A GIS-based Spatial Model for Predicting Habitat Suitability for Juvenile Mutton Snapper (*Lutjanus analis*) in Belize

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ABSTRACT

Because of their life history ecosystem-based management of tropical marine fisheries is complex. Locating suitable marine and coastal habitats for fishes in the Caribbean involves complex judgments that are important for the design of effective Marine Protected Areas networks. This paper evaluates the use of an ecosystem-based approach to fisheries management for a single species, that might be expanded for additional or multiple species. In order to determine the distribution of suitable habitat for juvenile *Lutjanus analis* in Belize, I developed a GIS-based habitat suitability model. The analysis used raster data within a weighted multi-criteria model using ArcGIS 9.2 and IDRISI Andes. Free-access GIS themes with associated metadata from Belize were collected online from the BERDS' (Biodiversity and Environmental Resource Data System of Belize) Spatial Data Warehouse. Data were then organized and geoprocessed into the model's raster inputs. Evaluated ecosystem parameters (i.e., raster inputs) included marine habitat type, swimming distance to spawning aggregation sites, distance to sediment sources, and fishing pressure gradient (derived from the 2005 overall catch and fishing effort reported by the Fisheries Department of the Belize Ministry of Agriculture and Fisheries). The rudimentary model predicted and mapped the distribution of suitable habitat for mutton snapper along Belize's coast. Most of these areas are not presently under conservation or management status. This type analysis might facilitate EBM decision making and thus may be useful for fisheries managers in Belize and elsewhere in the Gulf and Caribbean Region.

KEY WORDS: Marine fisheries ecology, raster GIS-modeling, suitable fish habitat.

Un Modelo Espacial SIG para Predecir Hábitat apto para Pargo Criollo (*Lutjanus analis*) en Belice

Por su historia de vida, el enfoque ecosistémico en el manejo de las pesquerías marinas tropicales es complejo. Localizar hábitat marino-costero apto para peces en el Caribe implica decisiones complejas que son importantes en el diseño eficaz de redes de Áreas Marinas Protegidas. Este trabajo evalúa el uso del enfoque ecosistémico en el manejo pesquero de una sola especie que podría expandirse a especies adicionales o a sistemas multi-especies. Con el fin de determinar la distribución de hábitat de *Lutjanus analis* juveniles en Belice, desarrollé un modelo SIG de aptitud del hábitat. El análisis utiliza datos raster dentro de un modelo multi-criterio ponderado utilizando ArcGIS 9.2 e IDRISI Andes. Temas SIG gratuitos de Belice fueron colectados en línea desde el sitio de datos espaciales de BERDS (*Biodiversity and Environmental Resource Data System of Belize*). Los datos luego se organizaron y manipularon en formato raster como entradas para el modelo. Parámetros ecosistémicos de entrada incluyeron tipo de habitat marino, distancia de nado a los sitios de agregación de desove y a fuentes de sedimentos, y gradiente de presión de pesca (derivado de los datos de captura total y esfuerzo pesquero reportado por el gobierno de Belice en el 2005). El modelo rudimentario predijo y localizó la distribución de hábitat apto para pargos criollos a lo largo de la costa de Belice. La mayoría de estas áreas no se encuentra actualmente bajo categoría de conservación o manejo. Este tipo de análisis podría facilitar la toma de decisiones con enfoque de manejo ecosistémico y podría entonces ser útil para administradores pesqueros de Belice y otras partes del Golfo y del Caribe.

PALABRAS CLAVES: Ecología de pesquerías marinas, modelo raster en SIG, hábitat apto para peces.

Un Modèle Spatial SIG pour Prédire Habitat Adéquat pour Vivaneaux sorbes(*Lutjanus analis*) au Belize

A cause de leur histoire de vie, l'approche écosystémique de la gestion des pêcheries tropicales est complexe. Localiser adroitement les habitats marins et côtiers de poissons dans les Caraïbes implique des décisions complexes qui sont importantes dans la conception efficace de réseaux d'aires marines protégées. Cette étude évalue l'utilisation d'une approche écosystémique de la gestion de pêche d'une espèce unique qui pourrait être étendu à d'autres espèces ou à des systèmes multiespèce. Afin de déterminer la distribution d'habitat de *Lutjanus analis* juvéniles au Belize, j'ai développé un modèle SIG d'habitat adéquat. Des données rasters ont été analysées dans un modèle pondéré de multicritères avec ArcGIS 9.2 et IDRISI Andes. Des thèmes SIG gratuits du Belize ont été recueillis en ligne dans le centre de données spatiales du BERDS (*Biodiversity and Environmental Resource Data System of Belize*). Les données ont été ensuite organisées et manipulées pour les rendre en intrants rasters du modèle. Les paramètres (rasters) inclus dans le modèle ont été : type d'habitat marin, distance de nage aux lieux d'agrégation de frai, distance aux sources de sédiments, et gradient de pression sur la pêcherie (dérivé des captures totales et des efforts de pêche reportés par le gouvernement du Belize). Le modèle rudimentaire a prédit la distribution d'habitats adéquats pour vivaneaux sorbes dans au long de la côte du Belize. La plupart de ces régions n'est pas actuellement sous qualité de conservation ou de gestion. Ce type d'analyse pourrait faciliter la prise de décision sous une approche écosystémique de la gestion des pêcheries et pourrait donc être utile pour les gestionnaires des pêcheries au Belize et ailleurs dans le Golfe et dans les Caraïbes.

MOTS CLÉS: Écologie de pêcheries marines, modèle raster en SIG, habitat adéquat pour poissons.

INTRODUCTION

Most of the fisheries in the Caribbean come from coral reefs and associated coastal ecosystems. Knowledge of the dynamics that regulate and maintain fish populations in the Caribbean is important to design and approach conservation and management practices of these economically important resources. The early life histories of coral reef fishes play an important role in their population dynamics. Most coral reef fishes have two life history phases: a pelagic early life stage followed by demersal juvenile and adult stages (Doherty *et al.* 1985, Doherty 1991, Leis 1991, Sale 1998, Cowen *et al.* 2000). The two phases are coupled when demersal adults spawn pelagic eggs, and when larval survivors or pelagic juveniles abandon the water column to become sedentary (Shulman and Ogden 1987, Grover *et al.* 1998). In their transition from pelagic to demersal phase, which can occur parallel to a distinct metamorphosis, juveniles confront new habitats, prey, predators, and competitors (Victor 1991).

The Mesoamerican Reef Region (MRR) in the western Caribbean, shared by southeastern Mexico, Belize, northeastern Guatemala, and northwestern Honduras, has been an important priority in the conservation efforts of coastal marine resources worldwide. Economic development plans in the MRR should link hydrologic and oceanographic processes such that development maximizes the ecological, social, and economic benefits to the landscape–seascape as a whole and not as separate fields or domains (Heyman and Kjerfve 1999). The MRR is characterized by a network of estuarine, coastal and marine systems that fish use and which include rivers, creeks, brackish lakes, mangroves, shallow bays, coastal lagoons, seagrass beds, and coral reefs. Failure to protect these habitats, as well as the capacity of fish to move freely among them, may have a detrimental effect on adult populations and therefore in the economy of local human communities.

Mutton snapper (*Lutjanus analis*) is a reef-associated and highly commercial fisheries species (Allen 1985). In the Gulf of Honduras (southern MRR), the species is harvested in waters accessed by fishers from Belize, Guatemala, and northwestern Honduras (Heyman and Graham 2000a, 2000b, 2000c). Juveniles and subadults occur over vegetated sand bottoms in bays and estuaries along mangrove coastal areas (Allen 1985). Adults occur offshore on complex habitats such as coral reefs (Burton 2002) and form spawning aggregations with a high degree of site fidelity (Domeier and Colin 1997). A well-known mutton snapper fishery has existed in southern Belize since the 1920s (Craig 1966), though the dynamics of the spawning aggre-gation was unknown until recently (Heyman *et al*. 2001, 2005). Based on multiyear observations, mutton snapper is one of the most prominent species in abundance, biomass, and egg production within transient multi-species reef fish spawning aggregations (Heyman and Kjerfve 2008.

Geographic Information System (GIS) and remote sensing tools, when combined with integrative ecological theories and scientific procedures, promise to bring the vast diversity of information into a more manageable outcome (Breman 2002). GIS technology essentially constitutes a vital solution to integrating theoretical approaches from geography, oceanography and ecology, with powerful spatial database and statistical functions (Wright *et al.* 2007). GIS modeling offers dynamic simulations of natural, physical, and social processes of our environmental space (Tomlin 1990, DeMers 2002, Longley *et al.* 2005).

Locating suitable marine and coastal habitats for mutton snapper involves complex judgments that go beyond simple design of Marine Protected Areas (MPAs). In GIS modeling, multiple analytical approaches can be established to evaluate various scenarios of site suitability. These approaches enable alternative developmental strategies to be examined and compared before making final decisions or commitments (Albrecht 1996). In order to predict distribution of suitable habitat for juvenile mutton snapper across coastal Belize, I developed a suitability GIS analysis with raster data (Tomlin and Johnson 1990). Free and open-accessed GIS themes from Belize were collected, organized, and geo-processed into my model's raster inputs. Evaluated ecosystem parameters included marine habitat type, swimming distance to spawning aggregation sites, distance to continental pollution sources, and fishing pressure gradient. This type analysis in adaptive management should facilitate EBM decision making and thus may be useful for fisheries managers in Belize and elsewhere in the Gulf and Caribbean Region.

METHODS

Study Region

Coastal Belize constitutes the western boundary of the Gulf of Honduras (GOH), southern Mesoamerican Reef Region (MRR), Western Caribbean. The GOH includes a network of coastal and marine littoral habitats comprising reefs, mangroves, sea grass beds, estuarine lagoons and embayments, inner and outer cays, and open ocean (Heyman and Kjerfve 2001). This convergence of multiple habitats provides for high biological diversity given that many species require several of these habitats during their ontogenetic development. The seasonal changes in oceanographic conditions also dictate the migration pattern of species which is reflected in fisheries landings data (W. D. H. and P. G. D. Unpubl. data).

Fishing contributes significantly to the regional economy and represents a source of protein for subsidence-based coastal communities (Heyman and Graham 2000 a, b, c, Heyman and Kjerfve 2001). Belize, Guatemala, and Honduras have designated protected areas in recognition of the coastal and marine ecosystems of the region (Heyman and Kjerfve 2001). These nationally developed protected areas can be viewed as a system of coastal and marine reserves which contribute to the health of the entire GOH ecosystem. The reserves are generally based on a multiple-use concept, and are designed for biodiversity conservation, tourism, and limited sustainable use by local communities.

Data

GIS themes from the Mesoamerican Reef region (MRR) were collected and organized for the purpose of this project (Table 1). An extensive data search across several public oceanographic, climatic, and environmental metadata sites for GIS-processed features and rasters, included the following entities:

i) The National Oceanographic Data Center,
ii) The National Climatic Data Center;
iii) The Goddard DAAC Ocean Color Data and Information;
iv) The EROS DAAC Archive Center (DAAC);
v) The National Geophysical Data Center;
vi) The SERVIR and Mesostor geodatabases for Mesoamerica (SERVIR); and
vii) The Biodiversity and Environmental Resource Data of Belize (BERDS).

In contrast to the other remote sensing metadata sites, only SERVIR (SERVIR website, http://www.servir.net/) and BEDS (BERDS website, http://www.biodiversity.bz/) provided free and open-accessed preprocessed GIS data for the purpose of this project. Most of the data had a spatial reference set to the NAD 1927 UTM projection (UTM, Zone 16 North, NAD 27 Central, Clarke 1866). Data lacking of spatial references were projected to the previous settings. The extent of the analyses was set to the derived shapefile of the marine habitats of Belize (Table 1) and the cell size to 100 (m).

Model Rationale

Caribbean fishes often depict highly variable patterns of recruitment in both space and time, and this variability can influence the dynamics of populations and communities. Although evidence suggests that larval behavior can also influence recruitment patterns at large scales (Tolimieri *et al.* 1998), the factors that usually affect larval survivorship range from fine-scale local larval ecology and microhabitat structure (Danilowicz *et al.* 2001), to very broad-scale physical oceanographic features such as fronts, eddies and major oceanic currents that eventually facilitate larval transport (Tolimieri *et al.* 1998). Physical transport can enhance larval settlement by increasing either larval supply or the duration of larval retention in suitable settlement (juvenile and subadults) habitats (Brown *et al.* 2005).

In Belize, snappers aggregate in sites close to reef patches and promontories with a suite of oceanographic variables that favors this reproductive behavior (Heyman *et*

Table 1. Downloaded data and derived layers for GIS analyses.

Data category	GIS format	Derived project layers
Ecosystems of Belize	Shapefile	1) Shapefile of the marine habitats of Belize.
		2) Shapefile of the marine protected areas (MPA) of Belize.
		3) Shapefile of the conservation status of the MPAs of Belize.
		4) Shapefile of the fisheries management status of the MPAs of Belize.
Topography and bathymetry of Belize	Shapefile	5) Shapefile of the boundaries of the study area.
Catch per unit effort of marine fisheries across Belize.	Shapefile	6) Shapefile of fisheries use.
Mesoamerican Barrier Reef Watershed	Shapefile	7) Shapefile of the river discharge of each watershed.
		8) Shapefile of basins > 50 Km^2.
		9) Shapefile of sediment loads to oceanic systems.
		10) Shapefile of river flush into ocean water.
Shapefile of MBR land	Shapefile	11) Shapefile of country limits.
Shapefile of patchy and barrier reef across the MBR	Shapefile	12) Not geoprocessed.
Bathymetry (1 km resolution) of the MBR	Raster	13) Not geoprocessed.

al. 2005, Heyman and Kjerfve 2008). Eggs and posterior larvae are believed to drift away from the spawning sites with oceanic currents to finally settle as juveniles in nursery habitats of mangroves and seagrass beds. Based on the previous information, the assumptions of my model were:

i) Reproductive mature mutton snappers aggregate to spawn around outer reefs,

ii) Surviving larvae recruit and settle in juvenile habitats such as mangrove and sea grasses, and

iii) Anthropogenic stresses, such as continental pollution sources and fishing pressure over marine ecosystems, have a detrimental effect on the settlement of juvenile mutton snapper.

I used the ModelBuilder application in ArcGIS 9.2 (ESRI 2007) to geoprocess my input data (Figure 1). Multiple ring buffer analyses using Spatial Analyst (ESRI 2001) at 10-, 20-, 30-, and 40-km distance intervals were performed to both pollution sources (using river mouths as surrogates) and physical reefs (using reef habitats as surrogates). On a scale from 1 (unsuitable) to 4 (highly suitable), output raster files were reclassified, setting an increasing scale with increasing distances from pollution sources and with increasing distances from open ocean and reef habitats. The latter habitats were assumed suitable only for eggs, larvae, and adults. For juvenile mutton snappers, seagrass habitat received a score of 4, mangrove and littoral forests of 3, dispersed algae of 2, and coral and open-ocean of 1. Fishing pressure was reclassified into 4 equal intervals of catch per unit effort (CPUE), going from 1 (greatest CPUE) to 4 (lowest CPUE).

A weighted multi-criteria GIS model (Aly *et al.* 2005) that incorporated the previously geoprocessed factors (*i.e.*, marine habitat type, swimming distance to spawning aggregation sites, distance to continental pollution sources, and fishing pressure gradient) was then established to create a map of habitat suitability for juvenile mutton snapper potentially occurring along coastal Belize. The most relevant procedure for multi-criteria evaluation is the weighted linear combination (Voogd 1983). In a weighted linear combination, factors are combined by applying a weight to each, followed by a summation of the results to yield a map of suitability (Eastman *et al.* 1995) as the following:

$$S = \sum w_i x_i,$$

Where:

S is the suitability,
w is the weight of factor i, and
x is the potential rating of factor i.

I then performed the multi-criteria weighted linear combination using the WEIGHT function in IDRISI Andes (Eastman 2006). A pairwise comparison matrix was built through subjective assignments of relative weights in order to assess the degree of consistency with which the weights were assigned. Saaty (1977) introduced a procedure by which an index of consistency, known as a Consistency Ratio (CR), can be produced. This CR indicates the probability that the matrix judgments were randomly generated (a CR ≤ 0.10 is considered a reasonable level of consistency). I used Raster Calculator in Spatial Analyst (ESRI 2001) to incorporate the weights from the weighted-linear combination into a raster calculation that would derive a new raster file from my model. The final raster was reclassified and geoprocessed to select only for locations with the highest suitability indices and produce a map of the distribution of suitable habitat for mutton snapper along Belize's coast.

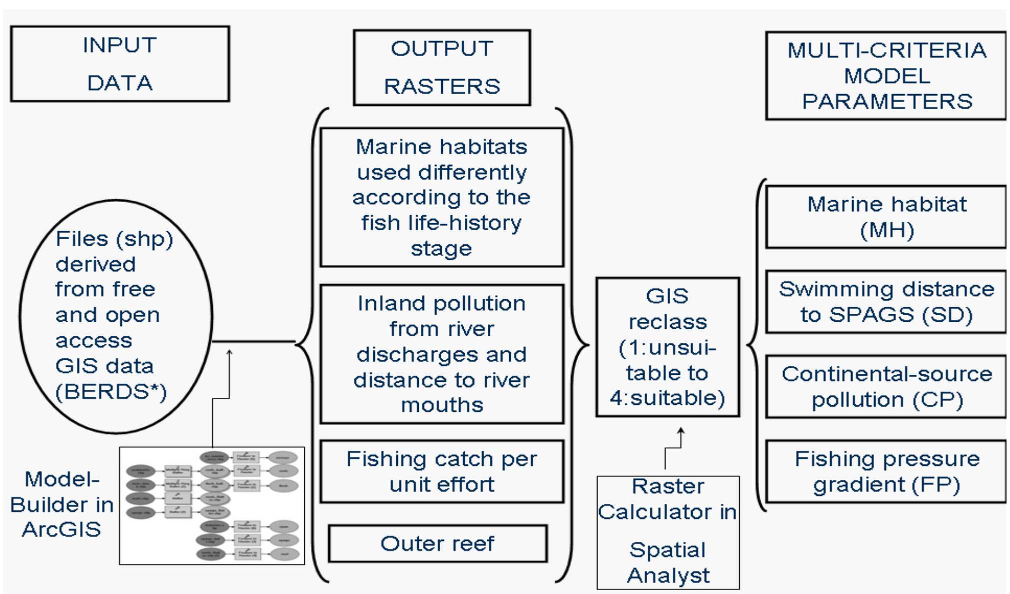

Figure 1. The ModelBuilder application in ArcGIS 9.2 (ESRI 2007) to geoprocess input data.

RESULTS

The solution to the pairwise comparison matrix was consistent (CR = 0.07). The Eigen values (Table 2) are the relative weights of factors in the weighted-linear-combination equation. The equation describing our suitability model was:

$$S = 0.5558(MH) + 0.2665(SD) + 0.1101(CP) + 0.067\ (FP),$$

Where:

S stands for habitat suitability for juvenile mutton snapper,
MH for marine habitat type,
SD for swimming distance to spawning aggregation sites,
CP for continental pollution source, and
FP for fishing pressure gradient.

The muticriteria selection model predicted suitable habitat for juvenile mutton snapper in Belize (Figure 2). The model predicted suitable habitat for mutton snapper in coastal areas with sea grasses, around coral reefs, or a combination of both. Most of the predicted suitable habitat (> 70% of the total habitat, determined with Spatial Analyst) followed in areas outside marine reserves (according to BERDS data).

DISCUSSION

Caribbean small-scale fisheries, like the mutton snapper fishery of Belize, cover geographically complex regions (Salas *et al.* 2007) and often constitute a considerable, if not the only source, of income and protein for many coastal communities that first experience the costs of fisheries overharvest. Multidisciplinary approaches and innovative tools for breaking down the complexity of the ecosystem-based fisheries management approach are constantly emerging. However, marine resource managers in the developing countries are generally faced with limited

Table 2. Solution to the pairwise comparison matrix (CR = 0.07). The Eigen values are the relative weights of factors in the weighted-linear-combination equation. MH is marine habitat type, SD swimming distance to spawning aggregation sites, CP continental pollution source, and FP fishing pressure gradient.

	MH	SD	CP	FP	Calculated Eigen-value weights
MH	1				0.5558
SD	1/2	1			0.2665
CP	1/5	1/3	1		0.1101
FP	1/9	1/7	1/2	1	0.0676

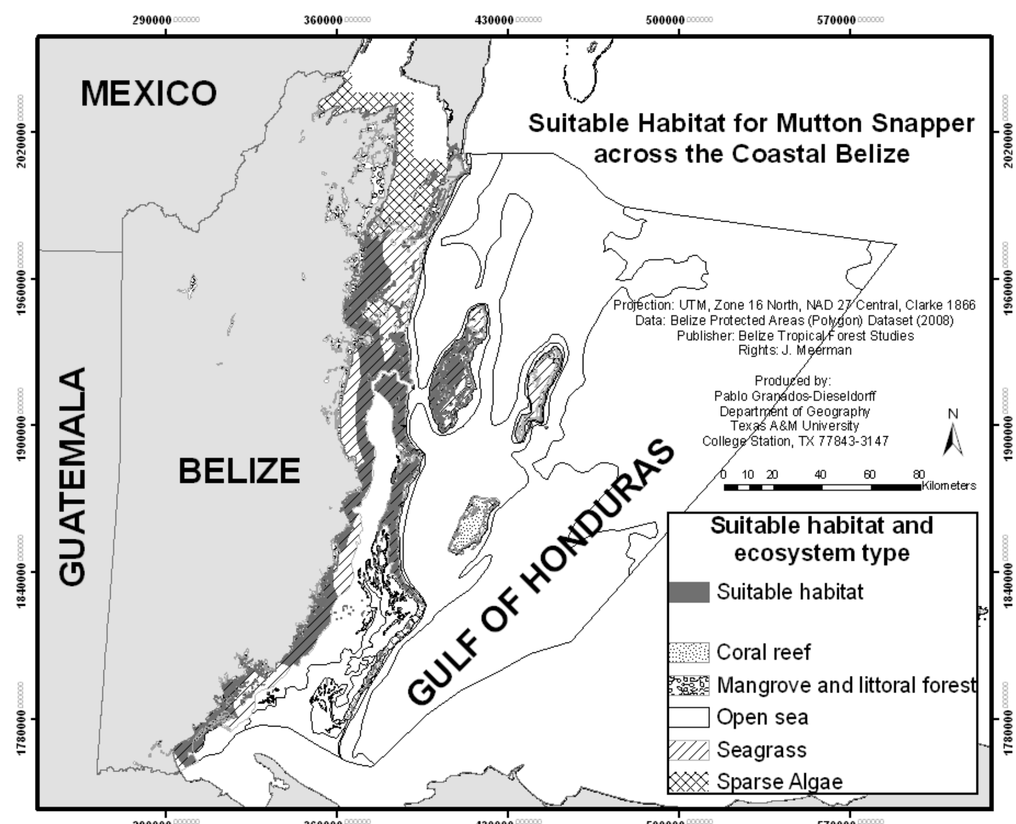

Figure 2. Suitable habitat for mutton snapper across the coastal Belize.

funding, infrastructure, technical training, and data availability for implementing novel approaches. Despite the limited GIS open-access and free data available for the region, my rudimentary GIS model predicted the distribution of suitable habitat for juvenile mutton snapper across Belize's marine habitats (Figure 2). Suitable habitat for juvenile mutton snapper was predicted in coastal areas with sea grass beds, around reefs, or a combination of both, most of which lacked of management status according to BERDS public data. If the model's predictions are validated later against field conditions in areas of relatively small size but with representation of the marine habitats considered by the multi-criteria equation, the model could be extrapolated to broader regions.

The model, however, is limited by its rudimentary nature (its intentional design in this study). Other oceanographic variables like current direction, high-resolution sea surface temperature, salinity data, and location of gyres, as well as hydrological data such as sediment discharge of surrounding international basins (e.g., Guatemalan and Honduran Basin), could improve the prediction power of a reformulated version. Moreover, the ecological assumptions of this preliminary model (*i.e.*, reproductive mature mutton snappers aggregate to spawn around off-shore reefs, juveniles recruit in seagrass and mangrove estuaries, and anthropogenic stresses, such as freshwater pollution and fishing pressure, have a detrimental effect on mutton snapper juvenile settlement) need to be validated against recent studies on the ecology of the species in Belize. Also, population dynamics factors (*e.g.,* predation, competition, catastrophic mortality) affecting the densities of larvae and recruits of mutton snapper in Belize were not considered in my model.

My rudimentary model should be considered as an adaptative initial tool (*sensu* adaptative management) to facilitate ecosystem-based-management decisions in real world situations. For example, the model concept can be used to assure representation of fisheries habitat connectivity in the design of Marine Protected Areas networks. Developing a relatively free spatial GIS-model tool and making it accessible to the public (as an open source) could considerably contribute to the design and management of coastal and marine resources in the study region. Fisheries managers of Belize and the rest of the Caribbean, with access to ArcGIS, could replicate and improve this model that virtually runs on free and open-access data.

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