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The ecological and economic potential for offshore mariculture in the Caribbean

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Offshore mariculture could enable increased seafood production and economic development while alleviating pressure on coastal ecosystems and wild fisheries. In the Caribbean, however, an integrated assessment of the ecological and economic potential for mariculture in the region is lacking. We assess site suitability and develop a spatial bioeconomic model to predict yields and profits for offshore cobia (*Rachycentron canadum*) mariculture across 30 jurisdictions in the Caribbean. We find that (1) approximately 1.4% of the study area may be technically feasible; (2) the model could avoid conflicts with other uses and sensitive habitats and protected areas; and (3) the model could be economically profitable, with the potential to produce almost half the amount of seafood that is currently harvested from wild fisheries globally. Here, we show that potential farm-scale production and profitability vary across and within countries and that accounting for the foreign investment risk associated with a country will impact estimated farm profitability.

Global seafood production is expected to exceed 151 million metric tons (MMT) by 2030, a 10% increase over current levels[1,2]. The vast majority of new production must come from aquaculture, given only modest potential increases from capture fisheries[3]. Marine aquaculture, or mariculture, is seen as having particularly strong growth potential[4]. As mariculture technology advances, production from offshore mariculture—generally defined as occurring at more than three nautical miles offshore and/or at depths >30 m (ref. [5])—is expected to increase[1]. By moving to deeper waters, further from the coast, offshore aquaculture could represent a viable strategy to minimize aquaculture's potentially adverse environmental and socioeconomic consequences[5,6]. Realizing this growth, however, requires an understanding of the sustainable and economically viable production potential at different spatial scales, along with an identification of hurdles impeding development.

In recent years there has been growing interest in aquaculture development in the Caribbean as a path forward to increase both local seafood supply and economic development[7–10]. Aquaculture production in the Caribbean to date has largely been land-based aquaculture of tilapia (*Oreochromis* sp.) and coastal pond aquaculture of white-legged shrimp (*Litopenaeus vannamei*)[11]. However, the potential for increased land-based aquaculture production in the region is limited due to the constraints of available land, freshwater and energy resources[12]. Similarly, expanded development of alongshore coastal mariculture in the region is probably unsustainable and difficult due to conflicts over space in highly utilized and ecologically sensitive coastal areas[13]. For example, coastal aquaculture can harm mangroves and coral reefs by increasing nutrient loads and causing physical damage to the habitat from farm infrastructure[13,14], with cascading effects on marine-based tourism, the backbone of many Caribbean island economies[14].

The development of offshore aquaculture offers a promising alternative[15,16], and submersible cages will allow its development in areas that were previously considered unsuitable due to wave intensity and/or high risk of damage from severe storms and hurricanes[16]. Small-scale trials raising cobia (*Rachycentron canadum*), pompano (Carangidae spp.) and red drum (*Sciaenops ocellatus*) in offshore environments were successful in the Bahamas and Puerto Rico[14]. Cobia has been identified as an ideal candidate species for mariculture in the Caribbean because of its relatively fast growth rate, high market value and tolerance for environmental fluctuations[12,17]

Despite the seeming promise, there are currently no analyses examining the Caribbean-wide potential for offshore mariculture development. Current studies examining mariculture potential tend either to analyse the bioeconomics of a single farm[18–20] or examine production potential at a larger scale, but only while considering biophysical constraints[15,21]. There are currently no studies that examine potential in terms of both production and value at a regional scale, and very little attention has been given to the economic impacts of investment risk for this emerging industry, which will probably be an important driver of the progress made in development of the mariculture industry. Here, we fill these gaps by presenting a framework that incorporates biological, environmental and economic factors to estimate the potential of offshore mariculture across the 30 national jurisdictions of the Caribbean.

Using *R. canadum* as an example species, we develop a spatial bioeconomic model that is applied to areas we identify as techinically feasible to: (1) estimate the offshore mariculture production capacity of the Caribbean region (in terms of cobia production and net present value (NPV) over a 10-year time period); (2) examine the impact of farm site selection on economic outcomes across and within countries and determine the importance of strategic farm site selection; and (3) identify potential barriers to offshore mariculture development in the region by comparing results under three development scenarios. Our development scenarios are defined as: (1) a 'suitable' scenario, where farms are developed in all areas that have been identified as techenically feasible in our suitability analysis; (2) a 'profitable uniform' scenario where only farms with a positive 10-year NPV are developed, assuming a uniform annual discount rate of 10% across the region; and (3) a 'profitable risk' scenario where only farms with a positive 10-year NPV are developed,

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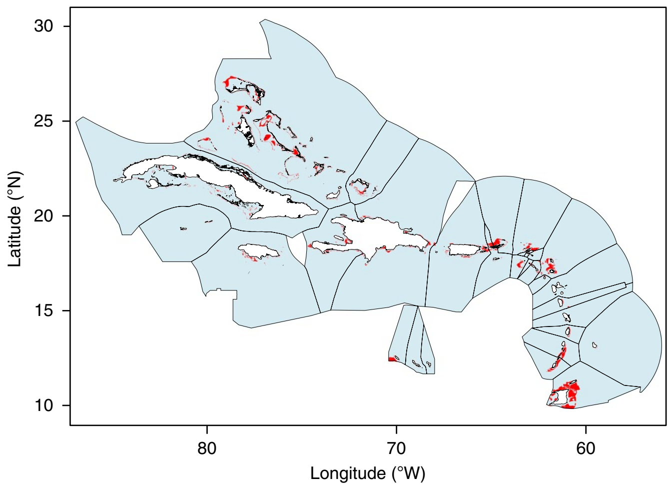

Fig. 1 | Offshore mariculture suitability in the Caribbean. Areas that were identified as potentially suitable for offshore cobia mariculture development (red) in the Caribbean, accounting for technical, environmental and use conflict constraints.

assuming country-specific discount rates that reflect the countries' relative investment risk for foreign investors.

Our approach integrates economic, biological and environmental data to estimate offshore mariculture potential spatially at a regional scale. The framework we developed can be applied to other farmed species and to other regions, to help chart a course for a sustainable and economically prosperous offshore mariculture industry in the Caribbean, and beyond.

Results

Suitability. Accounting for technical, environmental and use conflict constraints, we identify 40,628 km^2 of ocean space (1.37% of the study region) as potentially suitable for the development of offshore mariculture (Fig. 1). Depth is the most constraining factor in the suitability analysis, as 97.85% of the study area falls outside the depth range (25–100 m) considered technically feasible for offshore farm infrastructure (Supplementary Table 1). By comparison, the second most constraining factor is distance from shore, which excludes 72.3% of our study area. There is considerable spatial variability in the amount and distribution of suitable area for offshore mariculture in the Caribbean (Table 1; Fig. 1). The Bahamas, Cuba and Trinidad and Tobago have the largest potentially suitable area, and the spatial distribution and clustering of suitable sites within each of their waters (that is, exclusive economic zones (EEZs)) differs considerably (Fig. 1). Both the Bahamas and Trinidad and Tobago have more than twice the suitable area of Cuba, the country with the next largest amount of suitable area (Table 2). The large suitable area in the Bahamas can be attributed to its relatively large EEZ and extensive shelf area. Overall, Trinidad and Tobago has the largest percentage of its EEZ identified as suitable (11.18%), followed by Saba (6.92%) (Table 1). Suitable areas account for <5% of total EEZ area for all other Caribbean islands, due to the steep drop-off in water depth around most islands. No suitable areas are found in Martinique, Sint Maarten and Guadeloupe, in part because of the conservation status of otherwise suitable sites (Table 2).

Cobia production. Ignoring economic constraints (that is, in the 'suitable' scenario), the Caribbean's potential to produce cobia from mariculture is extremely large, with an approximate total annual production from suitable sites of 43.1 MMT. The median cobia farm occupying a 1 km^2 site in the Caribbean yields an annual supply of 946 metric tons. Not surprisingly, international variability in production is largely driven by the amount of suitable area within each EEZ; countries with the most suitable area also have the largest production potential (Tables 1 and 2; Fig. 2a). However, countries with the highest production potential do not necessarily have the most productive individual farms (Fig. 2). Cobia growth is a function of temperature, and growth rates vary across the region and within EEZs, in addition to showing a clear seasonal pattern (Fig. 3). The most productive farm sites are located within the EEZs of Jamaica and in the southeastern Caribbean, including in St. Vincent and the Grenadines, Barbados, St. Lucia and Trinidad and Tobago, where temperatures are closer to optimal (that is, closer to T_o) for cobia growth throughout the year (Fig. 3). Farms in Haiti and the Cayman Islands experience below-average growth rates during the peak summer months because water temperatures approach or exceed T_{max}.

Variability in growth rates, both spatial and seasonal, leads to differences in the length of time required to raise cobia to a market size of 5 kg (Supplementary Fig. 1). While the average farm in the Caribbean completes a harvest cycle in 13 months, harvest cycles range from 12 to 48 months. Longer harvest cycles affect the economics of cobia production by reducing harvestable biomass (due to increased time for mortality and escapes) and by increasing feed use and other operating costs. The economic feed conversion ratio (FCR)—calculated as total feed used divided by total harvested bio-

Table 1 | Estimated suitable and profitable areas, by EEZ

Country (ISO 3166-1 alpha-3 code)	Total EEZ area (km^2)	Suitable area (km^2)	Suitable area (%)	Profitable area (km^2)	Profitable area (%)
BHS	615,628	11,733	1.91	4,050	0.66
CUB	350,483	2,474	0.71	1,515	0.43
DOM	349,786	1,990	0.57	1,990	0.57
JAM	256,647	975	0.38	975	0.38
BRB	184,865	84	0.05	84	0.05
PRI	154,335	1,515	0.98	1,515	0.98
CYM	118,125	114	0.10	114	0.10
ATG	111,358	1,936	1.74	1,936	1.74
HTI	102,801	1,779	1.73	1,778	1.73
TCA	90,765	1,028	1.13	1,025	1.13
AIA	90,017	1,214	1.35	1,214	1.35
VGB	81,383	1,271	1.56	1,271	1.56
TTO	76,273	8,528	11.18	8,528	11.18
VIR	38,130	814	2.13	814	2.13
VCT	36,132	1,371	3.79	1,371	3.79
ABW	29,898	946	3.16	812	2.72
DMA	28,495	242	0.85	242	0.85
GRD	25,492	1,137	4.46	1,137	4.46
CUW	25,315	71	0.28	71	0.28
LCA	15,354	285	1.86	285	1.86
BES (Bonaire)	12,955	43	0.33	42	0.32
BES (Saba)	9,472	656	6.92	656	6.92
KNA	9,450	256	2.71	256	2.71
MSR	7,172	74	1.03	74	1.03
BLM	4,147	7	0.18	7	0.18
BES (Sint Eust.)	2,166	65	3.01	65	3.01
SXM	452	20	4.32	20	4.32

Table 2 | Supply (MMT) and total 10-year NPV (in US$ million) from all farms for each country under three different scenarios: (1) 'suitable' scenario, (2) 'profitable uniform' scenario and (3) 'profitable risk' scenario

Country (ISO 3166-1 alpha-3 code)	Supply (1) (MMT)	Supply (2) (MMT)	Supply (3) (MMT)	NPV (1) (US$ billion)	NPV (2) (US$ billion)	NPV (3) (US$ billion)
BHS	10.41	4.11	2.82	−39.31	15.28	8.76
TTO	9.79	9.79	9.79	69.27	115.5	69.27
DOM	2.34	2.34	2.34	14.73	28.92	14.73
CUB	2.33	1.55	1.16	−2.49	8.47	3.08
ATG	2.25	2.25	2.25	16.39	24.61	16.39
HTI	2.08	2.08	2.08	13.6	27.89	13.62
PRI	1.81	1.81	1.81	15.17	18.94	15.17
VCT	1.62	1.62	1.62	12.12	18.84	12.12
VGB	1.37	1.37	1.37	9.31	11.77	9.31
GRD	1.33	1.33	1.33	10.17	15.39	10.17
AIA	1.31	1.31	1.31	11.98	14.58	11.98
JAM	1.16	1.16	1.16	9.37	16.34	9.37
TCA	1.11	1.11	1.11	4.39	6.65	4.4
VIR	0.96	0.96	0.96	7.6	7.94	7.6
ABW	0.93	0.81	0.77	2.75	3.69	2.97
BES (Saba)	0.78	0.78	0.78	6.57	8.77	6.57
LCA	0.33	0.33	0.33	2.54	4.24	2.54
KNA	0.3	0.3	0.3	2.33	3.63	2.33
DMA	0.29	0.29	0.29	2.47	3.7	2.47
CYM	0.13	0.13	0.13	1.22	1.22	1.22
BRB	0.1	0.1	0.1	0.87	1.15	0.87
MSR	0.09	0.09	0.09	0.5	0.81	0.5
CUW	0.08	0.08	0.08	0.71	1	0.71
BES (Sint Eust.)	0.08	0.08	0.08	0.61	0.81	0.61
BES (Bonaire)	0.05	0.05	0.05	0.36	0.5	0.36
SXM	0.02	0.02	0.02	0.19	0.24	0.19
BLM	0.01	0.01	0.01	0.08	0.1	0.08

mass—is a measure of how efficiently a farmed animal converts feed into biomass, and is one of the main indicators used to compare the sustainability of different animal protein sources[22]. The FCRs of cobia farms in our analysis range from 1.92 to 9.97, with a median of 2.47. These findings are in agreement with the literature, in which FCRs for cobia range from 1.01 to 3.20[23]. Feed accounts for the vast majority of farm operating costs in our results, the median farm in our study spending 79.4% of operating costs on feed.

If farms are developed only if they are profitable after 10 years—assuming a 10% discount rate for all countries ('profitable uniform' scenario)—then the region-wide potential production is reduced by 16.7%, to 35.9 MMT relative to the 'suitable' scenario (Table 2; Fig. 2b). When risk to foreign investors is incorporated as a country-specific discount rate ('profitable risk' scenario), production potential is further reduced to 34.1 MMT. The biggest difference in production potential between the 'suitable' and 'profitable risk' scenarios is observed in the Bahamas, which has the largest amount of suitable area and shows a 73% decrease in average annual production when economics and risks are incorporated, followed by Cuba (50.1% decline) and Aruba (17% decline).

In terms of value, the median farm 10-year NPV across the Caribbean was found to be US$10.9 million assuming a uniform 10% discount rate ('profitable uniform') scenario, but 36% lower (US$7 million) with country-specific discount rates that incorporate investment risk ('profitable risk' scenario). Recognizing that farm site selection is more important in regard to maximizing profits in countries with high spatial variation in profitability, we found that in Cuba, the Bahamas, Haiti, Bonaire, Turks and Caicos Islands and Aruba, farm value varied considerably across each EEZ and therefore strategic site selection will be critical for prospective cobia farms (Fig. 4). For example, in the Bahamas the 10-year NPV of farms has a range of over US$20 million (from negative 11 million to 10.5 million, depending on farm location). Only the Bahamas and Cuba contained a considerable number of unprofitable farm sites under both discount rate scenarios, with a negative median farm value in both countries (Fig. 4).

Discussion

This study incorporates biological, environmental, economic and political data to estimate potential yields and profits for offshore cobia aquaculture across the Caribbean region. Our results reveal remarkable potential; we estimate a total annual production of 43.1 MMT if all suitable areas are developed, and 34.1–35.9 MMT if only profitable farms are developed. This potential yield is more than two orders of magnitude larger than total current seafood production in the region (~300,000 metric tons) and is around half of the total annual harvest from the world's capture fisheries (~80 MMT). Impressively, this output requires <2% of the Caribbean's marine space, a result similar to the findings of Gentry et al[13]. who estimated that current total fishery landings could be produced from farming finfish in 0.015% of the global ocean area. In fact, the Caribbean could match its current seafood production by farming

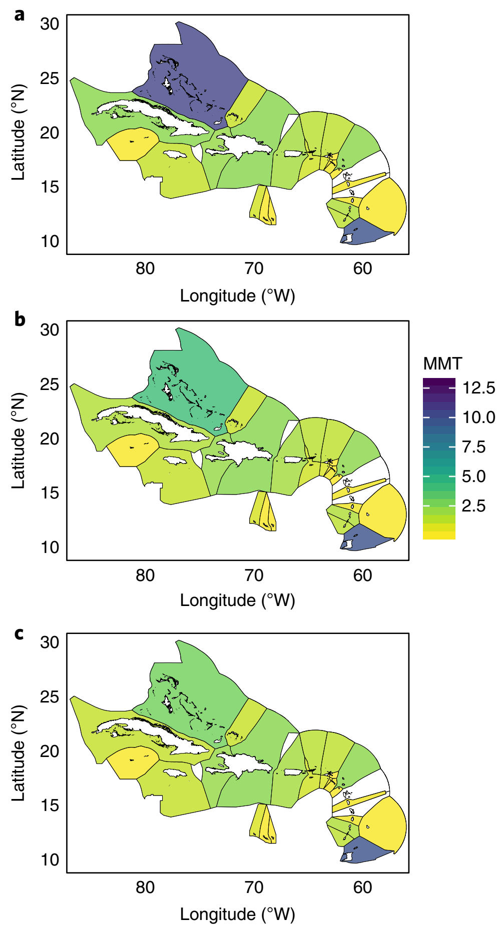

Fig. 2 | Estimated total average annual production (MMT) of cobia, by EEZ. a, 'Suitable' scenario. **b**, 'Profitable uniform' scenario. **c**, 'Profitable risk' scenario.

cobia in just 179 km^2 (0.006%) of its marine space. In addition to highlighting the total production potential of the Caribbean, this study also highlights those areas of the region in which cobia farming will be most productive and profitable.

This study provides an important contribution to the literature by integrating biophysical, economic and political factors in identifying potential sites for mariculture development[24]. Previous studies have found large potential for global mariculture development by identifying suitable areas using solely environmental data[15,21], and by estimating biological production rates that could occur in suitable areas[15]. To date, studies that have applied bioeconomic modelling to examine the economic feasibility of mariculture farms have largely been focused either on a single farm in a previously specified area[18,20,25,26] or on spatial variation in farm profitability within a single national jurisdiction[27], and there have been no bioeconomic studies of offshore mariculture potential that account for variable investment risk across countries. This analysis accounts for biophysical production potential, economic profitability and investment risk, and assesses the economic feasibility of offshore mariculture across the many jurisdictions of the Caribbean[28]. The framework provided by our study could be applied to other species in the Caribbean or to other regions.

Our results indicate that space for offshore development in the Caribbean is not a limiting factor. However, farm location can have a major impact on its realized profitability, highlighting the importance of strategic site selection that incorporates economic factors at both regional and within-EEZ spatial scales. In our study, the Bahamas showed excellent potential because of a large EEZ and large suitable area, which aligns with conclusions from previous studies[28]. However, we find that the majority of cobia farms within the Bahamas are not profitable because of slower growth rates resulting in lower farm production due to cooler average sea surface temperatures. Although cobia farming as a venture is not currently as promising for the Bahamas relative to other countries, farming of other species with optimal growth at a cooler temperature could be worthwhile. Cobia appears to be a species well suited for culture in the warmer waters found around Jamaica and in the southeastern Caribbean. The most profitable farms, without considering investment risk, were found in Haiti, Dominican Republic, Trinidad and Tobago and Jamaica; these countries may want to consider encouraging development through streamlined regulatory policies or other incentives.

Within individual countries, those with greater farm-to-farm variability in outcomes represent countries for which strategic site selection for mariculture development is particularly important. The 10-year NPV of farms sited in Cuba, the Bahamas and Turks and Caicos varies by millions of dollars annually, and not all suitable sites in these EEZs are economically viable. Within-EEZ variability in profits is driven primarily by variability in sea surface temperatures, highlighting the importance of carefully considering local oceanographic features when evaluating site location. Although we consider a range of factors that influence profitability beyond temperature (labour costs, fuel costs and construction costs), there are also numerous potentially important factors that we did not consider. The activities of wild fisheries have the potential to conflict with offshore mariculture development in cases where fishers are excluded from fishing near mariculture[29]. Comprehensive spatial data on fishing activity, particularly in near-shore areas, were not available for the Caribbean region so we were unable to evaluate the extent of overlap between exisiting fishing activities in the region and potentially suitable offshore aquaculture sites. However, given the high production possible from a small footprint (that is, we assumed 1 km^2 farms) and the large number of profitable sites in many EEZs, aquaculture development often may not require substantial displacement of fishing activity.

Additional economic and logistical factors not accounted for by our model and that could be considered in future analyses include: distance to markets or seafood shipping capabilities, proximity to onshore hatcheries and seafood processing facilities and the availability of a labour force[9]. In particular, our model does not impose constraints on the availability of feed. Feed is one of the largest limiting factors to aquaculture development, although the combined actions of fisheries reform, reduced feed use by non-carnivorous aquaculture and innovations in novel feed ingredients may help circumvent feed limitations of fed aquaculture in the future[30,31].

The results of our model are most sensitive to a few key assumptions, including the depth range that is technically feasible for offshore development and the market prices of cobia and cobia feed (Supplementary Table 1 and Supplementary Fig. 2). First, technology for offshore aquaculture is rapidly advancing, and it is likely that in the near future installing farm infrastructure at greater maximum depths will be technically and economically feasible. Caribbean island countries have large EEZs relative to their land areas, and depth was the largest constraining factor in our suitability assessment (Supplementary Table 1). As the suitable depth range for this industry expands, the area amenable to offshore aquaculture development will grow exponentially although there will also be higher costs associated with installation, maintenance and operations in deeper waters further from shore.

Second, our model uses current market prices for cobia and cobia feed and does not account for Caribbean production influencing global prices, an assumption that will not hold under significant levels of development. For example, the rapid increases in

Fig. 3 | Monthly cobia growth rates, averaged over 10 years, by EEZ. The mid-point of the colour bar (white) represents the overall average monthly growth rate of cobia across the Caribbean.

farm-raised salmon, catfish and sea bream have been accompanied by a substantial, albeit sometimes temporary, decrease in global market price[32]. Although data on the price of cobia feed are difficult to obtain, feed costs in our model account for 79.4% of operating costs, which is consistent with values previously reported in the literature for cobia farms[18,33,34]. Similarly, our model assumes that cobia produced in the Caribbean is sold as an export product at the current market price of US\$8.62 kg^{-1}. The increasing popularity of cobia sashimi[35], along with the recent Aquaculture Stewardship Council certification of Open Blue cobia farms, has opened up the potential for higher-end markets for cultured cobia, in which case US\$8.62 kg^{-1} may be a conservative estimate. A sensitivity analysis showed that at a cobia market price of US\$11 kg^{-1} nearly all suitable farms are profitable under both discount rate scenarios, with annual Caribbean supply >40 MMT in both cases. In contrast, production declines sharply to <1.5 MMT if the price falls below US\$7.50 kg^{-1} (Supplementary Fig. 2). Predicting how global price will be impacted as production increases in this rapidly developing industry is difficult, but global dynamics of cobia supply and demand should be carefully considered before any rapid development of cobia aquaculture takes place. One option for moving forward with offshore mariculture development in the Caribbean could be to diversify the species being cultured and choose those that are best suited in terms of optimal temperature-dependent growth for different regions.

Although our results demonstrate huge potential for increased seafood production and revenue from offshore cobia farming across many countries in the Caribbean, there is currently very little mariculture production in the region. Lack of aquaculture development in the Caribbean has largely been attributed to the absence of affordable credit to assist private sector development, and to investment environments that are not attractive to foreign investors. Risky investment environments are associated with higher discount rates that are notoriously difficult to predict or quantify[36]. Investment in offshore mariculture is generally considered risky due to the relative newness and unpredictability of the industry[37]. Our study attempts to account for the risk in foreign investment associ-

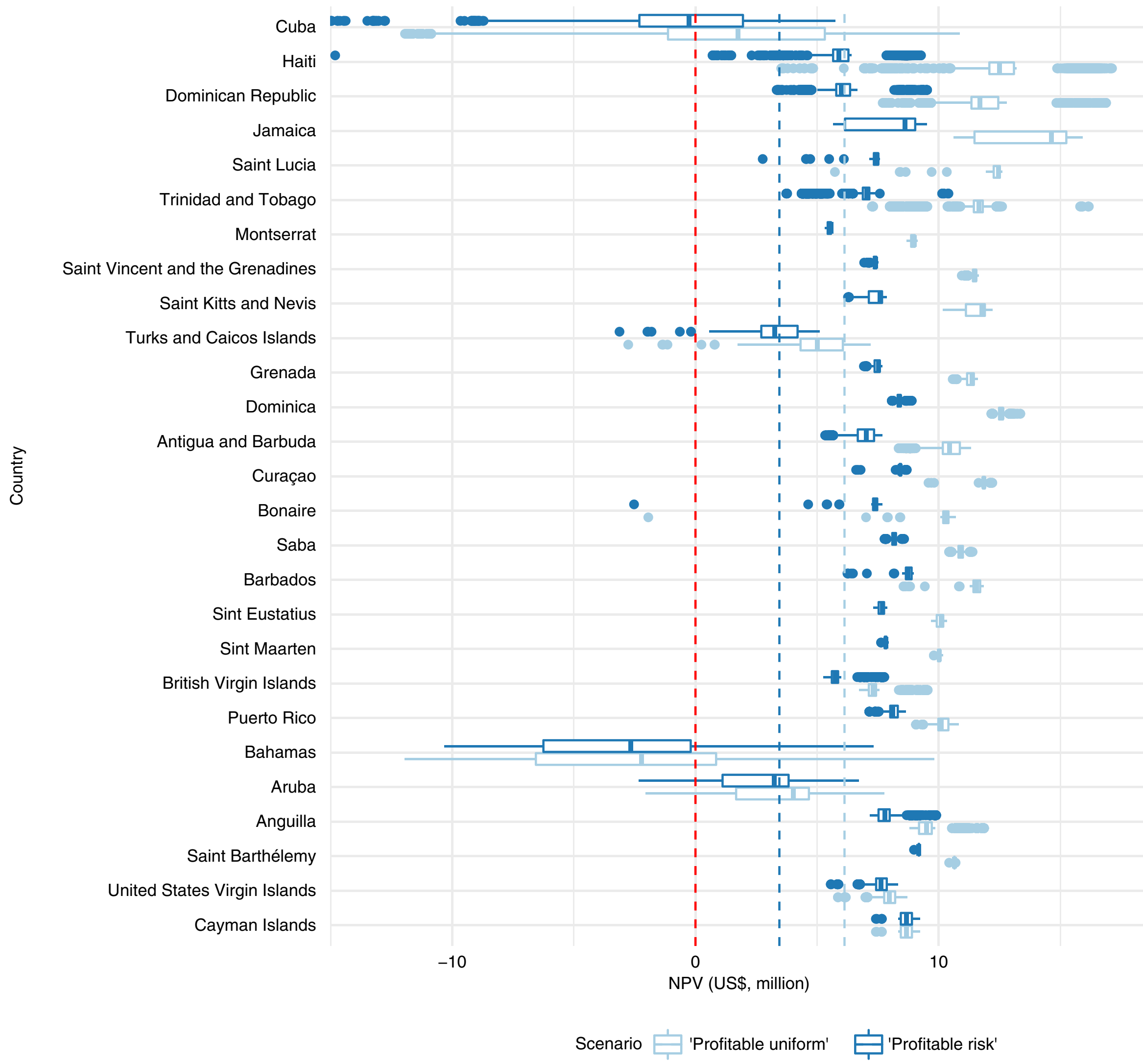

Fig. 4 | Ten-year NPV (in US$ million) per cobia aquaculture farm by Caribbean EEZ. The centre line of each box represents the median NPV; the lower and upper hinges correspond to the 25th and 75th percentiles, respectively; whiskers extend to ×1.5 interquartile range and points represent outliers. The red dotted line indicates a 10-year NPV of US$0, and the light blue and dark blue lines represent median 10-year NPV for the entire Caribbean under the 'profitable uniform' and 'profitable risk' scenarios, respectively.

ated with each country by incorporating political and economic indicators to define country-specific discount rates, which lowers the 10-year NPV value of farms in many countries. In Haiti for example, a country associated with high investment risk due to the country's low gross domestic product and high level of political corruption, accounting for investment risk translated to a loss in median farm-level NPV of nearly half a million US dollars, a loss that could sway an investor towards opportunities that are less risky. Interestingly, only the Bahamas and Cuba contain farms that become unprofitable after accounting for higher investment risk (Fig. 4).

Policy for aquaculture development varies considerably across the Caribbean, and can also play an important role in where and how aquaculture is developed[38,39]. Countries with aquaculture legislation and policies in place to promote the development of aquaculture, such as fiscal incentives, are more likely to attract foreign investors. For example, a country could exempt imported products required for aquaculture from import tax. To ensure that any development occurs sustainably, however, it is important for countries to have clear policies in place that include an evaluation of the environmental impacts of farms and general guidelines on where and how development should occur. Furthermore, clear policies and processes for aquaculture permitting and development can also attract development, because countries with overly lengthy or confusing permitting processes can be a deterrent for potential investors. For example, Snapperfarm, a small-scale offshore mariculture farm originally based in Puerto Rico, had difficulty obtaining permits to expand their operation and, as a result, the operation moved to Panama and is now operating as Open Blue[38,40].

In conclusion, sustainable aquaculture development can be greatly assisted by adopting a planned approach to development. This study offers a comprehensive look at the production potential of offshore mariculture in the Caribbean, and the results can be used to help guide and plan offshore mariculture development. Although our analysis focuses on a single species, the framework presented here can be used to explore the potential for other offshore mariculture species. Given that temperature is a major driver of our results, future studies should examine how optimal locations may change given the species being cultured and predicted increases in temperature associated with climate change. Lastly, our framework could be adopted in other regions interested in developing offshore finfish mariculture, and could be coupled with a more comprehensive assessment of trade-offs with other marine uses and management objectives.

Methods

Study region and overview. The study area includes the EEZs surrounding the 28 island countries of the Caribbean Sea, with EEZ boundaries defined using data from Flanders Marine Institute[41] and all analyses performed at 1 km^2 spatial resolution. We do not consider the potential for offshore aquaculture development in the high seas or disputed waters. We develop a spatial bioeconomic model to estimate the production potential, in terms of annual harvested biomass and 10-year NPV, for offshore cobia mariculture throughout the study area. We first identify 1 km^2 sites that are suitable for offshore mariculture development. Next, we apply a thermal performance curve to predict temperature-dependent individual growth and subsequent total production of cobia at each 1 km^2 farm site over a 10-year period using average sea surface temperatures from 2007 to 2016. Finally, cobia production estimates are coupled with an economic model to calculate farm-scale NPV values given a 10-year time horizon, including a scenario in which we account for differential investment risk across countries.

Suitability assessment. We identify 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 that we view as fixed constraints to development (Supplementary Table 1). We define suitable thresholds for each factor and use high-resolution spatial data in a Boolean overlay to identify 1 km^2 areas in our study region that are potentially suitable for offshore mariculture development given the defined thresholds. See 'suitablility analysis' section in Supplemenatry Information for a description of data layers and thresholds used to identify suitable areas for offshore mariculture.

Growth model. We model offshore mariculture production using a hypothetical farm design, per 1 km^2 site, applied across the study region to all suitable sites. Our hypothetical farm design is based on the total cage volume:farm area ratio of operational offshore mariculture farms[42,43], and has 16 SeaStation cages (each 6,400 m^3) configured in two eight-cell gridded mooring systems, for a total cage volume of 102,400 m^3 per 1 km^2 farm. The infrastructure of the farm has a footprint half the size of the total farm area (~0.48 km^2), which meets the guidelines issued in the National Oceanic and Atmospheric Administration's Fishery Management Plan for offshore aquaculture development in the Gulf of Mexico[44].

Temperature is one of the primary abiotic factors controlling growth in ectotherms, including cobia[45], and cannot be controlled in offshore mariculture farms[46]. To reflect spatial differences in productivity across farms caused by temperature variation, we use remotely sensed 1-km^2-resolution average monthly sea surface temperature data collected over a 10-year period (2007–2016)[47].We apply a thermal performance curve (see Supplementary 'Information on Thermal Performance Curve') to these data to estimate average monthly temperature-dependent individual somatic growth ($\bar{G}$, in kg month^{-1}) of cobia for each farm (i) in each calendar month (t) over the 10-year (y) sea surface temperature time series.[48]

$$\bar{G}_{i,t} = \frac{\sum_{t=1}^{120} G_{i,t,y}}{10} \quad (1)$$

We assume that fingerlings at each farm are stocked at an initial weight of 15 g and that cobia are harvested when individual fish reach a harvestable weight (HW) of 5 kg (ref. [17]). For each farm, we simulate cobia production (MT) for the number of complete grow-out cycles (g) each farm can complete in 10 years. We chose to model production in complete grow-out cycles rather than using a fixed 120-month time horizon, to ensure that farms are not in the middle of a grow-out cycle (and thus incurring costs) at the end of the simulation. We calculate g for each farm by dividing the cumulative individual growth by the target HW:

$$g_i = \frac{\sum_{t=1}^{120} \bar{G}_{i,t}}{\text{HW}} \quad (2)$$

Fish weight (w) in each month of a grow-out cycle is calculated as the cumulative growth since the stocking month (t_s):

$$w_{i,t} = \sum_{t_s}^{t} \bar{G}_{i,t} \quad (3)$$

We apply an instantaneous monthly mortality rate (M) and adopt 10 kg m^{-3}as a target harvest density, which is the average reported in a previous Caribbean study[17]. Total biomass (B) in each month of the simulation is a function of the initial number of stocked fingerlings (n_s), individual fish weight (w) and M:

$$B_{i,t} = w_{i,t} \times (n_{s,i} - n_{s,i}(1-e)^{-Mt}) \quad (4)$$

Cobia are harvested in months where $w_t \geq 5$ (under the assumption that harvest occurs at the beginning of the month) and, while $g \leq g_i$, farms are restocked with n_s.

Because the duration of grow-out cycles varies across farms (Supplementary Fig. 1), the initial number of stocked fingerlings (n_s) required for each farm to achieve the target harvest density is calculated from the total farm volume (102,400 m^3), harvest weight (HW = 5 kg), grow-out cycle duration (months) and natural mortality rate (M = 0.024).

Economic model. Our cost model of offshore cobia aquaculture in the Caribbean calculates total costs (TC) for each farm, i, which includes fixed one-time initial capital expenditures (E) and monthly operating costs (OC) over a 10-year period:

$$\text{TC}_i = E_i + \sum_{t=1}^{T} \text{OC}_{i,t} \quad (5)$$

Cost parameters values are listed in Supplementary Table 2 and were obtained from either published literature or personal communication with industry experts. Some parameters were fixed across our study region (Supplementary Table 2) while others are a function of the EEZ in which the farm is located (Supplementary Tables 3 and 4).

Initial capital expenditures (E) for each farm are calculated as:

$$E_i = (16 \times C + (C \times m_i)) + (I + (I \times m_i)) + l \quad (6)$$

where 16 represents the number of cages per farm and C is the cost of a single 6,400 m^3 SeaStation cage and mooring equipment; m = 0.10 for farms of depth >50 m, to account for a more complex and time-consuming installation, and m = 0 for farms of depth <50 m;[27] and l represents the cost of a 10-year lease for the farm site.

Operating costs for each farm are calculated per month (t) as:

$$\text{OC}_{i,t} = L_{i,t} + m_{i,t} + (H \times n_{s,i}) + F_{i,t} + \text{VC}_{i,t} + P_{i,t} \quad (7)$$

where L represents monthly farm labour costs; m represents monthly farm maintenance costs; H is the cost per fingerling; n_s is the number of fingerlings stocked per grow-out cycle; F represents monthly feed costs; VC is monthly costs assocatied with a farm support vessel (see equation 10); and P is monthly electricity costs equal to 0.09% of all other monthly operating costs[18].

Monthly farm labour costs (L) are calculated as:

$$L_{i,t} = (160 \times w \times s_z) + \left(\frac{d_i}{v} \times 60 \times s_z \times w\right) \quad (8)$$

where 160 is the total monthly labour hours required at each farm site for a full-time employee; w is the number of full-time employees at each farm; s is the EEZ-specific (z) hourly salary (we apply the minimum wage found for each country; Supplementary Table 3); d is the distance of the farm from shore (in m); v is the average vessel speed (Supplementary Table 2); and 60 represents the number of one-way trips per month to the farm assuming that one round trip is made each day.

Monthly maintenance costs (MA) for each farm are assumed to equal 0.5853% of the farm's capital expenditures (E), or 7% of capital costs annually:[49]

$$\text{MA}_{i,t} = 0.00583 \times E_i \quad (9)$$

F represents the monthly cost of feed as a function of farm biomass (B). Cost of feed is based on a feed price of US\$2.00 kg^{-1} and a tapered feeding strategy in which daily feed usage (30 days per month) corresponds to 3% of total farm biomass (kg) for the first three months, 2% for months 4–8 and 1% thereafter[17].

Vessel costs are calucated as:

$$\text{VC}_{i,t} = V + \frac{d_i}{j} 60 f_z \quad (10)$$

where V is the monthly cost of a vessel to support stocking, feeding, maintenance and harvesting for each farm and the monthly cost of vessel docking fees; 60 is the number of monthly one-way visits to the farm site assuming that one round trip is made each day; f is the EEZ-specific per-gallon cost of fuel; j is the average fuel efficiency and f is the average price per gallon of fuel in country z. Vessel costs are based on the vessel operations outlined in National Oceanic and Atmospheric Administration Technical Memorandum no. NMFS F/SPO-103 (ref. [50]) assuming a 10-year time period. The vessel has a 30 T payload and is capable of making at least one round trip per day to any farm within 25 nautical miles.

Farms earn revenue R by harvesting market-weight (5 kg) cobia. Thus, farms earn revenue only in months where individual fish weight reaches or exceeds 5 kg, otherwise R = 0. Revenue is a function of harvested farm biomass (kg) and cobia price (p), as in $R_{i,t} = B_{i,t} * p$. We assume a farm gate price of US\$8.62 kg^{-1}[18]:

$$\pi_{i,t} = R_{i,t} - \text{TC}_{i,t} \quad (11)$$

Cobia farms in the Caribbean are assumed to be price takers and thus production in month t does not affect price in month $t+1$. Total farm profit (π) is the sum of revenues less total farm costs.

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

$$\mathrm{NPV}_i = \sum_{t=0}^{T} \frac{\pi_{i,t}}{(1+\delta_{z|\mathrm{fixed}})^t} \quad (12)$$

where δ_z is the discount rate, which varies depending on the scenario (described below).

Production and NPV values for each EEZ are calculated for three main scenarios: (1) a 'suitable' scenario, where farms are developed in all areas that meet the criteria used in our suitability assessment; (2) a 'profitable uniform' scenario, where only farms with a positive 10-year NPV are developed assuming a 10% discount rate across all countries (δ_{fixed}); and (3) a 'profitable risk' scenario, where only farms with a positive 10-year NPV are developed assuming a country-specific discount rate (δ_{EEZ}) that incorporates the country's relative risk to foreign investors based on the economic and political climate.

Discount rate. Lack of foreign investment due to perceived financial risk has been identified as a major barrier to aquaculture development in the Caribbean[51]. Foreign investment risk reflects both political and economic risks in a country, which can be calculated as a single risk score using economic and socioeconomic indicators[52]. When estimating returns on an investment, the assumed discount rate can be adjusted to account for potential risks due to socioeconomic and political factors by assuming a higher discount rate[53]. We use variables that are representative of the political and economic climate of a country to calculate an 'investment risk' score for that country, where higher scores indicate a higher risk for foreign investment in a country[52] (Supplementary Table 5). For detailed methods on how country investment scores were calculated, see Supplementary 'Risk Adjusted Discount Rate'. A meta-analysis of published bioeconomic models for aquaculture found assumed discount rates ranging from 10 to 25%[54] (Supplementary Table 5).

Defining appropriate discount rates is often difficult and is dependent on many factors, particularly the cost of capital and various types of project risk[53]. Therefore, in addition to our country-specific discount rates representing investment risk, we also examine results assuming a uniform discount rate of 10% across all farms. The uniform discount rate of 10% is based on the average discount rate found in a meta-analysis of published bioeconomic models for aquaculture from the last 25 years[54].

Sensitivity analyses. The use of a current global market price for cobia is a large assumption in our model, as market dynamics in this rapidly developing industry are difficult to predict. Therefore, we evaluate the sensitivity of our results (annual Caribbean supply) to cobia prices ranging from US\$6.00 to 11.00 kg^{-1} (Supplementary Fig. 2).

The cost of feed typically represents the main component of aquaculture operating costs[33]. Changes in the price of feed are difficult to predict, but prices are expected to increase over the long term given increasing demand for high-quality feeds from both aquaculture and terrestrial animal production sectors[30,55]. Thus, we also examine how annual Caribbean supply would be affected by a 25% increase in the price of feed (Supplementary Fig. 2).

Code availability

Codes are available through github (https://github.com/lennon-thomas/Carib_aqua_16).

Data availability

The datasets generated and analysed in this study are available from the authors upon request.

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Author contributions
All authors contributed to research design and interpretation of results, and provided supporting information for the project. The TPC modelling was conducted by D.K., the suitability analysis and economic model was conducted by T.C. and L.T., and L.T., S.L. and T.C. wrote the paper.

Competing interests
The authors declare no competing interests.

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