015  
## 7 Deep sea bed mining claims 2016  
## \*\*Data and Analysis Description\*\*  
## 1 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 aquaculutre development in areas of high conservation priority.   
## 2 Stable light flares from NOAA's National Geophysical Data Center (NGDC) with ephemeral sources of lights removed were isolated using sepctra analysis to identify location of oil rigs in the ocean.   
## 3 Mobile data on 3,374 large (> 1000 gross tonnage) commercial and research vessels at sea in 2005 were obtained from the World Meterorological Organization Volunatry 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  
## 4 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).  
## 5 Global measured and estimated seafloor topography data from satellite altimetry and ship depth soundings  
## 6 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 1/3 degree grid with a 5 day resolution. OSCAR is generated by Earth Space Research (ESR).   
## 7 Worldwide spatial locations of contracts for seabed mining exploration and deep sea mining claims issued by the International Seabed Authority   
## \*\*Suitability Criteria\*\*  
## 1 Not an established, designated or proposed Marine Protected Area  
## 2 No existing benthic oil structures  
## 3 Not included in the top 10% of relative shipping activity in the Caribbean  
## 4 No coral reefs are present in the 1 km2 area  
## 5 Depths >=25 and < = 100  
## 6 Maximum average monthly zonal or meridonal current velocity < 1  
## 7 No mining claim or contract present  
## \*\*Data Source\*\*  
## 1 IUCN and UNEP-WCMC 2016  
## 2 Halpern et al. 2008  
## 3 Halpern et al. 2008  
## 4 UNEP-WCMC, WorldFish Centre,\xe6WRI,\xe6TNC\xe62010  
## 5 Kapetsky et al. 2013  
## 6 ESR 2009  
## 7 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 90 m, cage installation and inspection of mooring and anchoring systems is more difficult and costly (Scott and Muir 2000). We obtained spatial bathymetry data from Becker *et al* (2009), 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 monthly average current data from Ocean Surface Current Analysis Real-time (OSCAR) zonal and meridional surface current velocity estimates from JPL Physical Oceanography DAAC and developed by Earth Space Research (ESR 2009). The daily absolute maximum zonal and meridional velocities for each cell in our study area were calculated, and any cell with a maximum zonal or meridional velocity greater than 1 m/s were scored as unsuitable for the development of offshore aquaculture.

We also obtained spatial data on coral reef locations

To identify areas currently designated or utilized for purposes that would preclude offshore mariculture 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 with coral reefs present, 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 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 (Fredriksson et al. 2004; 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 (**???**). 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 (**???**) 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.

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 (**???**). 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 (**???**).

## \*\*Farm Specification\*\* \*\*Value\*\*  
## 1 Cage volume (m3) 6,400  
## 2 Number of cages 16  
## 3 Harvest size (kg) 5  
## 4 Harvest density (kg/m3) 15  
## 5 Harvest desnity (# of individiuals per cage) 16,000  
## 6 Natural mortality rate (M)   
## 7 Stocking density (# of individuals per cage)

## Bioeconomic Model

### Temperature Performance Curve

Temperature is one of the primary abiotic factors controlling growth in fish, including cobia (**???**), and is a factor that cannot be easily controlled in offshore mariculture grow-out settings. 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 (add citation for TPC?). 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:

where \*tmin is XX, tmax is XX, and max growth occurs at topt, and SST is the average monthly SST over the last 10 years for locations (Table XX)

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

number of cage *(sum of harvest from a cage over a year = biomass in month i-1 + growth k*  cages are stocked in a way to optimize growth.

where , is the initial stocking density of each cage, and , the total survival rate is assumed to be 95% (**???**).

Monthly biomass is then summed, to determine total annual biomass () at each farm.

Where estimates biomass (t) in month as a function of average monthly sea surface temperature.

### 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:

$TC\_{i,t=1} = SC\_{i,t=1} + OC\_{i,t=1} $

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 :

$ SC\_{i,t=1} = E\_{depth} + I\_{distance,EEZ} + P\_{EEZ} $

where 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 cost of fingerlings in year , and is the cost of feed in year .

#### Cobia price

The global market for cobia is currently very small, with just 8.5% of production (4,555 MT) exported in 2012. We assume that cobia aquaculture in the Caribbean will be an export commodity and thus increased production in the Caribbean will affect the global price of cobia as follows:

Where is the global price of cobia ($) in the following year and is the percent change in Caribbean production from the previous year. The constant 0.8 represents the price elasticity of demand and suggests that for every 1% increase in price there is a 0.8% decrease in consumption.

To set the price of cobia at a given production level, we construct a supply curve for cobia by estimating the total production of cobia (assuming only profitable farms are developed) at every price from 0 to XX at $0.05 increments. The price of cobia for each model run was then set at the intersection of the supply and demand curve. We applied a bio-economic model to estimate the production (in terms of cobia biomass yield (*mt*) and Net Present Value (*NPV*)) over a 10 year horizon for our 1 km2 hypothetical cobia farms in all cells that were identified as suitable. Only farms that generated positive NPV over the ten year period were considered economically feasible for development.

##### Net Present Value (NPV)

Annual total revenue, , for each farm was calculated as :

Where is the export tax as a function of EEZ.

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

\_t^{10}

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 sector's NPV over a 10 year time horizion for each site :

$A = \frac{\delta(NPV^i)}{1 - (1 + \delta)^{-T}$

The economic discount rate () was calculated for each EEZ (Table 5) and used to reflect relative investment risk associated with developing mariculture farms in each country. Methods used to calculate EEZ discount rates can be found in the Appendix.

Under each scenario, individual farms were developed in order of highest annual revenue.

## Production Limit Scenarios

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

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 (reference) 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 modelled in our study, it provides another regional production level benchmark for comparison.

We then investigated a range of potential regional production limit scenarios at the EEZ scale for the Caribbean (these may not all be relevant once we see results):

1. No ecological production limit- There is no regionally specified production limit (demand curve is limiting factor)
2. High ecological production limit- We set the production limit by identifying the EEZ worldwide with highest production per unit area from our production assessment and multiply that value by the total area identfied as suitable for offshore aquaculture development in each EEZ in the Caribbean (price is set based on this ecological production limit value)
3. Precautionary limit- The production limit for each EEZ is determined by multiplying the production per unit area value specified for the Gulf of Mexico (`rProductionrate,big.mark=",") by the total area identified as suitable for offshore aquaculture development in each EEZ (price is set based on ecological production limit value.
4. Current market price- Price is set at current global market price for cobia.

Under each scenario, individual farms were developed in order of highest annual revenue, and only farms with a postive 10 year NPV were developed.

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

* Total production (in terms of profit and weight) for the entire study (Caribbean) region (does this economic contratint restrict things to below ecologically demanding levels. if its below then econoomic 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)

## 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