MAPPING BELIZEAN BONEFISH, PERMIT, AND TARPON
FISHERIES AND THEIR THREATS

by

BRADFORD BATES

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A THESIS

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ABSTRACT

This research uses a multidisciplinary approach to provide a broad perspective on the location of Belizean Bonefish, Permit, and Tarpon (BPT) fisheries and their threats. Participatory mapping and ethnographic surveying of the professional sport-fishing guide community was completed. In addition to reporting the locations of BPT and their threats, this research uses high resolution satellite remote sensing (3m) to examine seagrass changes in a portion of the South Water Caye Marine Reserve (SWCMR) from 2001 to 2016. Professional sport fishing guides ranked gillnets as the most threatening activity to Belizean BPT stocks, and most guides reported that the quality of sport-fishing of BPT has declined over their career. One of these threats is the loss of seagrass, a crucial habitat for BPT. Remote sensing analysis of a study area in the SWCMR suggests spatial variability of seagrass decline and regeneration, with a 2.5% average increase in overall seagrass distribution with at least 30% cover, with most of the regeneration occurring in shallow waters sheltered from ocean wave action. Decline in seagrass distribution was observed in deeper waters subjected to ocean currents and potential dredging. The results of both studies are assimilated to discuss potential avenues of research and the prioritization of recreational fisheries management in Belize.
DEDICATION

This thesis is dedicated to my family, my advisor, Jon-Pierre Windsor, and Belize’s sport fishing community.
## LIST OF ABBREVIATIONS AND SYMBOLS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AR</td>
<td>Agricultural Runoff</td>
</tr>
<tr>
<td>BPT</td>
<td>Bonefish, permit, and tarpon</td>
</tr>
<tr>
<td>CBC</td>
<td>Carrie Bowe Caye</td>
</tr>
<tr>
<td>CZMAI</td>
<td>Coastal Zone Management Authority and Institution</td>
</tr>
<tr>
<td>D</td>
<td>Dredging</td>
</tr>
<tr>
<td>DV</td>
<td>Development</td>
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<tr>
<td>ESRI</td>
<td>Environmental Systems Research Institute</td>
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<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
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<tr>
<td>GN</td>
<td>Gill-net</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information System</td>
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<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>IF</td>
<td>Illegal Fishing</td>
</tr>
<tr>
<td>N/A</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>ND</td>
<td>No Data</td>
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<tr>
<td>PCA</td>
<td>Principal Component Analysis</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyvinyl Chloride</td>
</tr>
<tr>
<td>RP</td>
<td>Reference Point</td>
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<tr>
<td>SWCMR</td>
<td>South Water Caye Marine Reserve</td>
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<tr>
<td>CIA</td>
<td>Central Intelligence Agency</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
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<tr>
<td>MAR</td>
<td>Mesoamerican Reef Fund</td>
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<tr>
<td>RD</td>
<td>Reef Degradation</td>
</tr>
<tr>
<td>SAV</td>
<td>Submerged Aquatic Vegetation</td>
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<tr>
<td>SCUBA</td>
<td>Self-Contained Underwater Breathing Apparatus</td>
</tr>
<tr>
<td>SP</td>
<td>Shrimp-Farm Pollution</td>
</tr>
<tr>
<td>WGS</td>
<td>World Geodetic System</td>
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<tr>
<td>UNESCO</td>
<td>United Nations Educational, Scientific, and Cultural Organization</td>
</tr>
<tr>
<td>UP</td>
<td>Urban Pollution</td>
</tr>
<tr>
<td>UTM</td>
<td>Universal Transverse Mercator</td>
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ACKNOWLEDGMENTS

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CHAPTER 1
INTRODUCTION

Belize (17 15 N, 88 45 W) is a Central American country bordered by Mexico to the north (276 km), Guatemala to the west and south (266 km), and the Caribbean Sea to the east (386 km). In July of 2016, its estimated population was 353,858, comprising mostly Mestizo (~53%), Creole (~26%), Maya (~11%), with other ethnic groups making up lower percentages (Central Intelligence Agency). Although the Maya Mountains overlap Belize’s southwestern border and hold sub-montane broad-leaved and pine forests, the country is mostly flat with gentle rolling topography, overlain by a configuration of mostly lowland broad-leaved forest, lowland savanna, and agriculture (Meerman et al. 2001). Belize’s coastal waters are home to the world’s second largest coral reef system, which has been recognized by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) as a World Heritage Site (UNESCO World Heritage Center).

While much of Belize’s economic earnings come from the exportation of marine and agricultural products (13.1% 2007 est.), Belize is like other Caribbean countries in that tourism is the primary economic driver (Central Intelligence Agency). In 2007, direct contributions of travel and tourism to Belize’s entire economy GDP was about 15%, with reef- and mangrove-associated tourism occupying the sector majority. From economic surveying of Belizean sport-fishing professionals in 2007, Fedler reported that the total economic impact of bonefish, permit, and tarpon (BPT) fishing was $56.5M and supported 1,864 jobs (Fedler 2007). In 2013, the total
contribution of tourism to the country’s GDP (including indirect and induced impacts) was about 37%, and is expected to rise to 43.7%, by 2024, with direct economic impacts expected to remain about the same (~13-15%) (Cooper et al. 2009, World Travel and Tourism Council 2015).

The sustainability of Belize’s marine tourism industries relies on the long-term conservation of Belize’s coastal ecosystems such as coral reef, mangroves, and seagrass—all of which are utilized by fish, mammals, crustaceans, and fowl for habitat, feeding, and spawning grounds (Jackson et al. 2001). Recognizing the ecosystem services provided by these habitats, Belizean officials and non-government organizations have proposed and enacted policy measures, such as zones of controlled access through permitting, to protect the country’s coastal habitats from degradation by activities such as dredging, development, and pollution (Belize Coastal Zone Management Authority and Institution, Kareiva et al. 2011, Wildtracks 2009). Despite these political efforts—and the fundamental sustainability of “catch and release” fishing notwithstanding—threats to recreational fisheries continue to remain a serious challenge for conservation (Steinberg 2015). In describing the threats facing sustainable Belizean BPT fisheries at a country-wide scale, a multidisciplinary approach utilizing ethnographic participatory spatial data and case-study specific high spatial resolution remotely sensed imagery is a worthwhile research objective.

Local sport fishing guide knowledge is a valuable resource when assessing threats to and temporal changes in the spatial distribution of Belizean recreational fish stocks. Participatory mapping of fishery resources is a demonstrated reliable method for relatively fast and low-cost spatial planning (Calamia 1999, Close et al. 2005, Freitas et al. 2009). Decision-makers often disregard the value of traditional ecological knowledge because the information is often collected unsystematically, thus posing difficulties in integration of science-based
management plans (Close et al. 2005, Freitas et al. 2009). However, through systematic inquiries and analysis, local knowledge regarding fisheries and their threats, especially when collected on a regular basis, can provide considerable utility in sustainability science and decision-making.

Lastly, seagrass classification has been conducted worldwide and at a multitude of spatial and temporal scales. In 2013, The Mesoamerican Reef (MAR) Fund commissioned baseline seagrass and mangrove habitat mapping efforts for certain Belizean regions, including the Port Honduras Marine Reserve, using RapidEye imagery and Landsat 8 (MAR 2014). Gaston et al. recorded seagrass decline in the South Water Caye Marine Reserve (SWCMR) from 2001 – 2005 using a combination of Ikonos and Quickbird imagery, and estimated a 1.8% decline in seagrass cover. Many studies regarding temporal seagrass habitat change are conducted in 1-2-year time frames, however a decade scale analysis can provide significantly more information on the success of seagrass recruitment (Gillanders 2006).
CHAPTER 2
OBJECTIVES

There were two main research objectives. The methodologies and results for each objective are detailed separately, but the discussions of each are synthesized.

1) The first objective was to survey professional recreational fishing guides to delineate the general zones of bonefish, permit, and tarpon (BPT) fisheries across the Belizean coastal system, in addition to the threats to these fisheries. The resulting dataset of perceived BPT locations and habitat threats can be further used in several areas of applied research such as ecology, natural capital analysis, as well as policy measures that account for bonefish, permit, and tarpon fisheries, all of which are crucial components of Belize’s lucrative tourism industry.

2) The second objective was to analyze temporal changes in seagrass density and extent in subset of the SWCMR using remotely sensed imagery and field reference data. Furthermore, it was an objective to consider the potential anthropogenic causes for seagrass extent reduction.
CHAPTER 3

METHODOLOGIES

3.1 Known Locations of BPT and their Threats

3.11 Background

Guided sport fishing of bonefish, permit, and tarpon (BPT) is a major contributor to Belize’s vibrant tourism economy, directly and indirectly supporting thousands of jobs (Fedler 2007). As “catch-and-release” species, BPT stocks are not at risk from commercial fishing, however anthropogenic threats to BPT quality are nonetheless present. These threats are numerous and results from direct and indirect human actions, as well as ambient environmental factors. The increasing popularity of Belizean marine tourism, while economically beneficial for the country’s economy, puts increasing pressure on outdated urban infrastructure to manage solid and liquid pollution in the form of sewage (Young 2008).

In addition to these waste disposal challenges, there is increasing development of previously undeveloped areas. Development is fueled by Belize’s growing population as well as the tourism industry (Young 2008, World Resources Institute 2015). Although Belize’s government and people have a relatively strong sustainability ethic, any development results in the immediate destruction of some natural habitat and, in the longer term, stimulates transportation of people, goods, and services to the new developments, potentially disrupting migration, feeding, and spawning patterns for several marine species, including sport-fish (Danylchuk et al. 2011).
Sandy ocean floors with clear waters are a major appeal for tourists, thus incentivizing the removal of seagrass beds in areas adjacent to resorts or beaches. Dredging of seagrass beds is detrimental to the quality of recreational fishing activities for a number of reasons. Namely, BPT utilize seagrass beds and mudflats as feeding grounds, preying shrimp, toadfish, and small crabs, all of which reside in the substratum (Crabtree 1998). Professional recreational fishing guides frequent these sites to provide their patrons with opportunities to catch and release BPT.

Furthermore, dredging of seagrass beds results in temporary increases in turbidity via release of formerly stabilized nutrient-laden sediments, reducing dissolved oxygen levels in the water column. Temporary changes to turbidity are common and can result from natural causes, however changes in water column clarity can pose problems when turbidity exceeds normal conditions. Severe storms, nutrient loading from fluvial systems, and sustained dredging can cause these unnatural turbidity changes, thus challenging seagrass vitality (Stern et al. 1978, Orpin 2004, Erftemeijer et al. 2012).

Gill-net use has remained a consistent threat to all fisheries in Belize, especially in southern Belizean waters where illegal Guatemalan and Honduran fishermen have easy access (Steinberg 2015). Gill-nets efficiently function by restricting backwards movement by fish too large to pass through the netting. When a large fish enters the net and finds it cannot continue, it will attempt to swim backwards, but its gills become caught on the net’s fibers, thus restricting escape. Southern Belizeans report gill-nets being placed at river mouths where they indiscriminately catch fish, including juvenile tarpon and snook (Steinberg 2015). Belizean stakeholders such as recreational fishing guides and responsible commercial fishermen recognize the damages caused by gill-nets, thus resulting in cooperation between these groups and government rangers (Steinberg 2015).
3.12 **BPT Location**

Participatory spatial BPT fisheries data were collected in paper format during a series of research excursions to Belize. These data delineate fishing grounds in the Belize Barrier Reef System and the Belizean coastline. These recorded species include bonefish (Albula vulpes), permit (Trachinotus falcatus), tarpon (Megalops atlanticus), and Snook (Centropomus undecimalis). These paper maps were scanned, georeferenced, and all fishery zones manually digitized as polygons. Because the spatial data was generated by numerous Belizean professionals at different times, names for species occasionally vary depending on the language or vernacular of the participating fishing guides. If the informant’s writing was illegible, it was omitted from the database. Because the aim of the study is to discover the habitats of and threats to the main sport fishing species (BPT), snook was omitted from further analysis. After manually digitizing the fishery zones, the polygons were overlain and their attributes spatially joined to a hexagonal grid, each side of length 300m (total area ~23.4 ha) and clipped to a terrestrial shapefile. The spatial join to the hexagonal grid follows the methodology used by Levine et al. and is meant to decrease spatial specificity as well as reduce the disclosure of sensitive industry information (Levine et al. 2015).

3.13 **Threats to BPT**

Because Belize’s coastal ecosystems, cultures, and local economies geographically vary, understanding spatial distribution and severity of threats to Belizean bonefish, permit, and tarpon fisheries and stakeholder concerns requires a nationally distributed survey to those stakeholders who depend upon these species for their livelihoods. Recreational fishing guides make their living by providing their expert knowledge of the behavior of BPT to anglers. As such, they are heavily incentivized to stay abreast of events or activities that may threaten the profitability and
sustainability of their trade. It thus follows that a survey distributed to this community of recreational fishing guides is the prudent method by which information regarding the general spatial distribution and severity of threats facing BPT stocks and quality of recreational fishing.

The inclusion of traditional ecological knowledge in threat analysis is a powerful tool for delineating areas sensitive to anthropogenic changes to an environment (Johannes 1993). Several efforts to engage local stakeholders of fishery resources have been documented. The methodology by which researchers can collect participatory spatial data is not strict, and often takes form in community meetings of stakeholders and resource users, where one or two trained analysts digitize features using a GIS at the guidance of others (Levine et al. 2015). By interviewing Belizean fishing guides in-situ, Steinberg spatially identified and verbally described nationwide threats to Belizean BPT fisheries, dividing the country into three zones (Steinberg 2015). Close et al. conducted a study whereby they collected hand-marked paper maps, verbal input, then underwent spatial analyses with their results. If presenting informants with a paper map in the field, Close et al. advise initial careful design of the map, with distinct landmarks clearly displayed. They also warn that many informants may not be fully literate or accustomed to viewing advanced maps. In constructing survey questions, Close et al. advise straight-forward questions that do not require a significant amount of informant time to answer (Close et al. 2005).

Past studies have incorporated traditional ecological knowledge and other forms of ethnographic data. However, a common obstacle for the application of such information into ecological amelioration-minded policy measures is that it is often collected in a way not readily comparable with other forms of information (Close et al. 2005). Given these considerations, it was decided that the survey to be distributed should be systematic in nature and contain
questions whose answers are standardized and can be readily analyzed using descriptive
statistics.

To complete such a survey model, 8 known threats facing Belizean BPT are presented to
the subject for ranking on a scale from 1-10. The subject is given three additional blanks to write
in unlisted threats, with the same scale on which they may select an appropriate ranking. In
addition to ranking these threats on the scale, the subject is asked to physically mark on a map
where they have observed or heard reports of the threat taking place. Thus, a spatial region and
threat level is assigned to each category of threatening activity, allowing for spatial statistical
analyses. The map-book was a collection of 12 8.5x11-inch maps. The first page of the map-
book is a national overview depicting the boundaries of each of the following maps in the book.
Each boundary rectangle includes the page number to which it refers in the following pages. This
system allows the user to easily refer to the overview page to decide which page in the map-book
to turn to so that markings can be made. At a scale of 1:210,000, 11 maps were required to fully
cover the project-relevant regions in Belize. This scale was chosen because the objective of this
survey was to discover the general regions of perceived threats. Furthermore, this scale was
decided to be the appropriate balance between level of detail and spatial extent. The maps
include the ESRI satellite image basemap and include a UTM grid, both of which allowed
accurate eventual digitization. A land shapefile was used to highlight the border of land bodies to
ensure ease of identification of recognizable areas. Each survey packet mailed to a lodge
consisted of one map-book and five surveys. Each individual guide from the same lodge
competed his own survey while all guides used the same map-book to spatially identify where
the threatening activity occurs. Because all guides used the same map book, the resulting mapped
threats are assumed to be representative of the entire respective lodge. Another question on the
survey gauges the subject’s general outlook on the temporal quality of BPT fishing in Belize, simply asking them to report if fishing of BPT has improved or worsened over their guiding career. If the subject believed the quality of BPT fishing has worsened, he/she is asked to explain why he/she felt that way. The final question asks the guide for the number of years he/she has been professionally guiding in Belize. This last inquiry serves to gauge the experience of the subject and assumes a positive relationship between number of years guiding and general experience. The subject’s level of experience may be compared against each of their ranked threats, thus providing insight into potential differences in the perception of various threats by guides of different experience levels. For example, a less experienced guide may or may not consider dredging to be as severe a threat as a more experienced guide.

Surveys were mailed to a Belizean volunteer who distributed them to approximately 30 Belizean recreational fishing lodges. The distribution began in March 2016 and the last surveys were received in September 2016. For convenience, several surveys were returned in digital format, i.e. as an image of the completed paper survey. In-person surveying took place in Punta Gorda in June 2016 and September 2016. It was observed that one lodge misunderstood the directions dictating physical marking on the provided maps. Participants from this lodge instead wrote down the number of the maps portraying the areas within which the threat in question was spatially present, i.e. if a dredging occurred on Map 6, these respondents wrote a “6” on the main survey and did not provide a specific location. When the completed surveys were returned to the lead researcher (either in digital or paper format), responses and threat locations were digitized in ArcMap 10.2. In total, 23 questionnaires were completed and returned. Threat rank averages and years of experience-weighted averages were calculated. Threat ranks were weighted by years of experience because it was assumed that veteran guides have a more holistic historical
understanding of Belizean sport fishing, when compared to individuals who have guided for less time, and are thus aware of the temporal progression of BPT sport fishing quality and its fluctuations in response to natural and anthropogenic influences.

3.2 Satellite Remote Sensing of Seagrass Changes in the SWCMR

3.21 Background

Seagrass habitat maps exist for much of the Caribbean, however many of these maps are created using spatial resolutions of 30m or higher (Wabnitz et al. 2008) and do not provide a deep understanding of fine-scale temporal changes in seagrass cover over time. Several approaches to classify seagrass have been documented in the literature (Curran 2011, Gaston et al. 2009, Lathrop et al. 2006, Lyons et al. 2011). The Mesoamerican Reef Fund (MAR Fund) has taken efforts to classify marine habitat in Port Honduras Marine Reserve by applying image segmentation to RapidEye imagery (Mesoamerican Reef Fund 2014). Image segmentation is a robust classification method because the process statistically assigns spatially and spectrally similar pixels to discrete groups. In determining which group to assign a pixel, the algorithm weighs the pixel’s spectral and spatial values against a user-defined dissimilarity threshold. Setting this dissimilarity threshold is a process of user trial-and-error (Mesoamerican Reef Fund 2014). Once this threshold is determined, the heterogeneity of the area of interest may yield thousands of discrete image objects, which then must be combined into the user’s desired classes (e.g. seagrass, mangroves, open sand, etc.). This method of image classification has been utilized with success by researchers and agencies with copious financial and temporal capital, such as Remote Sensing Solutions gmbH. In such cases where processing and analyst time requirements are available, image segmentation is an ideal method of seagrass classification.
A more temporally pragmatic approach for image classification makes use of principal component analysis (PCA) and unsupervised classification using ISODATA clustering algorithms, as documented by Curran (Curran 2011). Under this approach, a PCA is run on the images. Furthermore, Curran masked out land to reduce confusion of the algorithm (Curran’s intent was to classify seagrass only). Curran then followed well documented methodology (Chauvaud et al. 1998, Ferguson and Korfmacher 1997, Su et al. 2006, Wolter et al. 2005) and ran a covariance matrix PCA so that the spectral bands would be compiled to only two components, which were then passed into an unsupervised isodata clustering classification algorithm. This process classifies the input data into statistically similar groupings, after which Curran generated a binary classification (seagrass or lack of seagrass).

Gaston et al. showed that from the years 2001-2005, seagrass coverage in a portion of the SWCMR declined by 1.8% overall, but some areas in the reserve lost as much as 40%. Their results show that even in protected marine areas, significant loss of seagrass habitat can occur (Gaston et al. 2009).

3.21 Study Area

The South Water Caye Marine Reserve (SWCMR) sits on Belize’s continental shelf and consists of thirty-two cayes situated along, and to the west of, the reef. The area’s main dry season is from January to April (approximate sum of 400mm of precipitation), but July and August are relatively dry months (~340mm of precipitation). The wettest month is November, with nearly 600mm of precipitation. These measurements, along with several other parameters are recorded at the Smithsonian Institute’s monitoring station on Carrie Bowe Caye (CBC), located just south of the South Water Caye island within the SWCMR. The average yearly temperature for the CBC is around 27.1°C. From a geomorphological and ecological perspective,
the rainfall is important because it dictates the rate of sediment and nutrient delivery to Belize’s coastal waters. Even though it lies about 11km east of the Belize mainland, the SWCMR is sensitive to these physical processes (Wildtracks 2009).

The SWCMR experiences three different weather systems: the trade winds, northers, and tropical storms (Wildtracks). As such, the region is subject to yearly tropical storms that mainly effect the eastern-most cayes and atolls. Storm turbulence often damages corals and heightens turbidity levels, thus reducing clarity in the water column. Furthermore, the elevated rainfall amounts during such events result in spikes of fluvial sedimentation of the reef system. Biologically-derived sediments occupy much of the sediment budget in the region. These sediments are the result of coral and algae fragmentation, but fragments from mollusks are also present in lower percentages in the back reef areas. In the region’s patch reefs (i.e. reefs occurring apart from the barrier reef) the sediments are often coarse and poorly sorted.

Within the SWCMR, tides average around 30cm, placing them in the microtidal category. Although relatively small, the tide is responsible for currents that carry nutrients, sediments, and small organisms towards shallow reefs (Heyman 2001). Near CBC, the currents reach speeds of 1-1.5kts and are mostly tide generated. In regards to sea level, it is thought that the north winds play a key role in regulating the sea level and are capable of depressing for several days near the beginning of the year. This phenomenon is thought to contribute more to the biodiversity of the shallow water reefs than tides (Heyman 2001).

This project’s study area, falling within the SWCMR, is a popular destination for snorkeling/SCUBA enthusiasts, recreational fishers, sailors, and researchers. This study area was chosen because of the level of traffic experienced by the SWCMR, Gaston et al.’s past seagrass mapping work, and the area’s accessibility. The northern section of the study area is shallower
and receives less wave action than the southern section, because of the eastern forereef’s wave-breaking effects. Because the forereef is not continuous in the southern section of the study area, higher energy ocean waves are admitted. Furthermore, the waters in the southern section are deeper and are capable of transmitting waves of higher amplitude, resulting in stronger currents than in the northern section of the study area.
3.22 Field Sampling

A field sampling campaign was conducted for the study area during 05/15 – 05/20 of 2016. 120 points were randomly generated inside of the study area using ArcMap 10.2. These
random points served as the sampling sites for the field campaign. The purpose of the sampling campaign was to generate a database of images of the submerged aquatic vegetation present on the sea floor at each of the reference points (RPs). All RPs were loaded into the “iGIS” application, a smartphone program that allows users to upload shapefiles and rasters onto a graphical user interface. “iGIS” uses the smartphone’s GPS to provide live reporting of the user’s location, allowing ease of navigation. A boat captain was hired and trained in the use of “iGIS” and used the application to navigate to each RP, where data collection would begin. The crew for each day of the field sampling campaign was comprised of 6 members: the boat captain, four field assistants, and the lead researcher. At each RP, the sampling grid was lowered into the water and GPS coordinates were recorded using a Garmin “etrex Legend” unit into a notebook. A free-diver used a digital camera to record a clear underwater image of the sampling grid and the type of seafloor present within its bounds. Generating a homogenous dataset in regards to light exposure and angle was a priority, thus underwater imaging was conducted at in the same time window every day (14:30-17:00) without cloud cover. Furthermore, because ocean currents challenged the diver’s ability to record images at ~90 degree angles above the square, multiple images were recorded until a clear, geometrically sufficient image was collected. After collecting the image, the same digital camera was used to record an image of the written GPS coordinates, thus yielding an alternating image repository of each RP’s observed sea floor cover and the corresponding GPS coordinates.

Because the digital camera collects and stores each image using a consecutive file-naming system, eventual referencing of the image and its location is easily accomplished. This process was conducted for 120 RP’s across the study area, resulting in 120 geotagged images of the seafloor to be used in the following image classification procedures.
3.23 Seagrass Percent Cover Estimation

Visual estimation of percent SAV cover was conducted by the lead researcher. Because the focus of the study was to spatially delineate the presence or absence of general submerged aquatic vegetation in the form of seagrass, it was deemed sufficient to use the Percent Cover Estimation methodology outlined in McKenzie’s Rapid Assessment of Seagrass Habitats in the Western Pacific (McKenzie 2003). A percent cover of SAV was be established by estimating SAV density occurring within a 1m x 1m PVC sampling grid that doubled as an establisher of scale. Under this seagrass estimation framework, the analyst visually estimates the percent cover of seagrass as it occurs within the 1m x 1m quadrat, illustrated in Figure 2.

![Figure 2. Example of seagrass percent cover estimations. Percent cover value is displayed in top left corner of each image (McKenzie 2003).](image)

This process was conducted for all 120 of the images for the 120 reference points. Species type was not included in the estimation, however it was observed that *thelassia testidunum* was the dominating species. When working with large image datasets like the one used in this study, rapid assessment is preferred because of its efficiency at recording the presence or absence of seagrass, as well as providing information regarding the seagrass’s
density as it appears within the sampling grid. A secondary benefit of this method is that additional analysts may view the same image dataset and record their own percent cover estimations, in effort to reduce analyst bias. Furthermore, image analysis software may be used to mathematically quantify the seagrass pixels for the highest accuracy, however this process is beyond the scope of this project’s main objective that is to produce a binary classification of seagrass cover (presence or absence of SAV). SAV was considered present when 30% or more of the sampling grid was filled with SAV. SAV was considered absent when less than 30% of the sampling grid was filled with SAV.

3.2.4 Image Acquisition

Two multispectral images of the study area were acquired for the purpose of measuring changes in seagrass cover in the South Water Caye Marine Reserve (SWCMR), Belize. The first image was collected by the IKONOS satellite sensor on September 12, 2001. The IKONOS image was provided by the University of Mississippi Geoinformatics Center as a panchromatic-sharpened product. The second image, collected on August 29, 2016 by Planet. These two sensors were chosen for their high spatial resolutions (IKONOS = 1 m; Planet = 3 m). Spectral region bandwidths for each sensor are shown in Table 1.
3.25 Image Processing and Classification

Image subsets of the study area were generated. Islands, visibly and known deep areas, and known shallow waters were masked, rendering imagery of only open water. Furthermore, the IKONOS and the Planet imagery were both divided into two north and south sections. This step was conducted because it was known priori that the waters in the southern portion of the study area are much deeper. The deeper water results in different radiance levels, due to increased absorption and attenuation of visible light. It was deemed through trial and error that these effects result in misclassifications of SAV. The outputs of these steps were four images, a southern and northern portion for each time period.

After these steps, image sections were passed into a principal components analysis. As specified by the analyst, 4 component bands were outputted for each image section. These component bands were then passed into an unsupervised isoclustering classification algorithm, with 60 target classes. The analyst compared the 60 output classes with the original imagery to combine classes to achieve a binary representation of SAV and non-SAV, with resulting class values of 1 and “NoData,” respectively. After combining the discrete classes, the IKONOS

Table 1. Sensor technical specifications.

<table>
<thead>
<tr>
<th>Spectral Region</th>
<th>IKONOS wavelength (µ)</th>
<th>Planet wavelength (µ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panchromatic</td>
<td>0.45 – 0.90</td>
<td>N/A</td>
</tr>
<tr>
<td>Blue</td>
<td>0.45 – 0.52</td>
<td>0.424 – 0.478</td>
</tr>
<tr>
<td>Green</td>
<td>0.52 – 0.60</td>
<td>0.515 – 0.61</td>
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<tr>
<td>Red</td>
<td>0.63 – 0.69</td>
<td>0.63 – 0.714</td>
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<tr>
<td>Red Edge</td>
<td>N/A</td>
<td>0.69 – 0.73</td>
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<tr>
<td>Near Infrared</td>
<td>0.76 – 0.90</td>
<td>0.76 – 0.85</td>
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</table>
images were resampled, using a majority resampling technique, to match the spatial resolution of the Planet imagery (3m x 3m). The majority resampling technique was chosen because it assigns output pixel values the most popular value within a 3x3 pixel neighborhood. This resampling technique is logical for SAV classification, as SAV beds often occur in discrete patches. After resampling, classifications from the same time year were mosaicked. Area was calculated based on the WGS UTM 1984 Zone 16 projection. Classification accuracy was assessed by comparing the ground-truth with classifications of the 2016 Planet imagery. The classification procedure resulted SAV classification accuracy of 85.6% and non-SAV classification accuracy of 83.3%.
CHAPTER 4

RESULTS

4.1 Guide-Reported Locations of Belizean BPT and their Threats

Figures 3 and 4 show the location of Belizean BPT, as reported by the sampled Belizean recreational fishing guides. When multiple fisheries were reported as present in the same area, their classes were combined. The largest area of bonefish and permit was reported to occur around Ambergris Caye, with less expansive tarpon fishing sites in shallow offshore zones surrounding Ambergris Caye. All three species were reported as present in the waters south of Ambergris Caye and near Belize City (Figure 3). Guides reported that the eastern edge of Turneffe Atoll harbored multiple sites for bonefish and permit, with small tarpon fishing sites on the atoll’s eastern edge. Lighthouse Reef and Glover’s Atoll were reported to harbor all three species. Guides reported several tarpon sites along Stann Creek district sea border, near or in estuarine environments. Much of this tarpon fishery area represents juvenile and migrating tarpon, as the species utilizes rivers when in juvenile states (Steinberg 2015). Along most of the barrier reef, all three species were reportedly found in areas abutting mangrove islands, with access to the reef and seagrass beds (Figures 3 & 4). Because BPT rely on seagrass beds for feeding and spawning, their perceived proximity to the habitat was expected.

The guide-reported sites of BPT and threats to BPT are depicted in Figures 3 and 4. Professional Belizean recreational fishing guides mapped 106 threat points in total. There are 47 sites where gill-net use was recorded, with 15 sites for development, 13 sites for both dredging
and reef degradation, 8 sites for agricultural runoff, 6 sites for illegal fishing practices, 3 sites for urban pollution, and 1 site for shrimp farm pollution. Expectedly, guides perceived the majority of the development as occurring in Northern Belize, near Ambergris Caye and Caye Caulker. Dredging was also perceived as mostly occurring in Belize’s northern waters, however these points are less aggregated than sites of development. In the north, heavy gill-net usage was reported along both the Corozal and Belize district’s sea borders, with southern gill-net points more isolated. Reef degradation was mainly perceived to be occurring on the southern portion of the barrier reef, however most of these points were supplied by the same informant. The majority of the BPT areas, in addition to the threat points, occurred on or near seagrass beds.
Figure 3. Northern Belize BPT and threats.
Figure 4. Southern Belize BPT and threats.
Table 2. Guide-ranked threats to Belizean BPT. ND = No data.

<table>
<thead>
<tr>
<th>Survey</th>
<th>AR</th>
<th>DV</th>
<th>D</th>
<th>GN</th>
<th>IF</th>
<th>RD</th>
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As seen in Table 2, gill-nets were the highest ranked threat with a mean and weighted mean of 9, followed by illegal fishing practices with a mean of 7 and weighted mean of 7. Out of the respondents, 10 reported that sport fishing has gotten worse in their professional career, 5 reported that sport fishing had improved, 6 reported mixed results, and 2 did not provide an answer. These perceptions are depicted in Figure 5. Respondents who reported mixed results cited that permit fishing had improved while tarpon fishing had declined. Additional mixed perceptions were that while fish populations have decreased, business has increased, i.e. more touring anglers are paying for guiding services. The most common response in the “Worse” category was that there is less BPT than previous years. Additionally, gill-nets and lack of law enforcement were cited as major reasons for the decline in BPT fishing quality. Over-fishing and increased pressure from sport-fishing guides were also reported as causes for the decline in BPT fishing quality. Respondents in the “Better” category provided no additional information aside from stating that BPT fishing has improved in their experience.

An objective was to determine if there was a difference in the perception of threats across guide age groups. Figure 6 illustrates the ranked threats for various age classes. It is noteworthy that not all age groups were sampled evenly. Because of this, certain age classes, especially the
“1-5 years” class, have as few as one subject, bias is present. Nevertheless, Figure 6 serves to provide a general understanding threat perception variability across years of experience classes. Perception of risk was averaged for each experience class.

When digitizing the mapped threats, the weighted average was used for each threat attribute. Weights were determined by the subject’s reported years of experience. Threat attributes are weighted because it was assumed that more experienced guides have a superior awareness of the reality of the various threats facing BPT sustainability than less experienced guides.


4.2 Changes in Seagrass Extent in the SWCMR

As shown in Figure 7, there was a decline in the spatial distribution of seagrass in the southern section of the study area and an increase in seagrass distribution in the northern section over the years 2001 to 2016. The overall northern section of the study area experienced approximately an 8% seagrass growth over the period, while the southern section experienced approximately a 6% decline.
Figure 7. Seagrass classification. >30% seagrass cover classifications for years 2001 and 2016. 2001 imagery is IKONOS and 2016 imagery is Planet. Red line indicates border between the northern and southern sections of the study area.
CHAPTER 5
DISCUSSION

5.1 Guide-reported locations of Belizean BPT and their threats

Gill-nets were ranked the highest among all threat types. These results align with anecdotal reports from professional recreational fishing guides and marine rangers. Illegal fishing practices were ranked the second-highest. While this threat category was intentionally vague, anecdotal reports suggest that these types of illegal practices include trespass from Guatemalan fishermen, improper anchor use, and use of hooks of the wrong size. Despite their effectiveness at catching large quantities of fish, gill-nets are widely considered detrimental to biodiversity and fisheries quality because they indiscriminately trap fish.

In designing and distributing the survey, it was discovered that knowledge and input from the country’s sport fishing communities has not been adequately included in national ecosystem management directives, such as the Coastal Zone Management Authority and Institute (CZMAI). Because Belizean sport fishing is a major driver of the country’s tourism economy, it is imperative that input from the sport fishing community is leveraged for their knowledge and ecosystem health diagnoses. Numerous surveyed guides expressed discontentment that their input is not sought out more by conservation managers. Sport fishing of BPT offers Belize enormous benefits in the form of natural capital. Because BPT are designated as “catch-and-release,” recreational fishing of these three fish is considered sustainable, as the stock of BPT is
unchanged by the presence of sport-fishing, assuming adherence to equipment and catch laws by anglers.

Sport fishing guides are widely considered to be experts on the relationship between coastal habitats and BPT fisheries. Because of this expertise, the georeferenced ranked threats presented in Figures 3 and 4 provide valuable insight into the locations and severity of numerous coastal activities and how they relate to BPT fishing quality. These data can be used to prioritize future research relating to Belizean BPT fisheries, coastal tourism sustainability, and general ecological risk.

Gaining local recreational fishing guide participation in the survey was a challenge for many reasons, including 1) Email was the primary means of contacting guides to seek participation. A large portion of Belizean guides either do not use email or do not regularly check their accounts, creating logistical difficulties for the Belizean survey distributor. 2) Hurricane Earl (August 2016) was a destructive event that resulted in significant damages along the Belizean coast. Numerous sport fishing lodges were affected by the hurricane, resulting in difficulties maintaining contact with lodges and guides who agreed to participate in the survey. Considering these research challenges, it is advisable for future similar research projects to include increased in-situ surveying of sport fishing professionals, as face-to-face inquiries are likely to result in higher participation.

5.2 Changes in Seagrass Extent in the SWCMR

This methodology’s classification accuracy was lower than Gaston et. al’s for a number of potential reasons: 1) Because the imagery used to classify the 2016 seagrass was collected approximately three months after the ground-truthing data, potential changes in SAV extent may have occurred. 2) GPS used for ground-truthing was of questionable accuracy (accurate within
~5m). 3) Random error introduced during the field sampling campaign. 4) Lack of bathymetric data for inclusion in principal component analysis and spatial trigonometric offset of field reference points.

Nevertheless, it is evident that the northern section of the study area experienced an increase in seagrass cover while the southern section experienced a decline. Differences in the physical geography of these sections likely has much to do with this contrast, since, unlike the southern section, the northern section is sheltered from ocean wave action by the barrier reef to the east. High energy wave action may contribute ocean sediments to the southern section, resulting in relatively higher sedimentation of seagrass beds. Further study of the study area’s temporal water quality changes are needed to determine if the declines in the southern portion resulted from water temperature, salinity, turbidity, or another water quality parameter.

Additionally, the linear shapes of some areas of decline (Figure 8) suggest that dredging for resort beach nourishment is occurring the area. In-situ experiences with resort owners in the SWCMR suggest that lodges and resorts nourish their beaches with nearby sediments. Given the linear edges of the sandy sea floors (Figure 8), as well as these areas’ proximity to resorts, dredging is likely to have occurred. Despite these small, isolated areas of potential sand mining, the study area still offers reliable sport fishing of bonefish and permit in the shallow waters between the forereef and the cayes. However, high-energy, tropical storm-driven waves and aeolian weathering regularly erode sands from beaches unsheltered by seawalls, breakwaters, or the natural littoral vegetation. This effect amplified by the historical removal of sediment entraining services provided by littoral vegetation such as mangroves. As sea levels rise, island resort owners will experience increasing pressure to nourish their beaches with sediments and
despite regulation and will likely seek the conveniently located sediments from the waters near their resorts.

Figure 8. Areas of potential dredging in the study area.

During the field sampling campaign, it was learned, both from visual observation and conversations with locals that area fishermen have hundreds of lobster traps placed in the region. Local lobstermen commonly use concrete blocks and used rubber care tires as traps. These traps are often placed directly on top of seagrass beds. During the field sampling campaign, a
professional fishing guide with several decades experience reported that this practice of placing
traps directly on seagrass beds negatively impacts seagrass beds, usually resulting in a radial
desertification effect. Further study and experimentation are necessary to identify if and how this
radial desertification effect occurs, but potential causes might include: dampening a seagrass
patch’s wave-attenuating potential, thereby admitting higher-velocity currents in the area
immediately surrounding the trap. Another potential explanation is that, as lobstermen return to
their traps to determine their success, the traps are moved, resituated, or otherwise dragged to a
nearby previously undisturbed seagrass patch, thus repeating the cycle of substrate suffocation.

5.3 Implications for Future Research and Management

With regard to gill-nets and illegal fishing practices, the Belizean sport fishing
community desire stricter fishing regulations and increased patrolling of the coast. Many guides
harbor resentment for Guatemalan fishermen, who reportedly practice unsustainable fishing
practices such as gill-net use and using wrong hook sizes, both of which inflict damage to
Belize’s fisheries. Government rangers are aware of the dangers posed by gill-net use and have
in many areas, such as the Port Honduras Marine Reserve, begun to partner with recreational
fishing stakeholders to identify areas where harmful fishing activities occur.

Both ethnographic surveying and remote sensing are powerful and efficient means of
gathering broad information regarding a region’s ecological well-being. In the case of Belize,
where the country’s economy is driven primarily by marine tourism activities, it is imperative
that natural capital is protected. While it is true that Belize is a globally-recognized leader in
environmental preservation, the country will be challenged by its growing population and the
steady influx of international tourists. Furthermore, as the country begins to explore its potential
oil reserves by means of off-shore drilling, and as urbanization increases in the southern part of
the country, Belize must balance the potential benefits offered by development with current economically lucrative activities which rely on the health of the country’s natural capital. Seagrass’s role in maintaining Belize’s ecosystems and economy cannot be understated. In addition to seagrass’s myriad of environmental services, the country’s BPT stocks rely largely on seagrass beds for their food supply and sport-fishing guides rely on BPT for their income. As such, recreational fishing in Belize exemplifies the benefits of exploiting natural capital, as BPT stocks are not reduced through activities directly relating to the sport. Per these results, the threats to BPT are derived outside of the industry. The maps of perceived threats can be used to prioritize future investigation of activities that threaten BPT habitats like seagrass flats, and thus threaten the quality and economic sustainability of Belizean recreational fishing.
REFERENCES


Survey: Bonefish, Permit, and Tarpon Sport-fishing In Belize

Please answer the following questions as best as you can. Your answers are anonymous and will only be used for scientific purposes.

1. On a scale of 1 - 10, please indicate how threatening each of the following is to sport-fishing of bonefish, permit, and tarpon in Belize. 1 = not threatening, 5 = somewhat threatening, 10 = extremely threatening (Circle a number for each activity).

- Agricultural runoff 1 2 3 4 5 6 7 8 9 10
- Development 1 2 3 4 5 6 7 8 9 10
- Dredging 1 2 3 4 5 6 7 8 9 10
- Gill-nets 1 2 3 4 5 6 7 8 9 10
- Illegal fishing practices 1 2 3 4 5 6 7 8 9 10
- Reef degradation 1 2 3 4 5 6 7 8 9 10
- Shrimp farm pollution 1 2 3 4 5 6 7 8 9 10
- Urban pollution (sewage, trash) 1 2 3 4 5 6 7 8 9 10

Please use the following blanks to rank any additional threats that you would like to include.

- _____________ 1 2 3 4 5 6 7 8 9 10
- _____________ 1 2 3 4 5 6 7 8 9 10
- _____________ 1 2 3 4 5 6 7 8 9 10

2. Try to pin down, generally speaking, where the threats are directly on the provided map.

Please use the following symbols for each threat:

AR: Agricultural runoff
DV: Development
D: Dredging
GN: Gill-nets
IF: Illegal fishing practices
RD: Reef degradation
SP: Shrimp farm pollution
UP: Urban pollution (sewage, trash)

3. Has sport-fishing changed in the past several years? Better, worse? If worse, why?

4. How many years have you been sport-fishing or guiding in Belize?

Please return completed survey to:
Jon Pierre Windsor
86 Churchill Street
Benque Viejo Del Carmen
Cayo District
Belize, Central America
Overview of Maps

Each box represents a different map in the packet.
The page numbers are in the center of each box.