



NOAA Technical Memorandum NMFS-XXX-##

Caribbean Ecosystem Status Report

Southeast Integrated Ecosystem Assessment Program

December 2024

U.S. DEPARTMENT OF COMMERCE

National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Northwest Fisheries Science Center



NOAA
FISHERIES

Caribbean Ecosystem Status Report

Southeast Integrated Ecosystem
Assessment Program¹

1. NOAA Fisheries, Southeast Fisheries Science Center

Table of contents

1	Introduction	1
1.1	About this report	1
1.2	Indicator selection	2
1.3	Notes on interpreting time series figures	3
2	Tracking performance toward fishery management objectives	4
2.1	Food production	4
2.2	Socioeconomic health	12
2.3	Equity	28
2.4	Engagement and participation	28
2.5	Bycatch reduction	34
2.6	Governance	34
2.7	Protection of ecosystems	39
3	Risks to meeting fishery management objectives	41
3.1	Sea surface temperature	41
3.2	Coral bleaching stress	41
3.3	Ocean acidification	43
3.4	Hurricane activity	43
3.5	Earthquake activity	45
3.6	Point source pollution	45
3.7	Turbidity	47
3.8	Water quality	47
3.9	Coastal development	47
3.10	Primary productivity	51
3.11	Sargassum inundation	51
3.12	Market disturbances	52
3.13	Human activity	52

Table of contents

4 Integrated ecosystem perspectives	57
.	57
5 Research recommendations	60
5.1 Risks to meeting management objectives	60
5.2 Fishery-dependent and fishery-independent data sources	60
5.3 Human dimensions	61
6 Acknowledgments	63
6.1 Contributions	63
6.2 Resources	63
7 Contributors	64
7.1 Editors	64
7.2 Contributors	64
References	65

List of Figures

1.1	Process for selecting indicators for the U.S. Caribbean Ecosystem Status Report.	2
1.2	Example time series plot, showing an indicator plotted with its mean and standard deviation, and trend analysis for the most recent five years of data. See text for a more detailed description of specific calculations.	3
2.1	Average density of queen triggerfish, red hind, lane snapper, yellowtail snapper, redband parrotfish, and stoplight parrotfish in Puerto Rico from the National Coral Reef Monitoring Program's Reef Visual Census data.	5
2.2	Average density of queen triggerfish, red hind, lane snapper, yellowtail snapper, redband parrotfish, and stoplight parrotfish in St. Thomas and St. John from the National Coral Reef Monitoring Program's Reef Visual Census data.	6
2.3	Average density of queen triggerfish, red hind, lane snapper, yellowtail snapper, redband parrotfish, and stoplight parrotfish in St. Croix from the National Coral Reef Monitoring Program's Reef Visual Census data.	7
2.4	Commercial fish density from PRCRMP fishery-independent surveys in Puerto Rico (top), commercial fish density from TCRMP fishery-independent surveys in the USVI (middle), and the slope of the log-transformed size spectrum from TCRMP surveys in the USVI (bottom).	8
2.5	Ratios of pelagic to demersal landings, based on reported commercial landings data for Puerto Rico (top), St. Thomas and St. John (middle) and St. Croix (bottom). Note differences in scale of the y-axes; years in the USVI are fishing years (July 1st to June 30th of the following year).	9
2.6	Average maximum length of demersal species in the reported landings for Puerto Rico (top), St. Thomas and St. John (middle) and St. Croix (bottom). Note that the years in the USVI are fishing years (July 1st to June 30th of the following year).	10
2.7	Proportion of commercial demersal landings in each of four maximum body length size classes in Puerto Rico.	11

List of Figures

2.8	Proportion of commercial demersal landings in each of four maximum body length size classes in St. Thomas and St. John. Note that the years are fishing years (July 1st to June 30th of the following year).	13
2.9	Proportion of commercial demersal landings in each of four maximum body length size classes in St. Croix. Note that the years are fishing years (July 1st to June 30th of the following year).	14
2.10	Total landings of lobsters (top row), conch (middle row), and all other commercial species (bottom row) from commercial landings data in Puerto Rico (left column), St. Thomas and St. John (middle column) and St. Croix (right column). Confidential landings appear as missing values. Note that the years in the USVI are fishing years (July 1st to June 30th of the following year).	15
2.11	Percent revenue contribution for the top ten species groups, stacked by their order of overall importance, for commercial fisheries in Puerto Rico.	16
2.12	Percent revenue contribution for the top ten species groups, stacked by their order of overall importance, for commercial fisheries in St. Thomas and St. John. Note that the years are fishing years (July 1st to June 30th of the following year).	17
2.13	Percent revenue contribution for the top ten species groups, stacked by their order of overall importance, for commercial fisheries in St. Croix. Note that the years are fishing years (July 1st to June 30th of the following year).	18
2.14	Total number of commercial fishing trips by gear type in Puerto Rico, separated by primary gear used on the trip.	19
2.15	Total number of commercial fishing trips by gear type in St. Thomas and St. John, separated by primary gear used on the trip. Note that the years are fishing years (July 1st to June 30th of the following year).	20
2.16	Total number of commercial fishing trips by gear type in St. Croix, separated by primary gear used on the trip. Note that the years are fishing years (July 1st to June 30th of the following year).	20
2.17	Proportion of commercial trips that are reported as diving trips for Puerto Rico (top), St. Thomas and St. John (middle) and St. Croix (bottom). Note that the years in the USVI are fishing years (July 1st to June 30th of the following year).	21
2.18	Ordination of gear type usage by landing site for Puerto Rico, color coded by region.	22
2.19	Ordination of gear type usage by landing site for St. Thomas and St. John.	23
2.20	Ordination of gear type usage by landing site for St. Croix.	24
2.21	Overall Gross Domestic Product in Puerto Rico (top) and the USVI (bottom).	25
2.22	Monthly unemployment rate in Puerto Rico (top) and the USVI (bottom).	26

List of Figures

2.23 Ocean economy GDP, ocean economy establishments, ocean economy employment, and ocean economy wages (from top to bottom), for Puerto Rico (left column) and the USVI (right column).	27
2.24 Equality in the distribution of revenues across the commercial fishery Puerto Rico (top), St. Thomas and St. John (middle) and St. Croix (bottom), as represented by the Gini index. Note that the years in the USVI are fishing years (July 1st to June 30th of the following year).	29
2.25 Total recreational catch in millions of pounds as estimated by the Sea Around Us database for Puerto Rico (top) and the USVI (bottom).	30
2.26 Commercial fishing engagement and reliance in Puerto Rico based on NOAA Fisheries Databases: commercial landings 5-year average for 2016–2020 and permit numbers; and Census data: Population by municipality/sub-district	31
2.27 Commercial fishing engagement and reliance in St. Thomas and St. John based on NOAA Fisheries Databases: Commercial landings 5-year average for 2016–2020 and permit numbers; and Census data: Population by municipality/sub-district.	32
2.28 Commercial fishing engagement and reliance in St. Croix based on NOAA Fisheries Databases: commercial landings 5-year average for 2016–2020 and permit numbers; and Census data: Population by municipality/sub-district	33
2.29 Indicator of bycatch prevalence as measured by the proportion of commercial trips using non-selective fishing gear types for Puerto Rico (top), St. Thomas and St. John (middle) and St. Croix (bottom). Note that the years in the USVI are fishing years (July 1st to June 30th of the following year).	35
2.30 The number of new management actions implemented in the U.S. Caribbean region based on the annual count of unique Federal Register sections within all Federal Register notices.	36
2.31 Percent of stocks/complex with informative annual catch limits as measured by stock assessments in Puerto Rico (top) and the USVI (bottom).	37
2.32 Number of Marine Resource Education Program industry participants (top) and number of SeaGrant workshop or meeting participants in the U.S. Caribbean region (bottom).	38
2.33 Monthly count of federal law enforcement incidents in the U.S. Caribbean region by date of incident creation (total n = 101) and monthly count of patrols (including land, sea, and international trade) conducted from a field office in Puerto Rico or USVI (total n = 363).	39
2.34 Percent coral cover and coral species richness (average number of species per transect) from TCRMP and PRCRMP biological surveys.	40

List of Figures

3.1	Monthly mean (top), minimum (middle), and maximum (bottom) sea surface temperature standardized anomalies, calculated over the U.S. Caribbean region.	42
3.2	Average monthly degree heating week values as reported by NOAA Coral Reef Watch Virtual Stations for Puerto Rico (top) and USVI (bottom).	43
3.3	Ocean acidification as measured by modeled surface aragonite saturation state, shown as standardized monthly anomalies for the U.S. Caribbean region.	44
3.4	Annual accumulated cyclone energy index, calculated as the sum of squared 6-hourly reported wind speeds for storms tracking through the U.S. Caribbean region.	44
3.5	Number of seismic events of >3.5 magnitude occurring annually in the U.S. Caribbean.	45
3.6	Annual count of identified point source polluters in the U.S. Caribbean based on TRI sites (Toxic Release Inventory), Superfund sites (Superfund Enterprise Management System), National Compliance Database listed sites, and Brownfield sites identified in Puerto Rico (top) and the USVI (bottom).	46
3.7	Standardized monthly anomalies of water turbidity as measured by the diffuse attenuation coefficient, for waters surrounding Puerto Rico (top), St. Thomas and St. John (middle) and St. Croix (bottom).	48
3.8	Water quality as measured by average enterococcus counts (+/- 1 S.E.) from beach water quality sampling at sites in Puerto Rico (top) and the USVI (bottom).	49
3.9	Impervious surfaces from development in the U.S. Caribbean.	50
3.10	Changes in ocean color showing mean chlorophyll a levels (standardized monthly anomalies) in the U.S. Caribbean region.	51
3.11	Annual mean sargassum inundation in square km of cover in the U.S. Caribbean.	52
3.12	Disturbance level (+/- 1 S.D.), calculated as the departure from mean seasonal landings patterns for top species in Puerto Rico (top), St. Thomas and St. John (middle) and St. Croix (bottom). Note that the years in the USVI are fishing years (July 1st to June 30th of the following year).	53
3.13	Population change in Puerto Rico (top) and USVI (bottom) according to census data.	54
3.14	Annual tourism activity in Puerto Rico (left) and USVI (right) as indicated by the number of cruise and air passengers visiting the islands.	55

List of Figures

3.15 Annual tourism activity in Puerto Rico and USVI as indicated by the number of hotel registrations (guests). Note that Puerto Rico data only include non-resident hotel registrations while for USVI data were available for all hotel registrations, so may include residents and non-residents. .	56
4.1 Traffic light plot representing the value of the indicator each year according to quintiles; colors show that the indicator moving between well below average (red, bottom quintile), below average (orange, 20-40% quintile), average (yellow, 40-60% quintile), above average (light blue, 60-80% quintile), and well above average (dark blue, top quintile), respectively (see legend). Indicators are grouped by category, and appear on the plot sorted by their loading (i.e., their influence) from a principal components analysis. In this way, indicators showing similar patterns across time are grouped more closely together.	58
4.2 Left: Yearly scores of the first two components of a principal components analysis (PCA) for three groups of indicators, based on indicator values from 2011 – 2023. Right: Loadings plots show the relative influence of each indicator in driving the temporal trends observed on the left panel. Loadings with an absolute value greater than 0.2 are considered to be significant.	59

1 Introduction

1.1 About this report

The purpose of this report is to synthesize diverse information sources to assist with implementation of ecosystem-based fisheries management in the U.S. Caribbean region, which includes Puerto Rico and the U.S. Virgin Islands (USVI). A suite of indicators that span physical, biological, social and economic elements of the ecosystem are reported with the goal of helping the Caribbean Fishery Management Council (CFMC) and other resource managers measure progress toward fishery management objectives. The report relied on both previously identified proposed indicators and expert vetting to select a suite of indicators that best address the fishery management plan (FMP) objectives for the U.S. Caribbean. Information in this report is organized into two sections: 1) tracking performance toward predefined fishery management objectives, and 2) potential risks to meeting those fishery management objectives.

The first set of indicators can be used to consider progress toward stated management objectives. Management objectives were gleaned from the Island-based Fishery Management Plans and categorized into seven groups: food production, socioeconomic health, equity, engagement and participation, bycatch reduction, governance, and protection of ecosystems. Each of these sections contains a selection of indicators that can be used to better understand how well these respective management objectives are being met. Note that for some indicators, directionality can be associated with positive or negative progress toward management objectives (e.g., increases in abundance of economically important species is generally associated with improved management). However for other indicators, directionality can be considered neutral (e.g., proportion of diving trips, changes in contribution to revenue), although changes in these indicators represent important shifts in the fishing dynamics of which managers should be aware. The risk indicator section quantifies major stressors (as identified by stakeholders) that capture the potential risks to meeting fishery management objectives. These indicators provide managers with an understanding of the backdrop against which management is occurring. Major changes in these indicators may be associated with decreased effectiveness of fisheries management, if the influences of external environmental or economic stressors are strong relative to influences from adjustments in fishing activity.

1 Introduction

This report was created in Quarto (<https://github.com/quarto-dev/quarto-cli/>) using the NOAA Quarto book template (<https://github.com/nmfs-opensci/NOAA-quarto-book>). A github repository houses all the indicator data and R code used to compile the report (<https://github.com/Gulf-IEA/Caribbean-ESR-2>).

1.2 Indicator selection

The CFMC's Science and Statistical Committee, as well as the region's Ecosystem-Based Fishery Management Technical Advisory Panel (EBFM TAP), recently completed a series of conceptual models linking key components of the ecosystem and human activities related to fishing (Seara et al. 2024). This report used these conceptual models as a starting list of proposed indicators and matched the indicators to address progress toward FMP objectives when possible (Figure 1.1).

Process for Caribbean ESR



Figure 1.1: Process for selecting indicators for the U.S. Caribbean Ecosystem Status Report.

For those objectives that did not have an immediate conceptual model-identified indicator, a decision matrix process was used for expert vetting (Montenero, Kelble, and Broughton 2021). This decision matrix was composed of a list of proposed indicators compiled from the conceptual models as well as proposed indicators provided via expert input. These potential indicators were vetted and edited by expert small working groups, who then scored a decision matrix of potential indicators against the

1 Introduction

following decision criteria: long term data availability, measurability, sensitivity to environmental changes, specificity, spatial and temporal scalability, relevance to specific FMP objectives, and responsiveness to management actions.

1.3 Notes on interpreting time series figures

Time series data are plotted in a standardized format for ease of interpretation (e.g., Figure 1.2). The x-axis represents the temporal dimension, which may be monthly, yearly, or irregular time steps, and the y-axis represents the indicator value in units specified in the axis label. Measures of uncertainty in the indicator values are also shown, when available. The dashed horizontal line represents the mean indicator value across the entire time series, and the solid horizontal lines denote the mean plus or minus one standard deviation. Red shaded areas and green shaded areas show years for which the indicator value is below or above one standard deviation from the mean, respectively. The blue vertical shaded box highlights the last five years of indicator values, over which additional metrics are calculated. Black circles to the right of each figure indicate whether the indicator values over the last five years are greater (plus sign), less than (minus sign), or within (solid circle) one standard deviation from the mean of the overall time series. Arrows to the right of each figure indicate whether the least squares linear fit through the last five years of data produces a positive or negative slope that is greater than one standard deviation (upward or downward arrows respectively), or less than one standard deviation (left-right arrow).

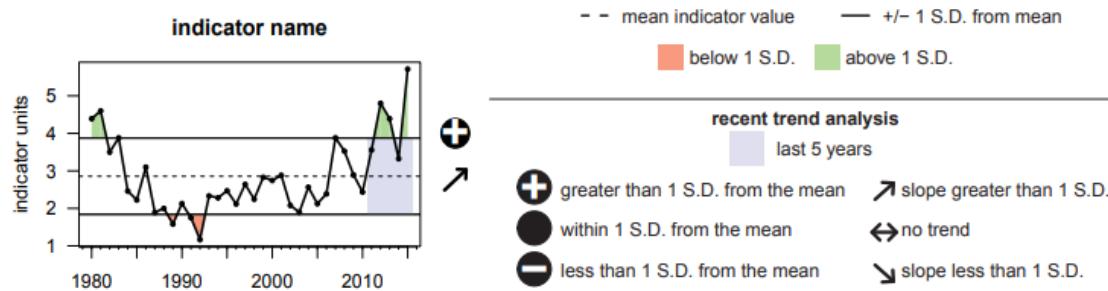


Figure 1.2: Example time series plot, showing an indicator plotted with its mean and standard deviation, and trend analysis for the most recent five years of data. See text for a more detailed description of specific calculations.

2 Tracking performance toward fishery management objectives

In this section, we report indicators that are intended to capture progress towards meeting Fishery Management Plan objectives related to food production, socioeconomic health, equity, engagement and participation, bycatch reduction, governance and protection of ecosystems. (test)

2.1 Food production

2.1.1 Abundance of economically important species

Fishery-independent surveys are conducted to understand the relative abundance trends of economically important fish species. NOAA, in collaboration with many academic and agency partners, has been conducting visual surveys of reef fish species in Florida since 1978 and surveys began in the U.S. Caribbean in 2001 (Smith et al. 2011). In 2013, these reef fish surveys were adopted by NOAA's Coral Reef Conservation Program's National Coral Reef Monitoring Program (NCRMP) that is led by the Southeast Fisheries Science Center in the U.S. Atlantic and Caribbean (Towle et al. 2021). Six target fish species (lane snapper, yellowtail snapper, red hind, queen triggerfish, redband parrotfish, and stoplight parrotfish) were selected as key indicators for the condition of living resources in the U.S. Caribbean, due to their status as targeted species by recreational and commercial fishers. Trends in fish density for these species of interest are highly variable, but density has been at or above the time series average in recent years for most species. A notable exception is stoplight parrotfish, which have gradually declined over time in all regions and density is currently below average in St. Croix (Figure 2.1, Figure 2.2, Figure 2.3).

Fishery-independent surveys can be used to look at changes in the overall fish community and understand processes affecting multiple suites of species. The Puerto Rico Long-Term Coral Reef Monitoring Program (PRCRMP) has conducted annual surveys of fish and benthic organisms since 1999 (Puerto Rico Department of Natural and

2 Tracking performance toward fishery management objectives



Figure 2.1: Average density of queen triggerfish, red hind, lane snapper, yellowtail snapper, redband parrotfish, and stoplight parrotfish in Puerto Rico from the National Coral Reef Monitoring Program's Reef Visual Census data.

2 Tracking performance toward fishery management objectives



Figure 2.2: Average density of queen triggerfish, red hind, lane snapper, yellowtail snapper, redband parrotfish, and stoplight parrotfish in St. Thomas and St. John from the National Coral Reef Monitoring Program's Reef Visual Census data.

2 Tracking performance toward fishery management objectives



Figure 2.3: Average density of queen triggerfish, red hind, lane snapper, yellowtail snapper, redband parrotfish, and stoplight parrotfish in St. Croix from the National Coral Reef Monitoring Program's Reef Visual Census data.

2 Tracking performance toward fishery management objectives

Environmental Resources 2019). Similarly, the USVI Territorial Coral Reef Monitoring Program (TCRMP) conducts annual to semi-annual surveys of coral health, fish community structure and coral health (<https://www.vitcrmp.org/>). The PRCRMP, TCRMP, and NCRMP programs are all supported by NOAA's Coral Reef Conservation Program and are complementary, with PRCRMP and TCRMP sampling at fixed sites and NCRMP sampling at stratified random sites. Commercial fish density is calculated by taking the average number of commercially targeted fish per transect over time. The slope of the size spectrum is calculated by binning all observed commercial fish lengths into size categories and then fitting a linear regression through the log-transformed histogram; a more negative slope represents relatively fewer large fish and potentially increased fishing impacts. In Puerto Rico, average commercial fish density fluctuates but is stable over time; insufficient data were available with which to estimate the slope of the size spectra. In the USVI, commercial fish density has increased since the early 2010s, with notable peaks in 2018 and 2021. The slope of the size spectrum has been relatively stable over time but with sudden drops in 2011 and 2018. A single-year increase in density combined with a simultaneous decrease in the size spectrum conveys the sudden appearance of many small fish, suggestive of a large recruitment event across multiple species in 2018 (Figure 2.4).



Figure 2.4: Commercial fish density from PRCRMP fishery-independent surveys in Puerto Rico (top), commercial fish density from TCRMP fishery-independent surveys in the USVI (middle), and the slope of the log-transformed size spectrum from TCRMP surveys in the USVI (bottom).

2.1.2 Pelagic:demersal ratio of landings

The ratio of pelagic to demersal species is thought to be responsive to nutrient inputs and the quality of benthic habitat in marine ecosystems (de Leiva Moreno et al. 2000); in the context of small islands in the tropical seas, it may convey the availability and productivity of pelagic habitats relative to the size of the shelf and productivity of coral reef habitats. Ratios of pelagic to demersal landings were calculated based on total pounds reported in the Caribbean Commercial Landings data, following a classification of all species based on their reported ecology in FishBase (Froese and Pauly 2024). In St. Croix, the pelagic-demersal ratio is much higher than the other islands, due to the small shelf area and limited availability of reef habitat; interannual fluctuations for this island are largely influenced by landings of dolphinfish and tunas. In Puerto Rico, the pelagic-demersal ratio has increased in recent years; this may be partially due to changes in reporting that occurred in 2020 (addition of electronic reporting option). In St. Thomas and St. John, the ratio has gradually increased over time; the large peak in the 2018–2019 fishing year could have been a result of hurricane-induced reef habitat loss and subsequent reduction in landings of demersal fish species (Figure 2.5).

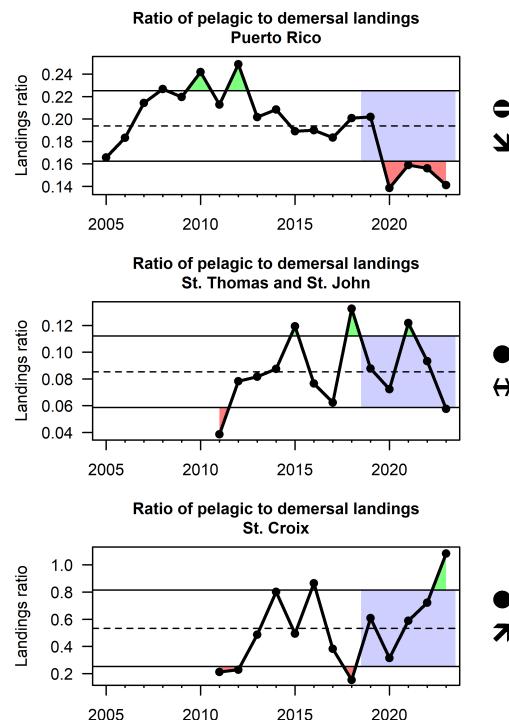


Figure 2.5: Ratios of pelagic to demersal landings, based on reported commercial landings data for Puerto Rico (top), St. Thomas and St. John (middle) and St. Croix (bottom). Note differences in scale of the y-axes; years in the USVI are fishing years (July 1st to June 30th of the following year).

2.1.3 Maximum length in the landings

The average maximum length (L_{max}) of a species in the landings has been proposed as an indicator of whether large-bodied species have been depleted and are no longer fished (Rochet and Trenkel 2003). The L_{max} indicator is derived by assigning a maximum body length for each species (as reported in FishBase) and then calculating the average body length for the landings in each year (based on the Caribbean Commercial Landings database). This analysis was limited to demersal species only, as pelagic species tend to be larger-bodied and the index would otherwise be highly correlated with the pelagic-demersal ratio. The average maximum length in the demersal landings decreased over time in Puerto Rico from 2005–2012, but has been relatively stable since (Figure 2.6). In the USVI, there has been no overall trend over time, though there was a sharp decline in St. Thomas and St. John in the 2017–2018 fishing year and a sharp increase in St. Croix in the 2018–2019 fishing year. These changes may reflect changes in fishing behavior tied to impacts from the 2017 hurricanes.

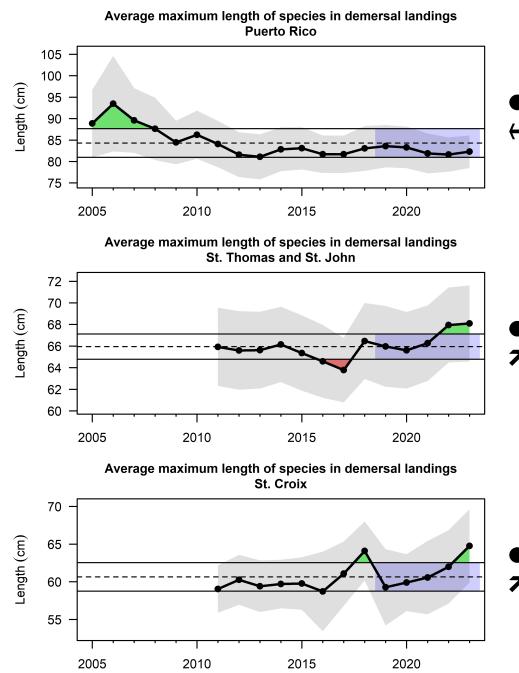


Figure 2.6: Average maximum length of demersal species in the reported landings for Puerto Rico (top), St. Thomas and St. John (middle) and St. Croix (bottom). Note that the years in the USVI are fishing years (July 1st to June 30th of the following year).

2 Tracking performance toward fishery management objectives

The proportion of landings within different Lmax classes can also be shown to better understand changes driving the average Lmax value. In Puerto Rico, there is a generally increasing trend of “plate-sized” fish in the 60-100cm category which is driven by increased landings of deepwater snapper species and yellowtail snapper, while a decrease in the 100-200cm Lmax group is driven by declining landings of large-bodies parrotfishes, snook, and some large groupers (Figure 2.7). Recent decreases in the 40-60cm Lmax group are driven by landings of lane snapper and queen triggerfish.

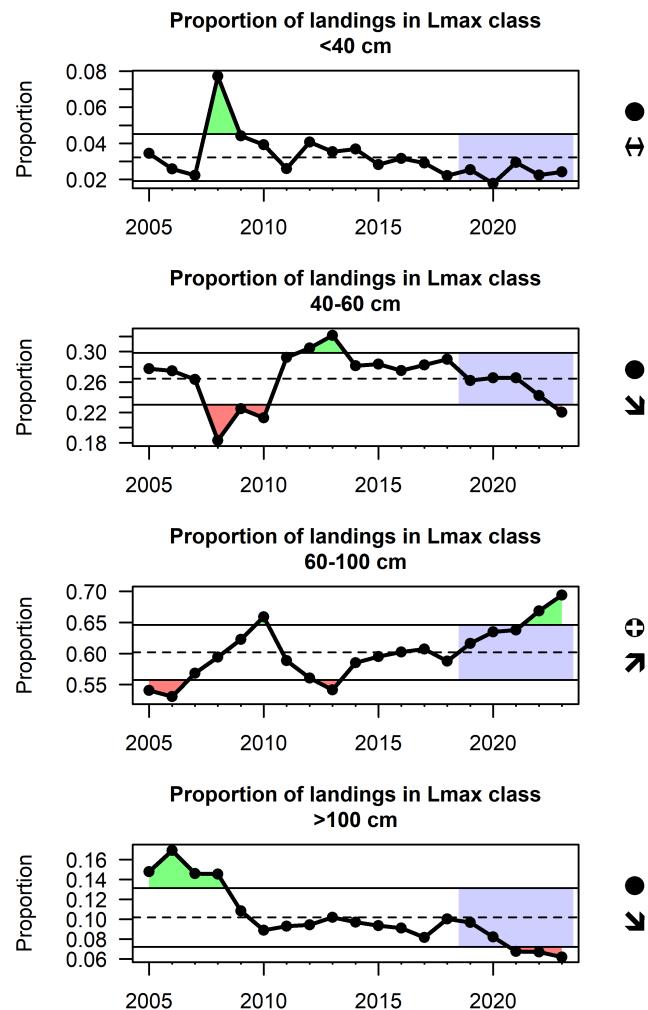


Figure 2.7: Proportion of commercial demersal landings in each of four maximum body length size classes in Puerto Rico.

In St. Thomas there is a notable decrease in the smallest size class (dominated by

2 Tracking performance toward fishery management objectives

landings of surgeonfishes and longspine squirrelfish) as well as a recent decrease in the 40-60cm Lmax group, driven by landings of queen triggerfish, gray angelfish, and white grunt. Landings in the 60-100cm Lmax group have fluctuated over time and are influenced by landings of red hind, yellowtail snapper and blue runner (Figure 2.8).

In St. Croix, changes in the maximum body size of demersal species landings is being influenced primarily by changes in the targeting of parrotfishes. The <40cm Lmax group includes redband parrotfish and princess parrotfish and has increased in recent years, while the 40-60cm Lmax class, composed of redfin and redtail parrotfish, has decreased in recent years. The 60-100cm Lmax class has fluctuated over time and is driven by landings of stoplight and queen parrotfish (Figure 2.9).

2.1.4 Commercial landings

Total landings of conch, lobster, and finfish indicate the ability of U.S. Caribbean fisheries to provide food and revenues, and may be driven by a combination of trends in underlying abundance, market demand, fishing effort, and regulations. Self-reported landings from the Caribbean Commercial Landings Data were compiled; data were originally compiled by paper logbooks, but starting in 2020 some trips in Puerto Rico were reported using electronic reporting (a mobile application). Since 2005, lobster landings have increased in Puerto Rico and decreased in the USVI, with particularly low values in 2017–2018 for St. Thomas and 2018–2019 for St. Croix. Conch landings have been more variable with little trend over time, though there was a sudden decrease in Puerto Rico conch landings in 2020. Note that harvest of queen conch is prohibited in federal waters around Puerto Rico and St. Thomas/St. John, though they are allowed in territorial waters, during their respective open seasons. Landings of other species have decreased significantly over time, particularly starting in 2010 (Figure 2.10). This coincides with initial implementation of annual catch limits in U.S. Caribbean federal waters and may be caused by changes in reporting rather than true reductions in landings.

2.2 Socioeconomic health

2.2.1 Commercial revenues

The relative revenue contribution to commercial fisheries by species conveys the changing reliance on different species across the U.S. Caribbean. Revenues were calculated from the Caribbean Commercial Landings data based on the weight of

2 Tracking performance toward fishery management objectives

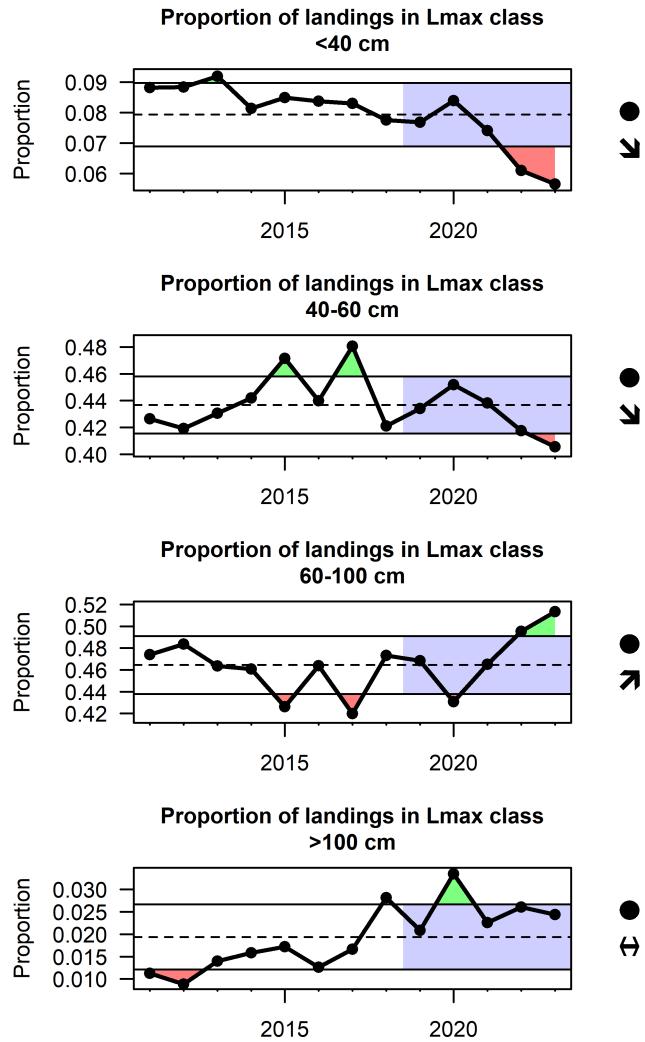


Figure 2.8: Proportion of commercial demersal landings in each of four maximum body length size classes in St. Thomas and St. John. Note that the years are fishing years (July 1st to June 30th of the following year).

2 Tracking performance toward fishery management objectives

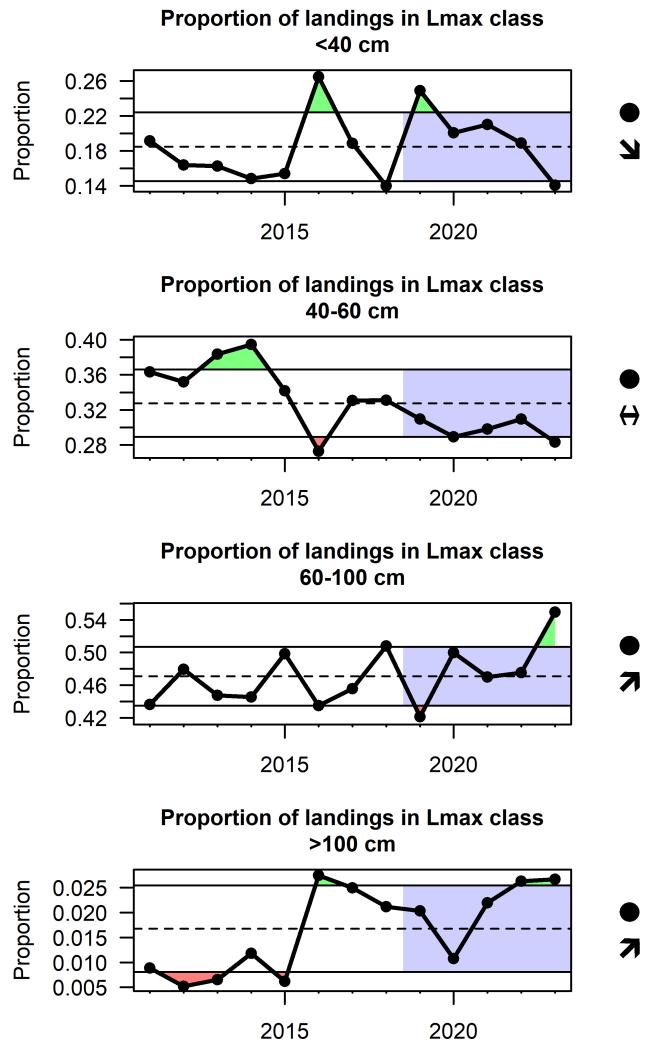


Figure 2.9: Proportion of commercial demersal landings in each of four maximum body length size classes in St. Croix. Note that the years are fishing years (July 1st to June 30th of the following year).

2 Tracking performance toward fishery management objectives

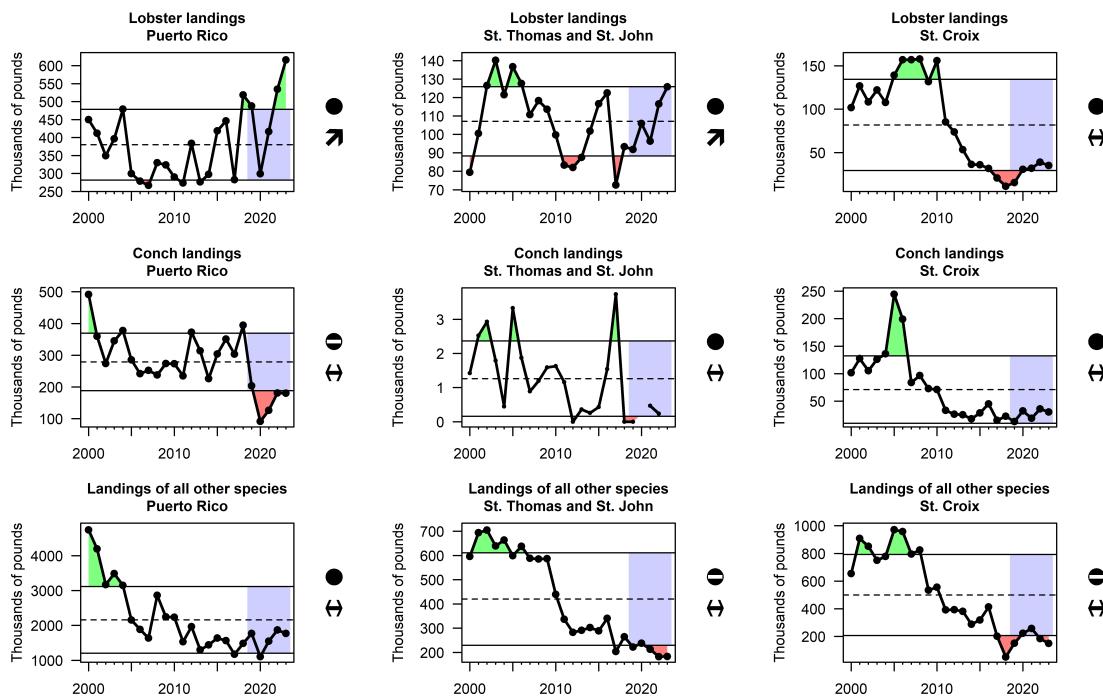


Figure 2.10: Total landings of lobsters (top row), conch (middle row), and all other commercial species (bottom row) from commercial landings data in Puerto Rico (left column), St. Thomas and St. John (middle column) and St. Croix (right column). Confidential landings appear as missing values. Note that the years in the USVI are fishing years (July 1st to June 30th of the following year).

2 Tracking performance toward fishery management objectives

landings in each trip and the reported price; anomalously high prices and missing values were replaced by the overall average price for the given species group. In Puerto Rico, approximately a third of the revenues have consistently come from snapper species; this is followed by lobster and conch, which were both increasing in their revenue contribution up to 2017 (Figure 2.11). In St. Thomas and St. John, there has also been increasing dependence on lobster, which supplies roughly a third of the revenues for those islands (Figure 2.12). Revenues in St. Croix are not dominated by a single species group; parrotfishes, tunas and mackerels, lobsters, snappers, and dolphinfish make up approximately 75% of the revenues (Figure 2.13).

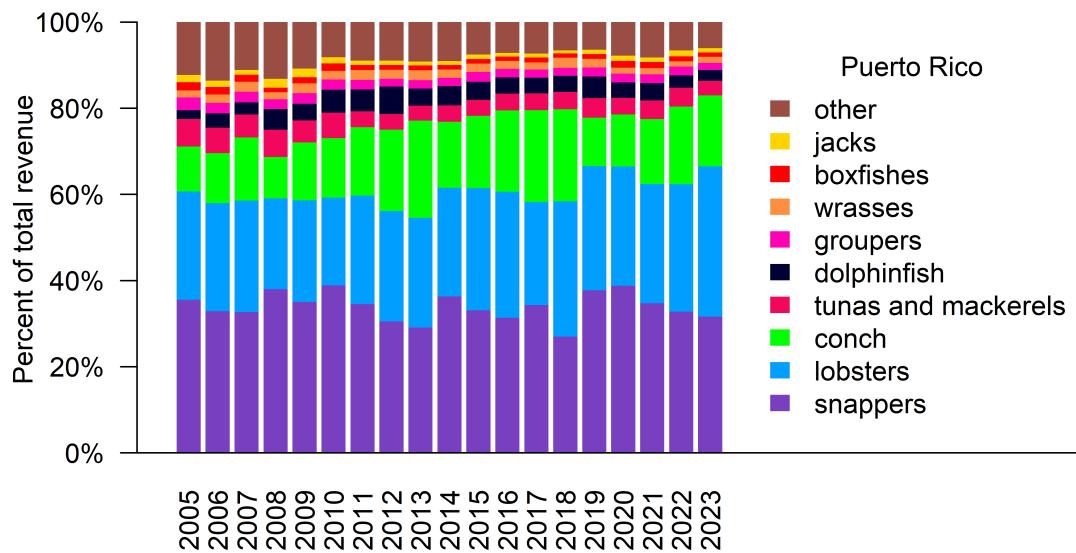


Figure 2.11: Percent revenue contribution for the top ten species groups, stacked by their order of overall importance, for commercial fisheries in Puerto Rico.

2.2.2 Commercial fishing trips

Commercial fishing trips are a useful socioeconomic indicator because they capture the amount and type of effort, which may be driven by market factors, regulations, and costs of entering the fishery. The total number of trips, broken down by gear type, was extracted from the Caribbean Commercial Landings database by identifying

2 Tracking performance toward fishery management objectives

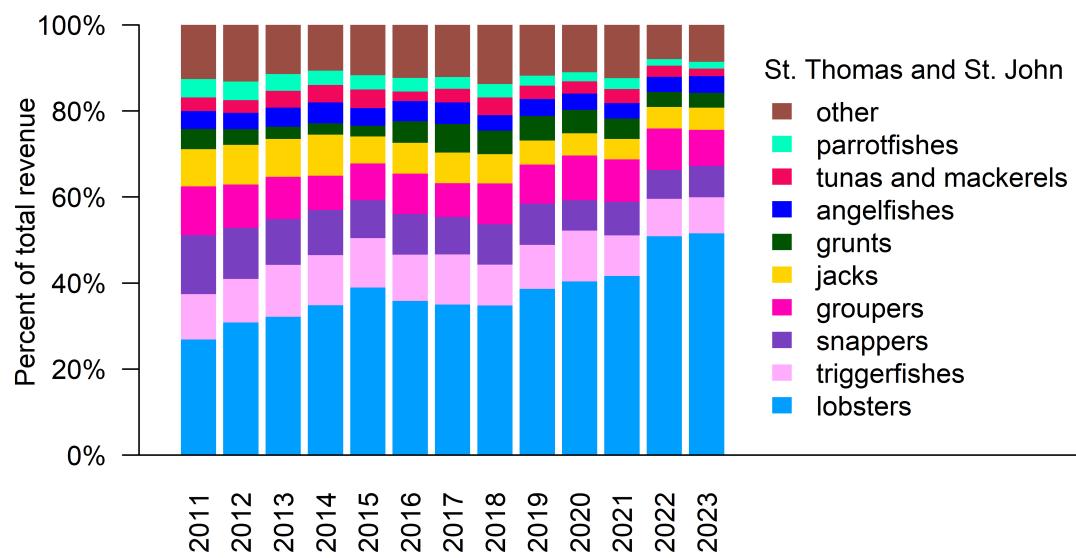


Figure 2.12: Percent revenue contribution for the top ten species groups, stacked by their order of overall importance, for commercial fisheries in St. Thomas and St. John. Note that the years are fishing years (July 1st to June 30th of the following year).

2 Tracking performance toward fishery management objectives

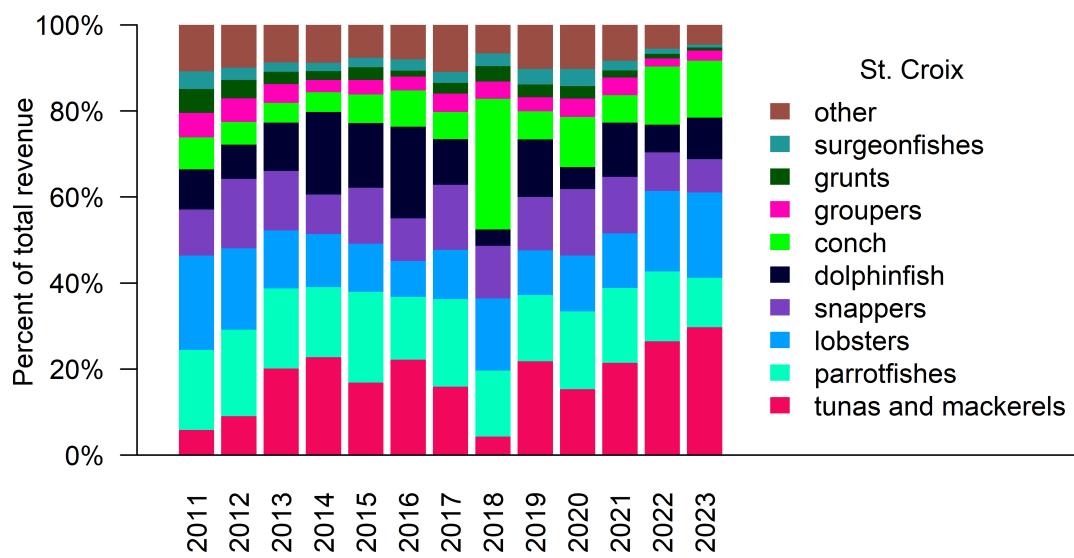


Figure 2.13: Percent revenue contribution for the top ten species groups, stacked by their order of overall importance, for commercial fisheries in St. Croix. Note that the years are fishing years (July 1st to June 30th of the following year).

2 Tracking performance toward fishery management objectives

unique trips based on date and vessel number and extracting the primary reported gear used for each trip. In Puerto Rico, trip numbers have generally decreased over time, with marked decreases in 2017 and 2020; sudden changes in the hook and line fishing in 2012 are due to changes in reporting forms (Figure 2.14). Effort has similarly declined in St. Thomas and St. John; marked declines after 2010 are likely due to reduced reporting (Figure 2.15). Similarly, in St. Croix the number of trips has declined, with the 2018–2019 fishing season reporting particularly low effort (Figure 2.16). Gear types are plotted using the same order and color codes, to facilitate comparisons among the islands.

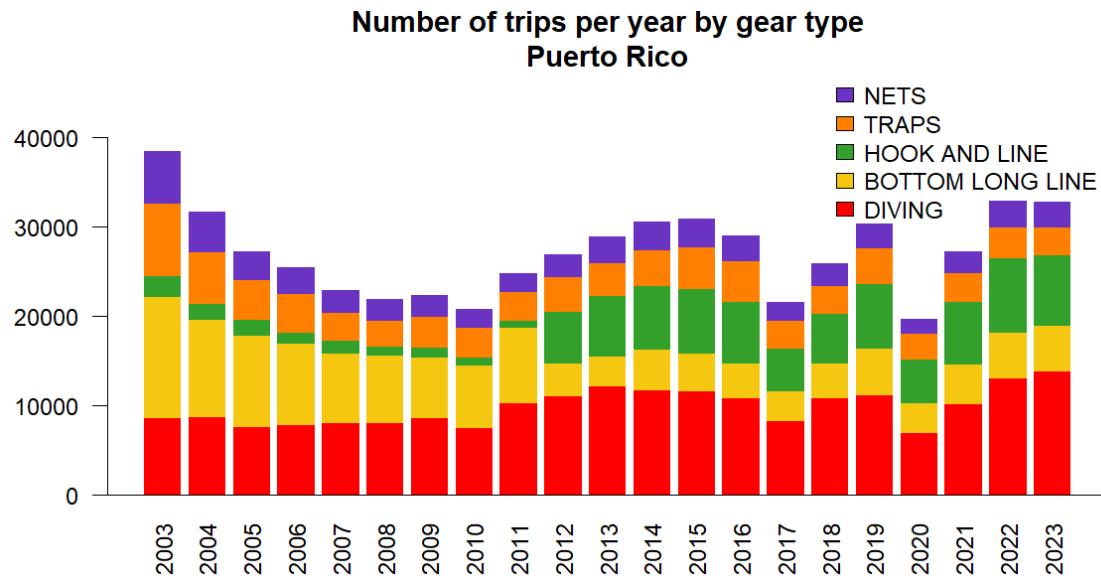


Figure 2.14: Total number of commercial fishing trips by gear type in Puerto Rico, separated by primary gear used on the trip.

Given the potential for changes in reporting to impact trip numbers, it can be more informative to look at the composition of gear types. In particular, diving is often a way of entry for new or part-time fishermen as it generally requires lower up-front investments. Peaks in the proportion diving trips in 2017 and 2018 could be a result of lost traps and infrastructure due to hurricanes (Figure 2.17).

Ordination of gear types based on reporting landing sites conveys how different regions across the U.S. Caribbean depend on different methods of fishing. Ordinations were conducted using non-metric multidimensional scaling (NMDS) based on matrices representing the proportion of gear types used by landing site. The NMDS algorithm seeks to place different sites in an X-dimensional space, such that the physical distances between each pair of sites best represents the differences in gear types em-

2 Tracking performance toward fishery management objectives

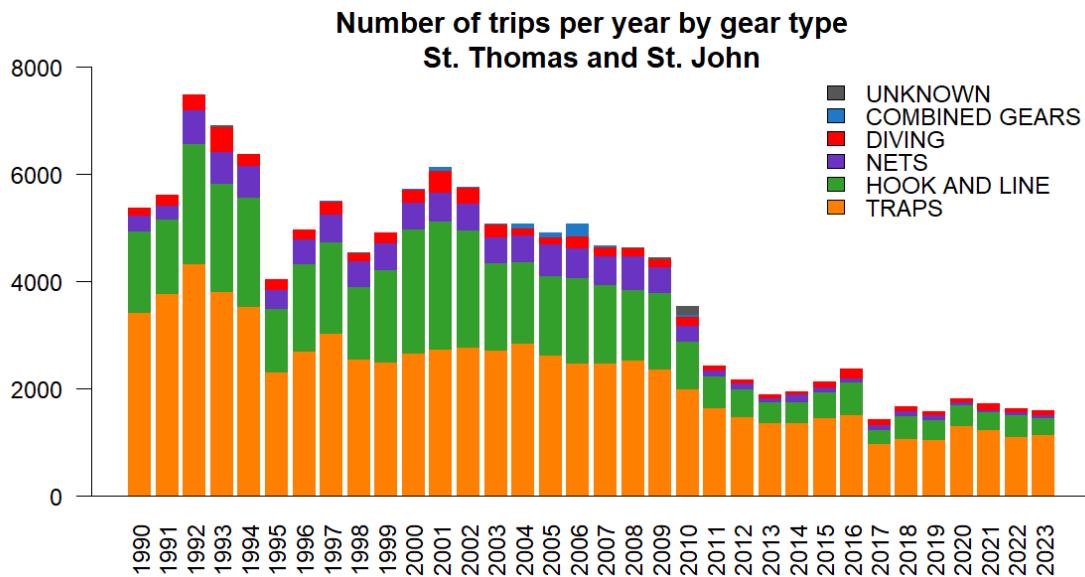


Figure 2.15: Total number of commercial fishing trips by gear type in St. Thomas and St. John, separated by primary gear used on the trip. Note that the years are fishing years (July 1st to June 30th of the following year).

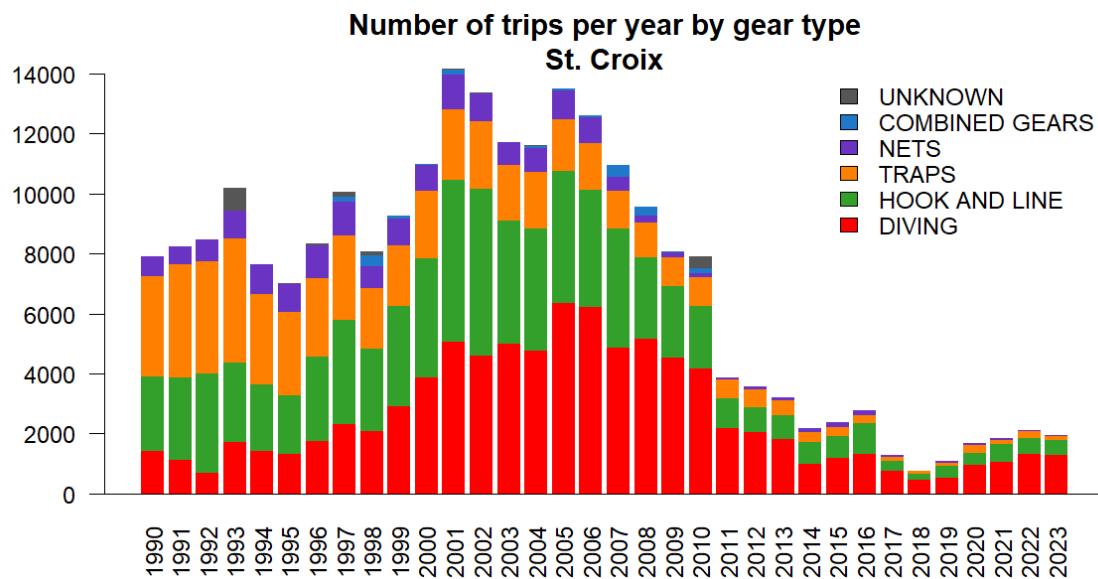


Figure 2.16: Total number of commercial fishing trips by gear type in St. Croix, separated by primary gear used on the trip. Note that the years are fishing years (July 1st to June 30th of the following year).

2 Tracking performance toward fishery management objectives

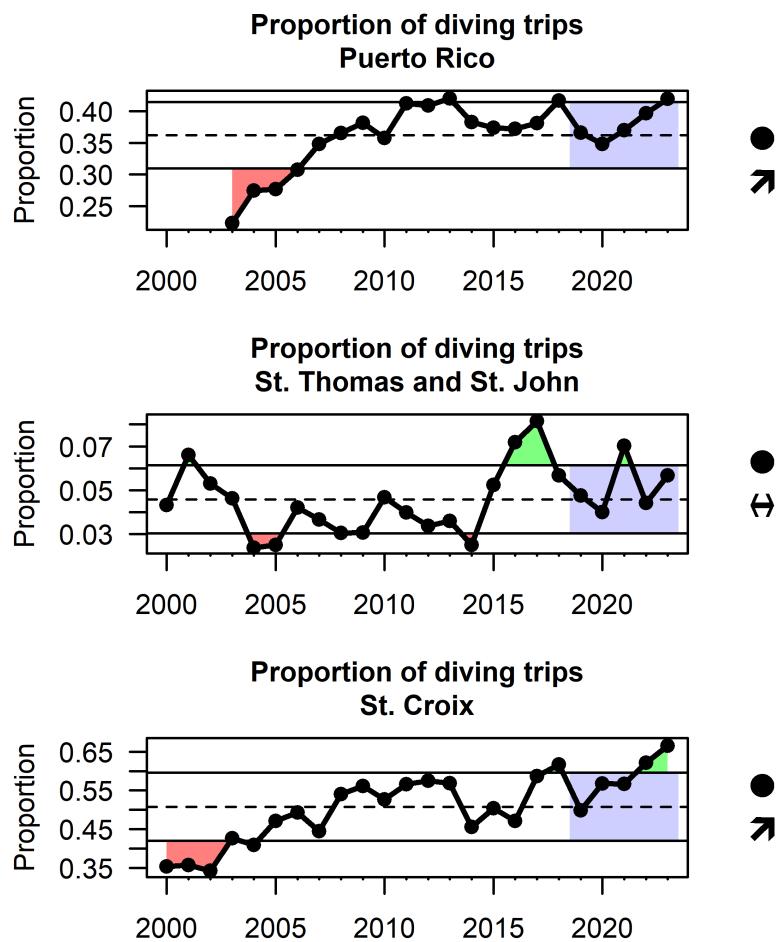


Figure 2.17: Proportion of commercial trips that are reported as diving trips for Puerto Rico (top), St. Thomas and St. John (middle) and St. Croix (bottom). Note that the years in the USVI are fishing years (July 1st to June 30th of the following year).

2 Tracking performance toward fishery management objectives

ployed. Thus, sites that appear more closely together in the figures are more similar in their gear usage, and the position of the gear type labels denote the relative importance of those gear types in those sites. In Puerto Rico for example, hook and line and bottom long line are closely related and are particularly prevalent in the northern landing sites (in red), whereas nets and traps are more prevalent in the South (blue) (Figure 2.18). In St. Thomas and St. John, there is an association of traps and hook and line fishing (Figure 2.19), whereas in St. Croix, those gear types are not associated with each other but nets and spearfishing are closely associated within landing sites (Figure 2.20).

Ordination of gear type usage by landing sites Puerto Rico

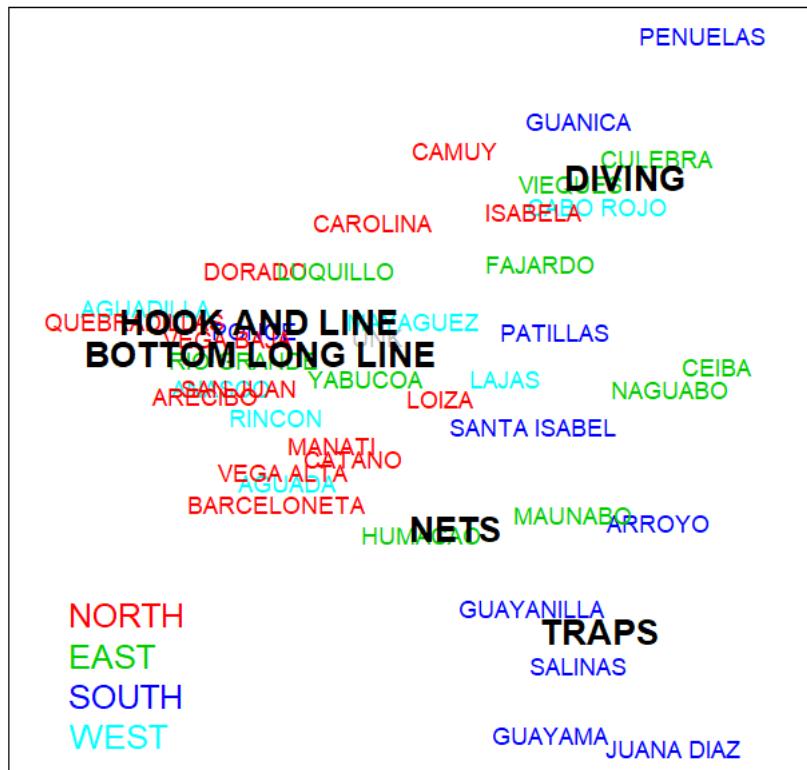


Figure 2.18: Ordination of gear type usage by landing site for Puerto Rico, color coded by region.

Ordination of gear type usage by landing sites St. Thomas and St. John

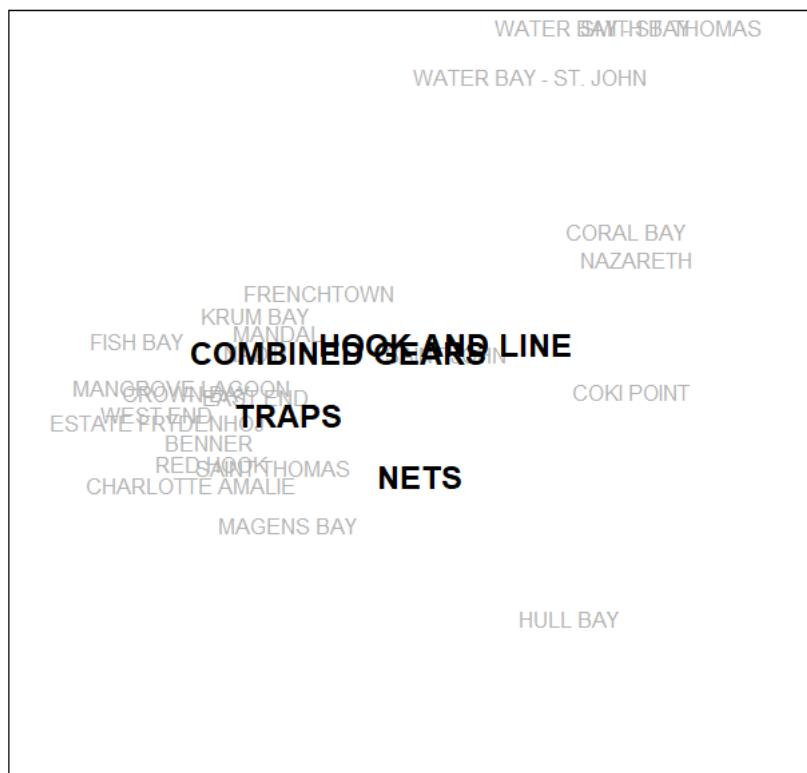


Figure 2.19: Ordination of gear type usage by landing site for St. Thomas and St. John.

Ordination of gear type usage by landing sites St. Croix

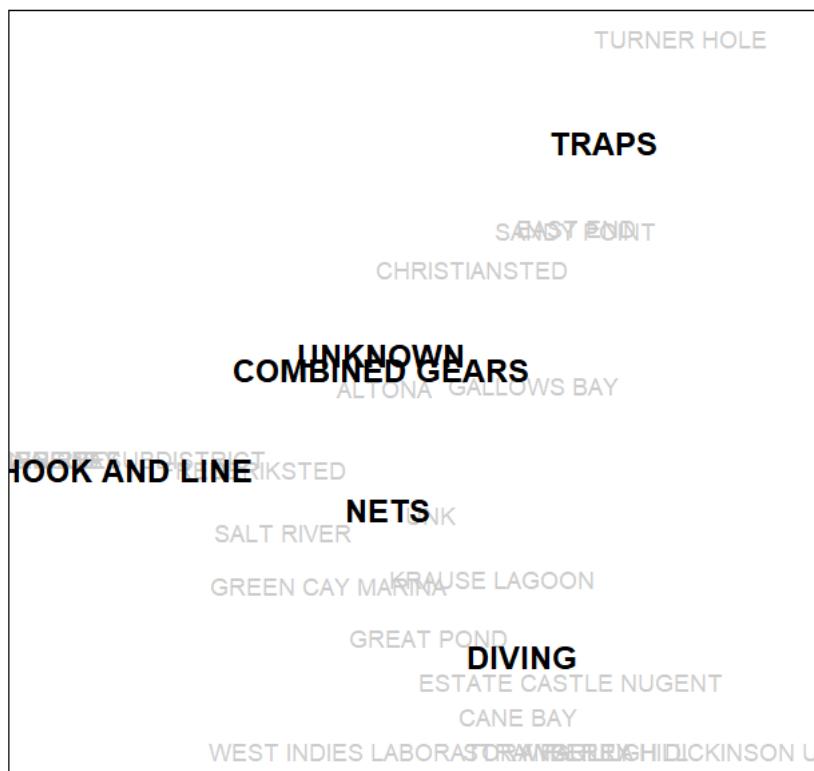


Figure 2.20: Ordination of gear type usage by landing site for St. Croix.

2 Tracking performance toward fishery management objectives

2.2.3 Economic activity

Some indicators of economic activity come in the form of gross domestic product (GDP) and employment trends. GDP data come from the World Bank, and indicate an overall general economic expansion in Puerto Rico (World Bank 2024a). GDP in the USVI (World Bank 2024b) declined substantially from 2007–2014, but has been increasing steadily since (Figure 2.21). Several key trends emerge when analyzing GDP in the USVI, but the broader economic story is one of dependency on external market forces and vulnerability to external shocks. The impact of major disruptions, both natural and financial, has shaped the territory's economy. For instance, the destruction caused by Hurricanes Irma and Maria in 2017 introduced significant economic and social challenges. Estimates based on USVI fiscal data indicate that public revenues were cut in half following the storms, severely constraining government capacity. This shock compounded pre-existing fiscal pressures, as USVI public revenues had already been significantly affected by the 2007–2009 Great Recession. Given that tourism serves as a primary economic driver, the downturn in the aftermath of these events further limited growth in the region.

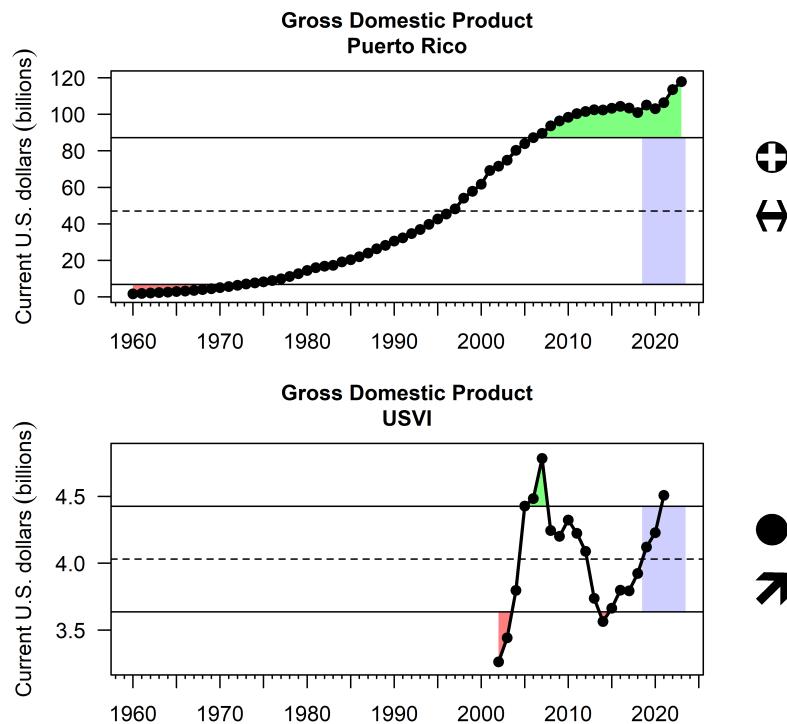


Figure 2.21: Overall Gross Domestic Product in Puerto Rico (top) and the USVI (bottom).

2 Tracking performance toward fishery management objectives

GDP can sometimes underestimate the ocean-dependency of the regions' local island economies; another indicator that is useful is employment/unemployment rate data, which come from the U.S. Bureau of Labor Statistics (U. S. Bureau of Labor Statistics 2024) and the U.S. Employment and Training Administration (U.S. Employment and Training Administration 2024). Unemployment has shown a declining trend over time in Puerto Rico and the USVI. In the USVI, there were notable spikes in the unemployment rate in 2018 and 2020, following major hurricanes Irma and Maria and the COVID-19 pandemic.

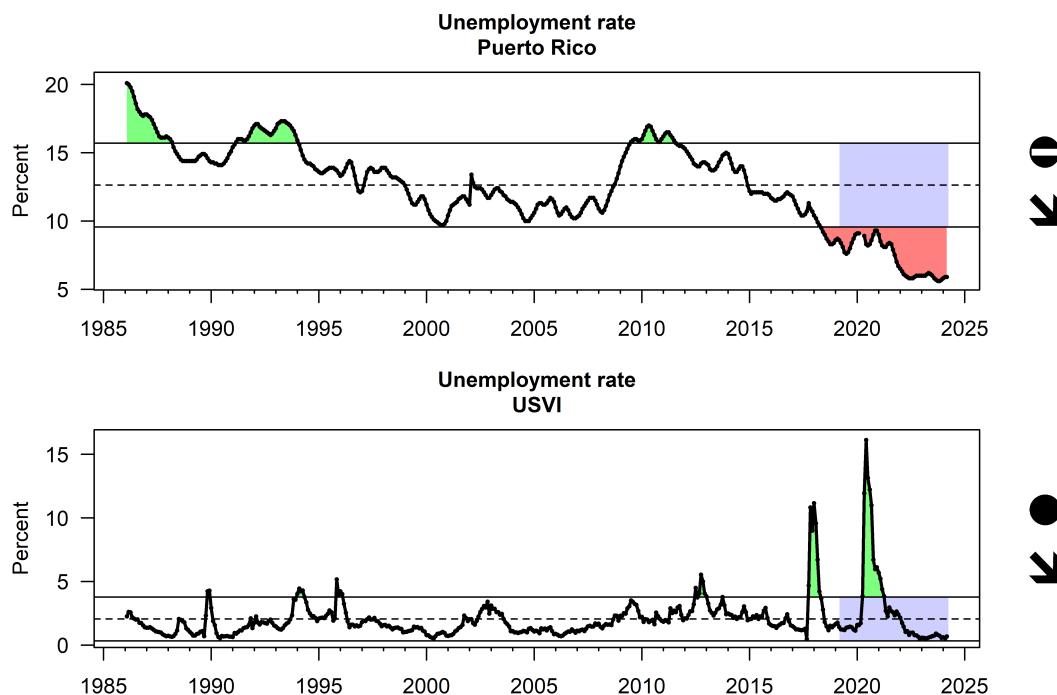


Figure 2.22: Monthly unemployment rate in Puerto Rico (top) and the USVI (bottom).

2.2.4 Ocean economy

Due to their unique geography, culture and setting, the islands of Puerto Rico and the USVI are more reliant on the surrounding ocean and marine environments than many parts of the continental United States. Data from the Bureau of Labor Statistics Quarterly Census of Employment and Wages (<https://www.bls.gov/cew/downloadable-data-files.htm>) provide data on the number of establishments, employees, and wages earned for each county by industry (as

2 Tracking performance toward fishery management objectives

defined by NAICS code). These data underpin the Economics: National Ocean Watch (ENOW) methods created by NOAA's Office for Coastal Management to track contributions of the ocean economy to the overall economy. There were significant changes to the way ocean economy metrics were calculated for the U.S. Territories in 2016 (Clements, Feliciano, and Colgan 2016), and revised metric data are only available from 2019-2021 through ENOW. It is therefore difficult to assess trends over time until additional data are collected (Figure 2.23).

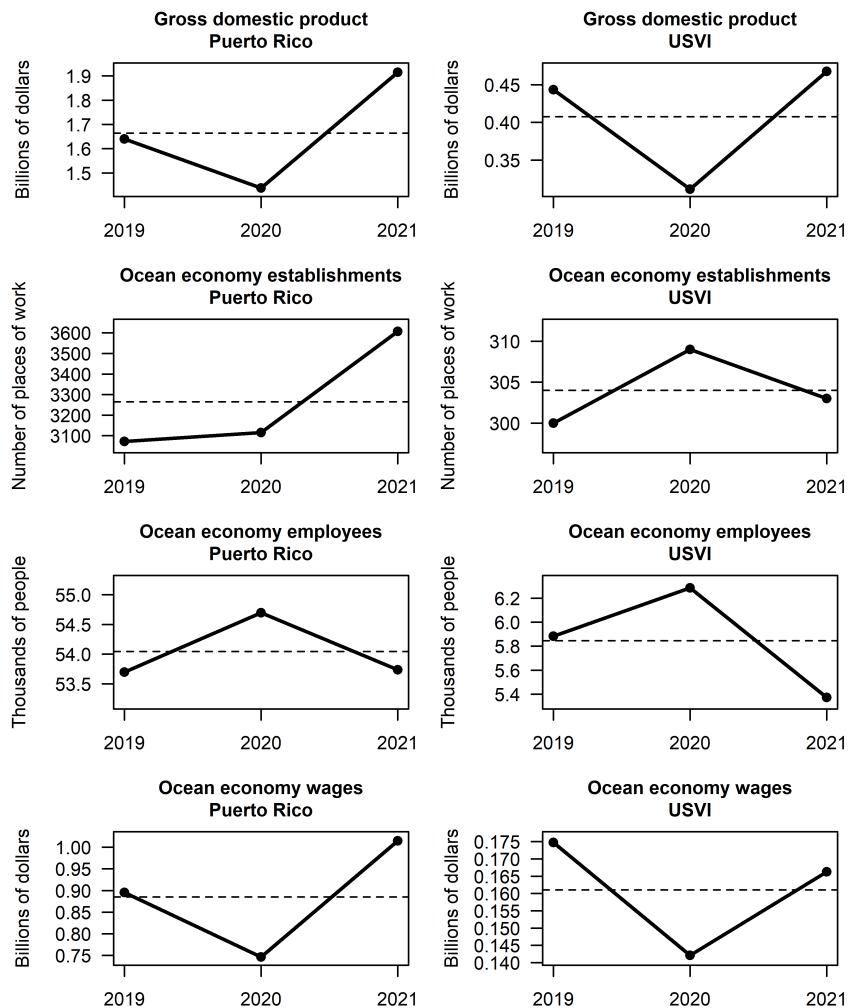


Figure 2.23: Ocean economy GDP, ocean economy establishments, ocean economy employment, and ocean economy wages (from top to bottom), for Puerto Rico (left column) and the USVI (right column).

2.3 Equity

2.3.1 Commercial revenue distribution

Equality in the distribution of revenues across the fishery can be represented by the Gini index which is a value ranging from zero to one, with zero representing perfect equality (revenues distributed equally among all participants) and a value of one representing maximum inequality (all revenues going to a single individual, Gini 1936). The Gini index was calculated based on reported revenues from the Caribbean Commercial Landings database, as they are distributed across the individual vessel or fisher permits (Figure 2.24). Overall, the Gini index values suggest that consolidation across U.S. Caribbean fisheries is high compared to other U.S. regions (Brinson and Thunberg 2016), though this may be an artifact of reporting if more experienced fishermen are more consistent in their reporting. In St. Thomas and St. John, the index shows a gradual increase throughout the time period, while there is no particular trend apparent in Puerto Rico and St. Croix. There are spikes in inequality in Puerto Rico in 2018 and in St. Croix in 2017-2018 which may be related to fishing industry impacts from hurricanes.

2.4 Engagement and participation

2.4.1 Recreational landings

Recreational catch and effort is a major data gap in the U.S. Caribbean. The Marine Recreational Information Program collected complete years of data in Puerto Rico up until 2016, and in the USVI there are no regular monitoring programs. The Sea Around Us database estimates reported catches based on imputations and assumptions (Pauly and Zeller 2015). In Puerto Rico, catch was reconstructed by supplementing the MRIP survey with a variety of other studies conducted at various points in time. In the USVI, catch was reconstructed based on a telephone survey conducted by the USVI Division of Fish and Wildlife to estimate resident participation and catch rates, and adding a conservative estimate of tourist catches. These reconstructed estimates suggest that recreational catch has been declining over the last several decades in Puerto Rico, whereas catch has increased over the same period in the USVI (Figure 2.25).

2 Tracking performance toward fishery management objectives

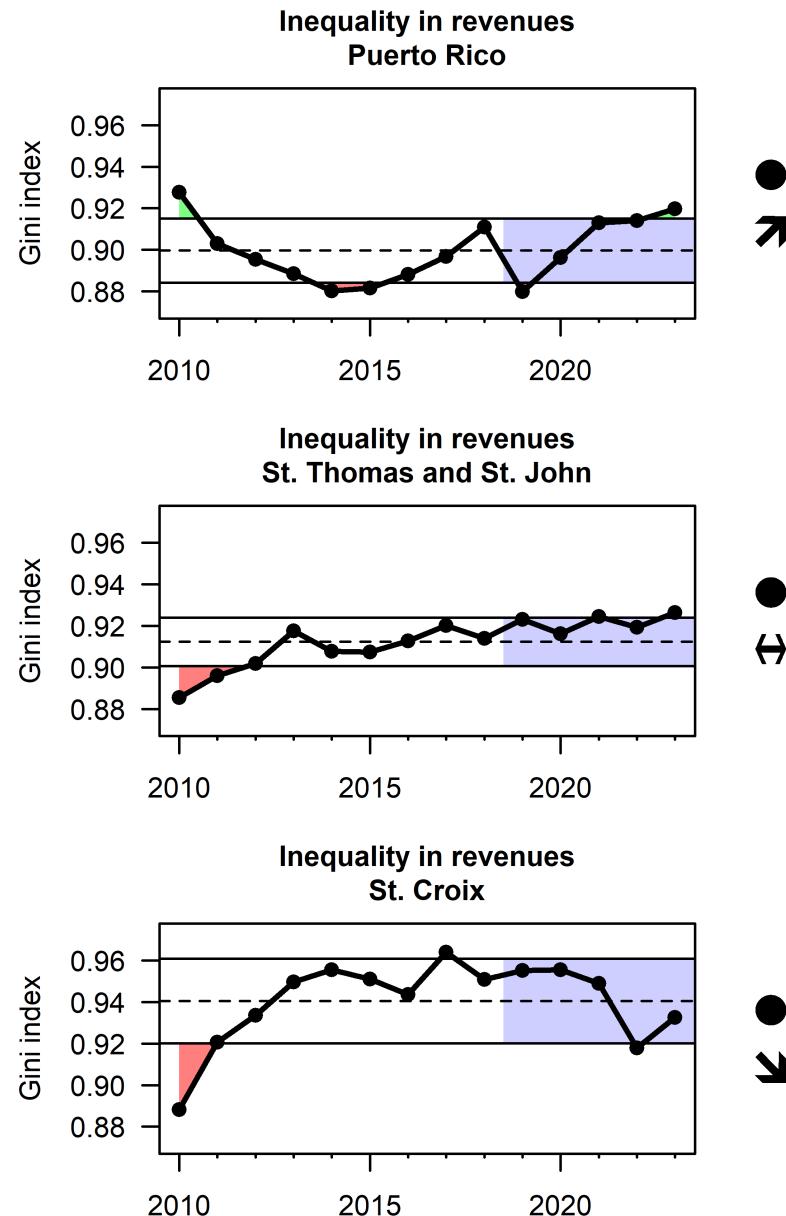


Figure 2.24: Equality in the distribution of revenues across the commercial fishery Puerto Rico (top), St. Thomas and St. John (middle) and St. Croix (bottom), as represented by the Gini index. Note that the years in the USVI are fishing years (July 1st to June 30th of the following year).

2 Tracking performance toward fishery management objectives

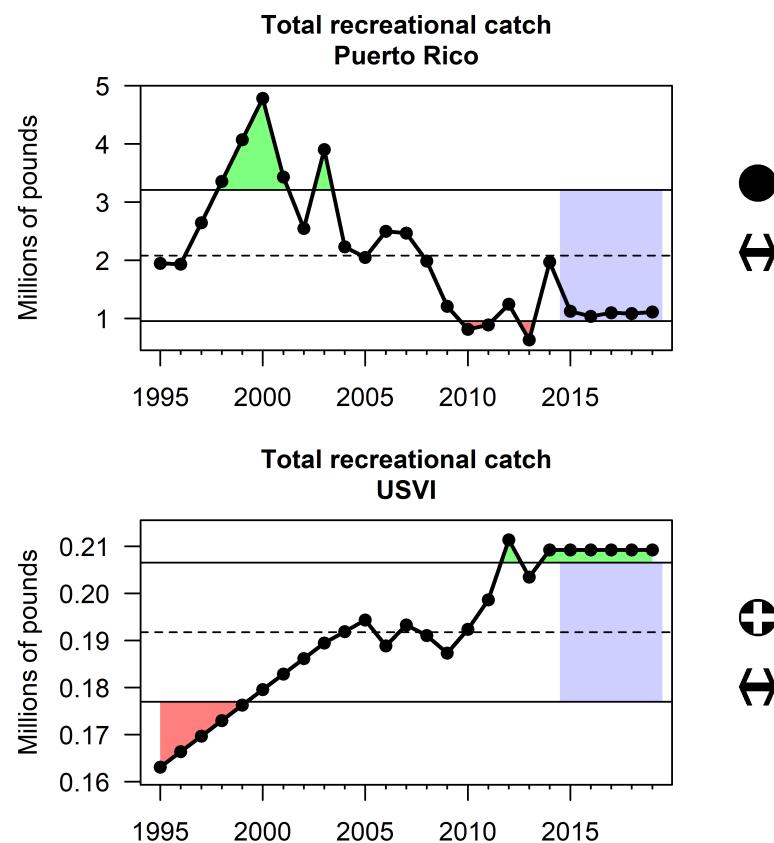


Figure 2.25: Total recreational catch in millions of pounds as estimated by the Sea Around Us database for Puerto Rico (top) and the USVI (bottom).

2 Tracking performance toward fishery management objectives

2.4.2 Commercial fishing engagement and reliance

Fishing engagement and reliance indices measure the importance and level of dependence on commercial or recreational fishing for coastal communities (NOAA Fisheries 2024). Commercial fishing engagement measures the presence of commercial fishing through fishing activity as shown through permits, fish dealers, and vessel landings. A high rank indicates more engagement. Commercial fishing reliance measures the presence of commercial fishing in relation to the population size of a community through fishing activity. A high rank indicates more reliance. Coastal communities on the west and east coasts of Puerto Rico, the north side of St. Thomas, and the southwest of St. Croix had particularly high commercial engagement and reliance for 2016–2020 (Figure 2.26, Figure 2.27, Figure 2.28).

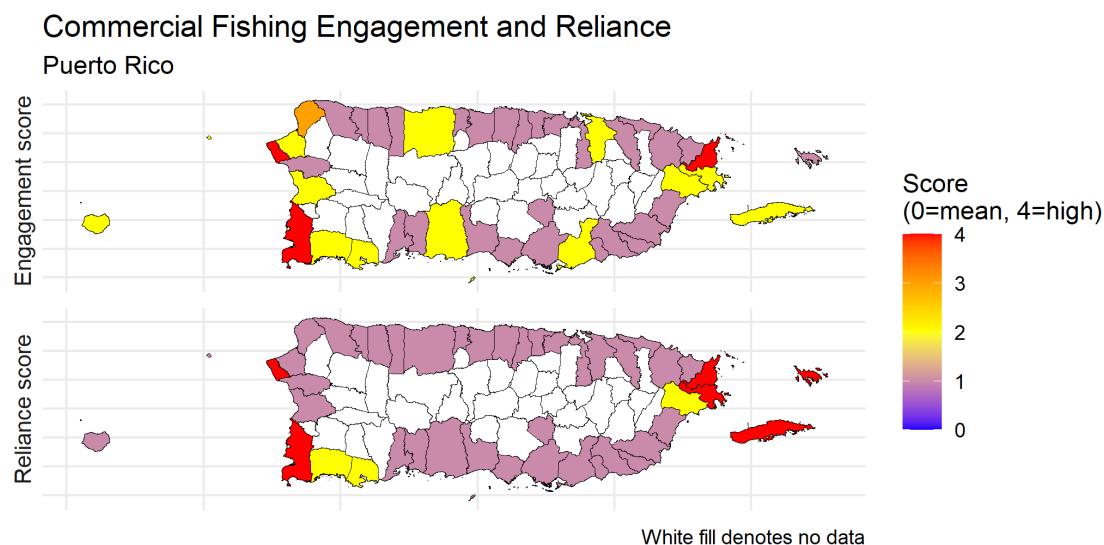


Figure 2.26: Commercial fishing engagement and reliance in Puerto Rico based on NOAA Fisheries Databases: commercial landings 5-year average for 2016–2020 and permit numbers; and Census data: Population by municipality/sub-district

2 Tracking performance toward fishery management objectives

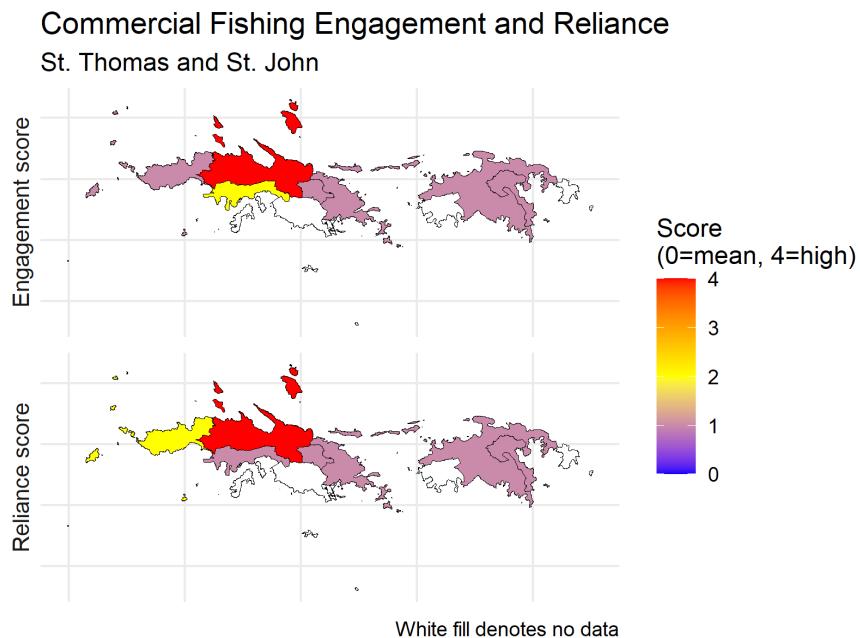


Figure 2.27: Commercial fishing engagement and reliance in St. Thomas and St. John based on NOAA Fisheries Databases: Commercial landings 5-year average for 2016–2020 and permit numbers; and Census data: Population by municipality/sub-district.

2 Tracking performance toward fishery management objectives

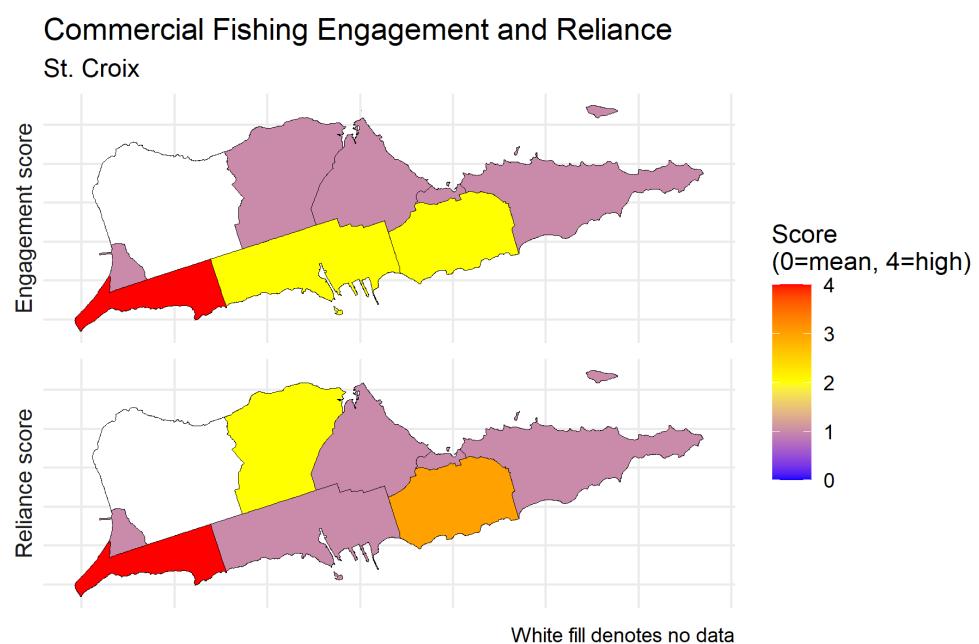


Figure 2.28: Commercial fishing engagement and reliance in St. Croix based on NOAA Fisheries Databases: commercial landings 5-year average for 2016–2020 and permit numbers; and Census data: Population by municipality/sub-district

2.5 Bycatch reduction

2.5.1 Changes in gear type

Data on bycatch in the U.S. Caribbean are generally lacking; target species and bycatch are not differentiated on most logbook forms and the region has minimal observer program coverage (and only on the pelagic longline fleet). The selectivity of gear can be considered as some gear types are highly selective (e.g. spearfishing and diving) while other gear types capture a wide range of target and non-target species. We calculated the proportion of non-selective gear (traps and nets) from the Caribbean Commercial Landings database as a proxy for bycatch in the fisheries. Overall the use of these gear types is decreasing in Puerto Rico and St. Croix while it is increasing in St. Thomas and St. John (Figure 2.29).

2.6 Governance

2.6.1 Regulatory trends

In the Southeastern United States (including the U.S. Caribbean), management history (MH) data has been cataloged and standardized by the National Oceanic and Atmospheric Administration (NOAA), the National Marine Fisheries Service (NMFS), the Southeast Fisheries Science Center (SEFSC), Fisheries Statistics and Sustainable Fisheries Divisions in collaboration with the Cooperative Institute for Marine and Atmospheric Studies (CIMAS) of the University of Miami in collaboration with the Rosenstiel School of Marine, Atmospheric, and Earth Science and the Southeast Regional Office (SERO). The Github repository SEFSC-ODM-Management-History (<https://github.com/SEFSC/SEFSC-ODM-Management-History>) was used to access and process the available management history data.

The records in the database represent Federal Register (FR) changes in management actions that affect federally managed species. FR notice data were available in the management history database from 1985-2021. The number of unique FR sections within each FR notice were summed annually as an index of regulatory trends in the U.S. Caribbean. The FR section is the part, chapter, and section in which a specific regulation is contained within an FR notice. Management actions have occurred in waves, often increasing with changes to Fishery Management Plans, like the establishment of the Reef Fish FMP in 1985, the establishment of the Queen Conch FMP in 1997, and a major amendment to the FMPs of the U.S. Caribbean region in 2005. The data were

2 Tracking performance toward fishery management objectives

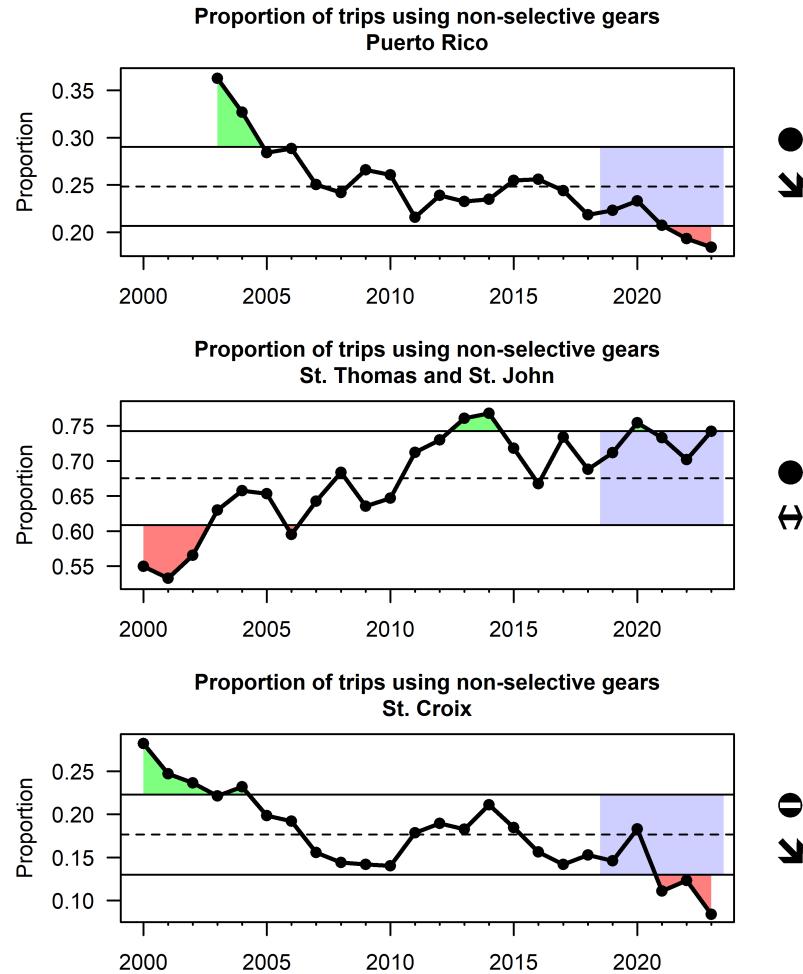


Figure 2.29: Indicator of bycatch prevalence as measured by the proportion of commercial trips using non-selective fishing gear types for Puerto Rico (top), St. Thomas and St. John (middle) and St. Croix (bottom). Note that the years in the USVI are fishing years (July 1st to June 30th of the following year).

2 Tracking performance toward fishery management objectives

only available through 2021, but in 2022 the U.S. Caribbean transitioned from a single Caribbean-wide to three island-based fishery management plans. This major management change was associated with several new regulations and will likely impact the regulation trends indicator in future iterations of this report.

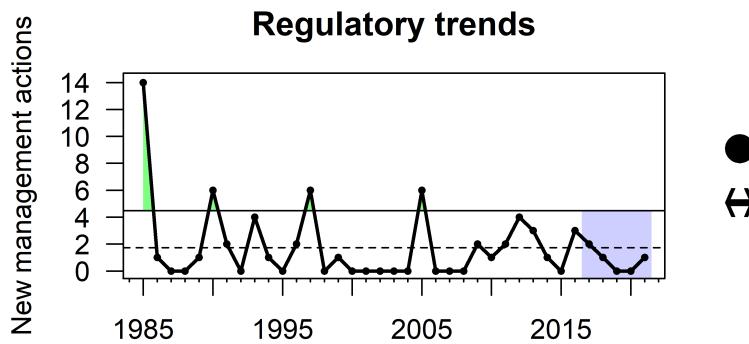


Figure 2.30: The number of new management actions implemented in the U.S. Caribbean region based on the annual count of unique Federal Register sections within all Federal Register notices.

2.6.2 Species with informative catch limits

U.S. Caribbean fisheries are highly diverse; over 300 individual species have been recorded in the landings database and there are 54 stocks or complexes within the three Island-based Fishery Management Plans. At the same time, the region is extremely data-limited, with high uncertainty in landings data and lacking reliable indices of abundance, and most annual catch limits are derived using Tier 4 of the control rule included in the FMPs (based on landings over a defined time period). The percentage of stocks or complexes with annual catch limits informed by stock assessments is a useful indicator for tracking progress toward more robust management advice in the region. In recent years, progress has been made and some stock assessments have been accepted for management advice (Figure 2.31).

2.6.3 Education and outreach events

Programs such as the Marine Resource Education Program (MREP) and NOAA Sea-Grant have made substantial gains in outreach and education in the U.S. Caribbean region. MREP is a program developed for fishermen, by fishermen, and is widely recognized as a key venue for engaging industry members and building trust. Sea Grant is

2 Tracking performance toward fishery management objectives



Figure 2.31: Percent of stocks/complex with informative annual catch limits as measured by stock assessments in Puerto Rico (top) and the USVI (bottom).

2 Tracking performance toward fishery management objectives

a federal-academic collaboration that supports research, education and extension to support coastal resource conservation, conducting outreach in the form of workshops and meetings. The number of participants benefiting from MREP and SeaGrant programs has increased rapidly in recent years. Cumulative numbers of graduates and attendees are reported because once knowledge is gained it remains in the fishing community and is also spread by word-of-mouth (Figure 2.32).

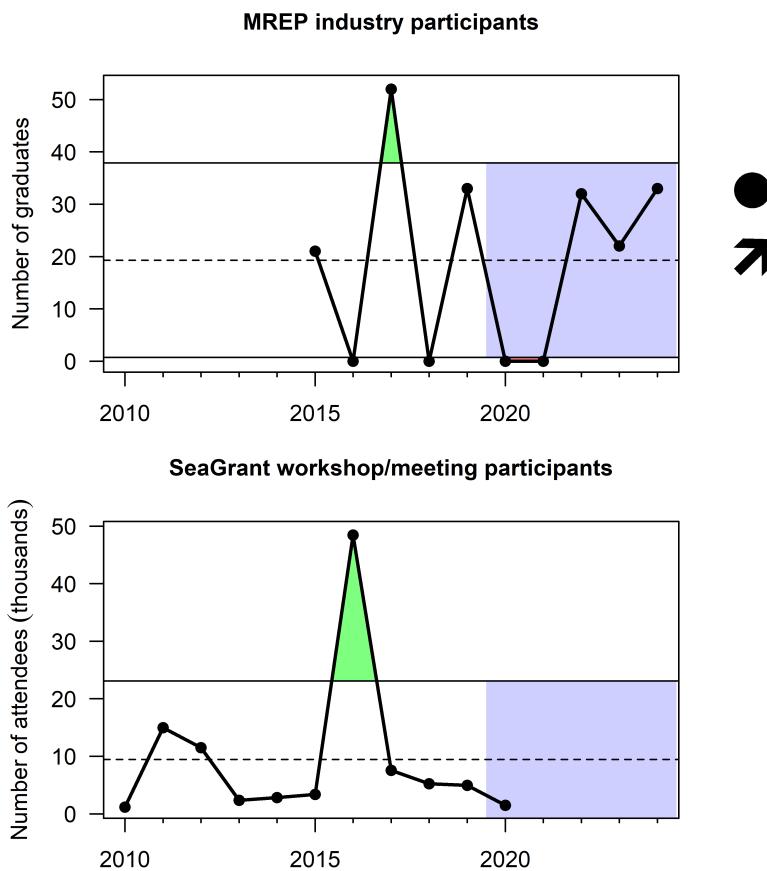


Figure 2.32: Number of Marine Resource Education Program industry participants (top) and number of SeaGrant workshop or meeting participants in the U.S. Caribbean region (bottom).

2.6.4 Enforcement actions

The number of recorded law enforcement incidents and patrols may be indicative of changes in availability of law enforcement resources. The majority of incidents in

2 Tracking performance toward fishery management objectives

the region are created by two NOAA personnel, in conjunction with multiple state and federal partner agencies. Law enforcement conducts patrols, investigations, outreach and education, and compliance assistance to stakeholders. These cumulative efforts aid in governance of fishery management objectives. Data on federal law enforcement incidents where the investigating officer was from the St. Thomas, USVI or San Juan, PR field offices or the word “Caribbean” was mentioned in the brief synopsis were pulled from the NOAA Office of Law Enforcement NOAA Enforcement Information System (NEIS). Similarly, data on federal patrols conducted from a field office in PR or USVI were available in NEIS. Incidents and enforcement have been fairly stable over the short available time series, with some inter-annual variability (Figure 2.33).

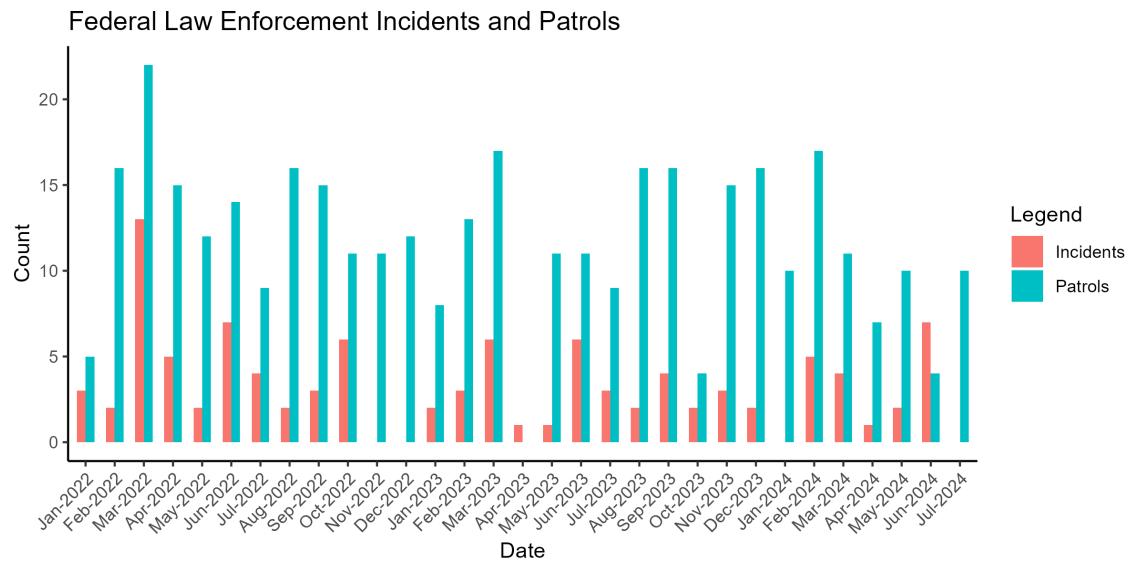


Figure 2.33: Monthly count of federal law enforcement incidents in the U.S. Caribbean region by date of incident creation (total n = 101) and monthly count of patrols (including land, sea, and international trade) conducted from a field office in Puerto Rico or USVI (total n = 363).

2.7 Protection of ecosystems

2.7.1 Coral cover and coral species diversity

Coral reef ecosystem integrity is a major concern for stakeholders in the U.S. Caribbean region (Seara et al. 2024). The PRCRMP and TRCMP have measured benthic cover at fixed transects for over two decades, allowing for a comparison over time. Coral species richness was calculated based on the average number of

2 Tracking performance toward fishery management objectives

hard coral species per 10-m long transect, and percent coral cover is measured by assigning substrate type to randomly assigned points within still images of the benthic transects (TCRMP) or using the continuous intercept method over a fixed transect line (PRCRMP). Trends in species richness for both Puerto Rico and the USVI fluctuate over time with no clear trend, although there has been a sudden decline in recent years. Percent coral cover has dropped significantly throughout the 25-year time period with large declines occurring in 2005 and 2019, coinciding with major bleaching events (Figure 2.34).

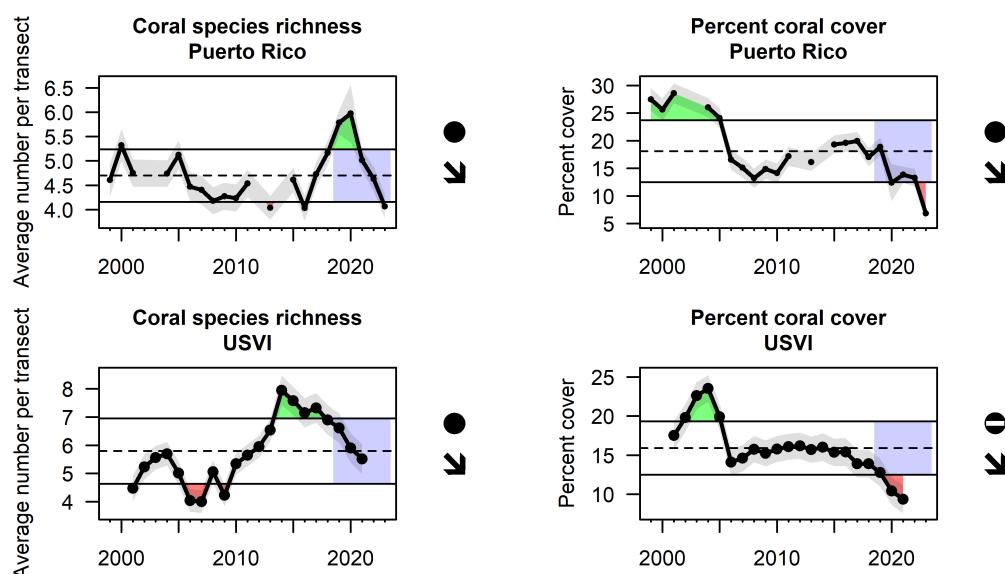


Figure 2.34: Percent coral cover and coral species richness (average number of species per transect) from TCRMP and PRCRMP biological surveys.

3 Risks to meeting fishery management objectives

In this section, we report indicators that capture identified risks to the ecosystem that could impact the ability to meet Fishery Management Plan objectives. Unless otherwise specified, physical indicators reported for the U.S. Caribbean region were calculated over a bounding box with limits of longitude 68 degrees W to 64.5 degrees W and latitude 17.5 degrees N to 18.75 degrees N.

3.1 Sea surface temperature

Ocean temperatures affect species distributions and other aspects of population dynamics and have impacts on habitats such as coral reefs. Monthly mean, minimum, and maximum sea surface temperatures were calculated based on the 1/4 Degree Daily Optimum Interpolation Sea Surface Temperature (OISST) Analysis (Reynolds et al. 2007). Mean temperatures in the U.S. Caribbean region have been increasing at an average rate of 0.25 degrees Celsius per decade. In the last several years, monthly mean, monthly minimum, and monthly maximum temperatures have all been well above the historical average, and in the last five years the temperature trend has been a significant increase (Figure 3.1).

3.2 Coral bleaching stress

Accumulated heat stress, which can lead to coral bleaching and death, is measured by summing degree heating weeks for the previous 12-week period from sea surface temperature data (NOAA Coral Reef Watch 2019). Bleaching stress was generally below average prior to the mid-2000s, when a sudden bleaching event occurred in 2005; this event is now the second most severe event in the time series. In 2024, a bleaching event of unprecedented severity occurred across the U.S. Caribbean and beyond (Figure 3.2).

3 Risks to meeting fishery management objectives



Figure 3.1: Monthly mean (top), minimum (middle), and maximum (bottom) sea surface temperature standardized anomalies, calculated over the U.S. Caribbean region.

3 Risks to meeting fishery management objectives

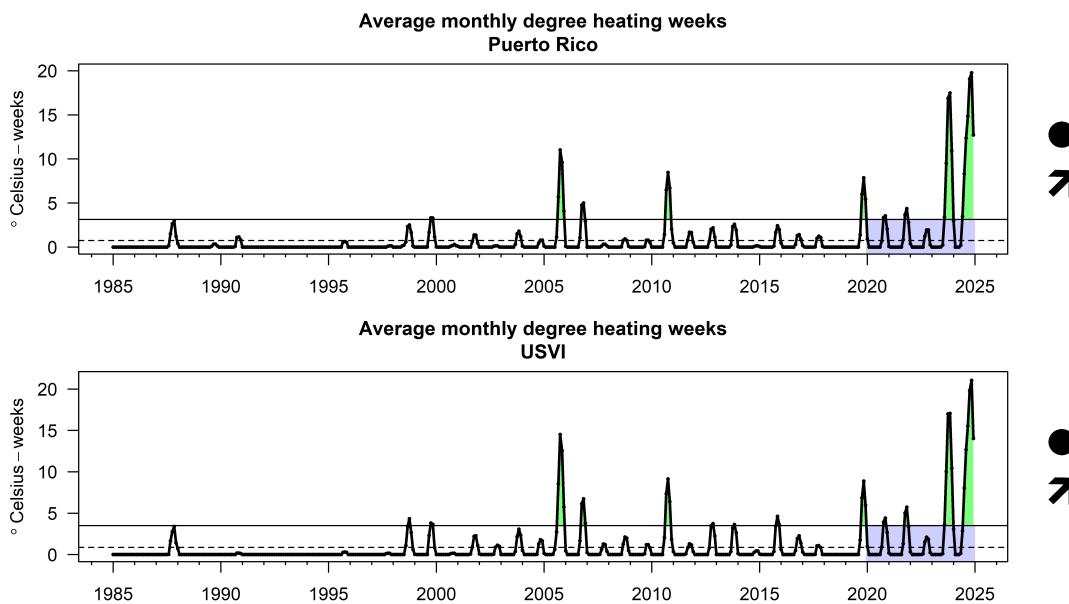


Figure 3.2: Average monthly degree heating week values as reported by NOAA Coral Reef Watch Virtual Stations for Puerto Rico (top) and USVI (bottom).

3.3 Ocean acidification

Ocean and coastal acidification can impact organisms directly or indirectly; a decrease in aragonite saturation state can make it difficult for corals and other calcifying organisms to form hard structures, contributing to lower reproduction or survival rates. When the aragonite saturation state falls below 3, corals begin to experience physiological stress, and calcification rates decline and skeletal structure begins to weaken; calcification stops completely and skeletal structure begins to dissolve at aragonite saturation states below 1 (Andersson et al. 2009). In-situ measurements of aragonite saturation states are scarce, and a synoptic long-term view is only available from modeled products. Aragonite saturation state was derived for the U.S. Caribbean region from the MOM-TOPAZ hindcast (Gomez and Lee 2023). An overall negative trend occurs, with an acceleration of this trend apparent after 2008 (Figure 3.3).

3.4 Hurricane activity

Hurricane activity can be captured by the accumulated cyclone energy (ACE) index, a measure of overall tropical cyclone activity measured as the sum of squared wind

3 Risks to meeting fishery management objectives

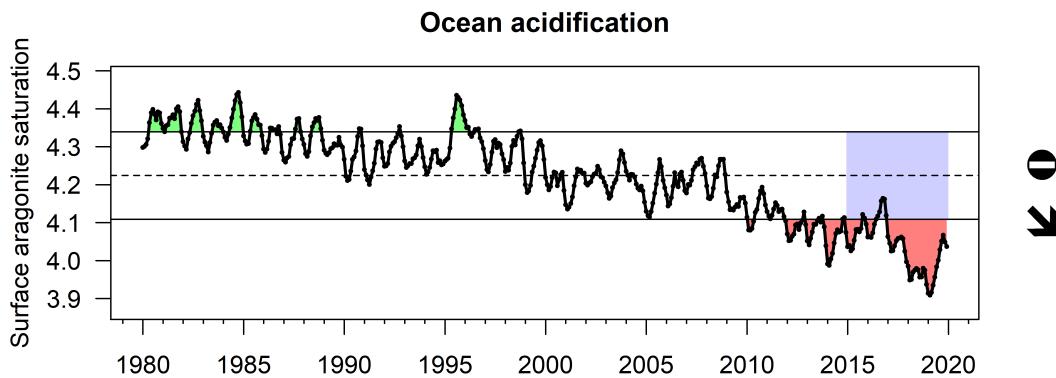


Figure 3.3: Ocean acidification as measured by modeled surface aragonite saturation state, shown as standardized monthly anomalies for the U.S. Caribbean region.

speeds. The ACE index was calculated for storms that track within the U.S. Caribbean region as documented by the International Best Track Archive for Climate Stewardship database (Knapp et al. 2010). The index has fluctuated throughout the past seven decades, with multiple notable peaks (Figure 3.4). During the year 2017, hurricane activity was at an unprecedented high, due to two major hurricanes that struck the islands: Irma and Maria.

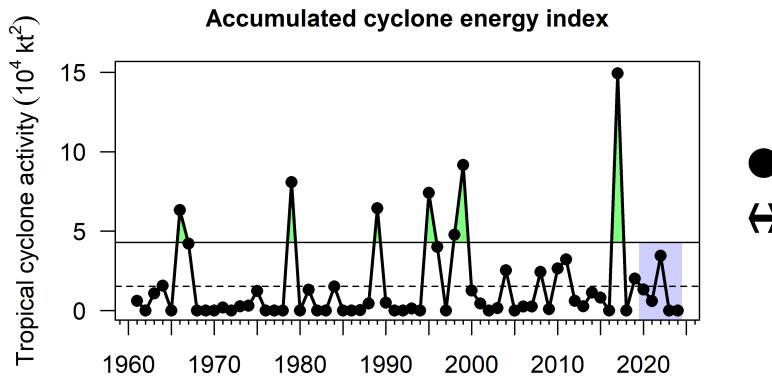


Figure 3.4: Annual accumulated cyclone energy index, calculated as the sum of squared 6-hourly reported wind speeds for storms tracking through the U.S. Caribbean region.

3.5 Earthquake activity

Earthquakes can induce landslides and cause impacts to infrastructure including homes and the electrical grid, and can be a source of stress in the affected human population (Agar et al. 2022). Individual seismic events are reported by the United States Geological Survey (USGS) in near real-time (Sumy, Welti, and Hubenthal 2020). A major earthquake swarm occurred in Southwest Puerto Rico in early 2020; in this year there were over 400 events of greater than 3.5 magnitude on the Richter scale (Figure 3.5).



Figure 3.5: Number of seismic events of >3.5 magnitude occurring annually in the U.S. Caribbean.

3.6 Point source pollution

Impacts from terrestrial pollution can be captured from several databases maintained by the Environmental Protection Agency (EPA). These databases provide information on companies that have been issued permits to discharge wastewater into rivers, on the release of toxic chemicals and waste management activities at facilities, and on sites declared through the Comprehensive Environmental Response, Compensation, and Liability Act (commonly known as Superfund sites). The number of pollution sites reported increased in the 2000s, but has decreased slightly in both Puerto Rico and USVI in recent years (Figure 3.6). Note that this indicator does not represent the timing of when pollution was impacting the ecosystem, but rather the timing of investigation and registration in EPA's monitoring program or attention to the environmental impacts of pollution.

3 Risks to meeting fishery management objectives

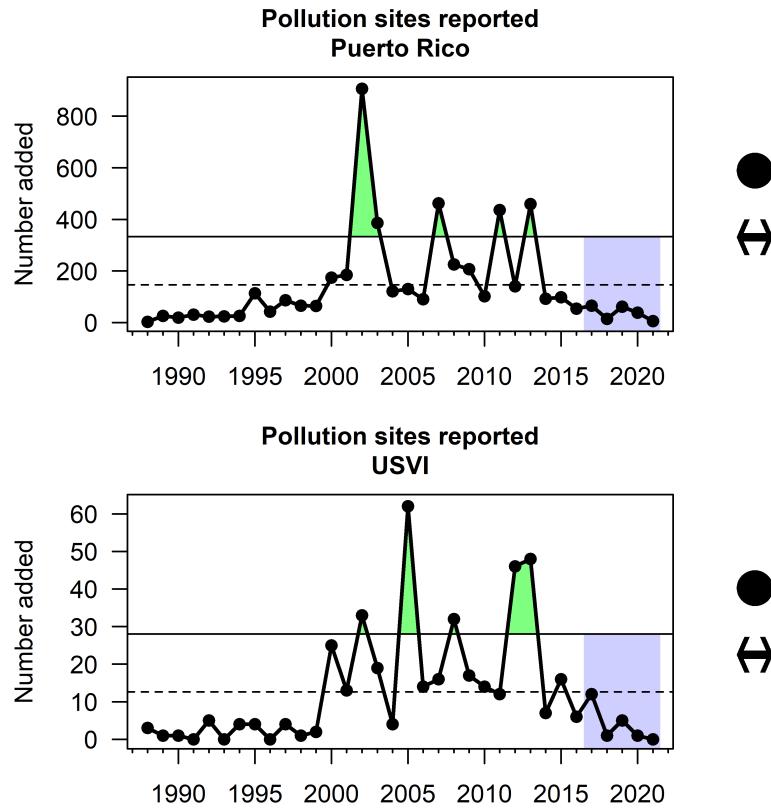


Figure 3.6: Annual count of identified point source polluters in the U.S. Caribbean based on TRI sites (Toxic Release Inventory), Superfund sites (Superfund Enterprise Management System), National Compliance Database listed sites, and Brownfield sites identified in Puerto Rico (top) and the USVI (bottom).

3.7 Turbidity

Coastal pollution, runoff, and water quality issues are of major concern to fishing-dependent communities in the U.S. Caribbean (Seara et al. 2024). Water clarity can be measured by the diffuse attenuation coefficient, which indicates how strongly light intensity is attenuated within the water column; however, satellite sensors cannot differentiate between organic and inorganic water particles contributing to water clarity. NOAA's Coastwatch program provides estimates of the attenuation coefficient for penetration of light at 490nm (Wang, Son, and Harding Jr. 2009) based on multiple satellite sensors. No overall trend is apparent in any of the U.S. Caribbean islands, although there is increasing variability in turbidity values over time. Elevated anomalies in Puerto Rico in the year 2017 are likely due to hurricane activity.

3.8 Water quality

The presence of enterococci bacteria in water samples is used as a primary indicator of fecal contamination, which poses both environmental and human health risks (United States Environmental Protection Agency 2024). Water quality, biological, and physical data collected by the USGS, the EPA, and over 400 state, federal, tribal, and local agencies are publicly available via the EPA Water Quality Portal (<https://www.waterqualitydata.us/>). Data on enterococci abundance in beach samples throughout Puerto Rico and the USVI were downloaded and daily counts were averaged annually. Throughout the U.S. Caribbean region, there has been a substantial increase in the enterococcus count over time, with particularly high measured levels since 2015 in Puerto Rico and since 2020 in USVI Figure 3.8.

3.9 Coastal development

Impervious surfaces such as pavement, sidewalks, roofs and roads, as well as other forms of development, reduce the infiltration of water into the ground. Impervious surfaces often contribute to higher storm water runoff, greater sediment yields into coastal areas, and increased pollutant loads, all of which can degrade water quality (NOAA Digital Coast). This indicator influences water quality and turbidity in nearshore coastal habitat areas. As of 2022, the highest amount of impervious surfaces is seen in the San Juan metropolitan area (Figure 3.9).

3 Risks to meeting fishery management objectives



Figure 3.7: Standardized monthly anomalies of water turbidity as measured by the diffuse attenuation coefficient, for waters surrounding Puerto Rico (top), St. Thomas and St. John (middle) and St. Croix (bottom).

3 Risks to meeting fishery management objectives



Figure 3.8: Water quality as measured by average enterococcus counts (± 1 S.E.) from beach water quality sampling at sites in Puerto Rico (top) and the USVI (bottom).

3 Risks to meeting fishery management objectives



Figure 3.9: Impervious surfaces from development in the U.S. Caribbean.

3.10 Primary productivity

Primary productivity is a measure of the total energy available in an ecosystem, and is closely correlated with chlorophyll a concentrations. Average chlorophyll a concentrations are derived from the European Space Agency Climate Change Initiative's Ocean Colour product, which provides a bias-corrected composite of measurements merged from multiple satellite sensors (Hu, Lee, and Franz 2012). Concentrations are plotted as standardized monthly anomalies as there is a seasonal signal that could mask long-term trends. Estimates show a decadal cyclical pattern, with no overall or recent trend apparent (Figure 3.10).

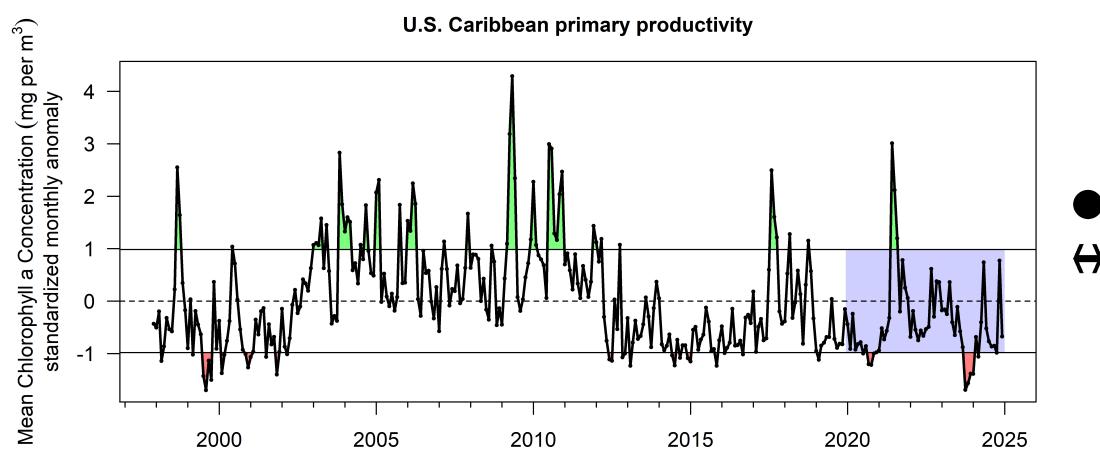


Figure 3.10: Changes in ocean color showing mean chlorophyll a levels (standardized monthly anomalies) in the U.S. Caribbean region.

3.11 Sargassum inundation

Sargassum (brown macroalgae *S. fluitans* and *S. natans*) is a designated essential fish habitat important for many pelagic fish and protected species; however, when large blooms collect in nearshore environments they can reduce oxygen, suffocate beaches and have detrimental impacts on marine species(Hu et al. 2016). Mean monthly Sargassum wet biomass is estimated from satellite measurements using the algorithm of Wang et al. (Wang et al. 2019). Sargassum blooms were largely absent from the U.S. Caribbean prior to 2011, but bloom activity has been generally increasing since that year (Figure 3.11). Major inundation events occurred in 2018 and 2021.

3 Risks to meeting fishery management objectives



Figure 3.11: Annual mean sargassum inundation in square km of cover in the U.S. Caribbean.

3.12 Market disturbances

Alterations to typical fishing patterns can be quantified by analyzing the seasonality of how fishing activity is distributed throughout the year and detecting deviations from average patterns. A market disturbance indicator was developed by calculating the proportion of landings in each month of the year, and summing the square of deviations between those monthly proportions from the mean proportions across all years:

$$D_y = \sum_{m=1}^{12} (P_{m,y} - \bar{P}_m)^2$$

This calculation was carried out for the species with highest landings that have not been subject to seasonal closures; the mean and standard deviation are calculated for the disturbance indicator across those species. In Puerto Rico, there is little trend in the disturbance indicator; however there were higher disturbance indicator values in 2005 and 2017. In St. Thomas, the indicator increases throughout time and detects a major disturbance in the 2017–2018 fishing season (i.e., July 1st 2017 to June 30th 2018). In St. Croix, disturbance levels were high in 2017–2018 and also 2019–2020 (Figure 3.12).

3.13 Human activity

Human activity has an impact on the marine ecosystem indirectly through its influence on coastal development and pollution, as well as directly through marine tourism, fishing and demand for seafood. Human activity is exerted by the local population as well

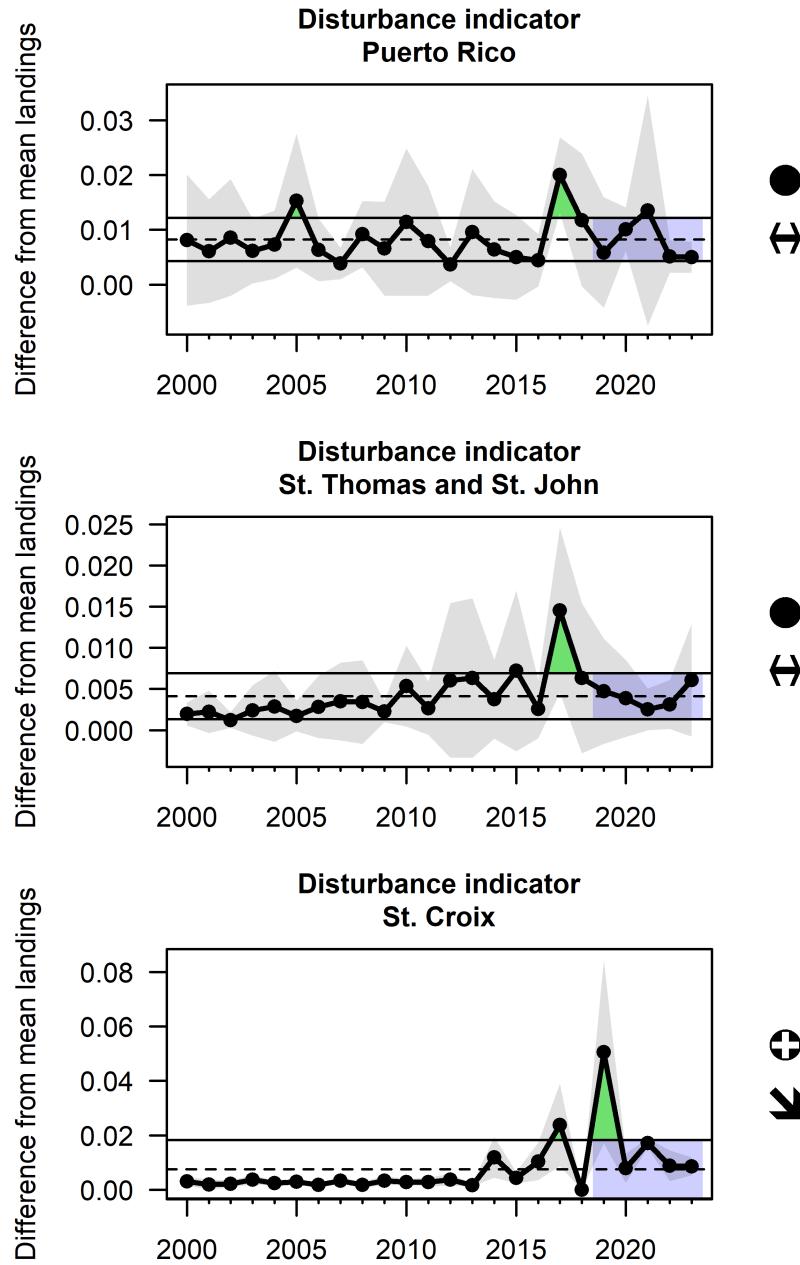


Figure 3.12: Disturbance level (+/- 1 S.D.), calculated as the departure from mean seasonal landings patterns for top species in Puerto Rico (top), St. Thomas and St. John (middle) and St. Croix (bottom). Note that the years in the USVI are fishing years (July 1st to June 30th of the following year).

3 Risks to meeting fishery management objectives

as the extensive tourism industry that exists in the U.S. Caribbean. Total population estimates are reported by the U.S. Census Bureau and tourism activity can be measured through hotel occupancy rates (data from the Puerto Rico Tourism Company and USVI Bureau of Economic Research) and the number of air and cruise passengers (data from the Puerto Rico Ports Authority and USVI Bureau of Economic Research). Human population in the U.S. Caribbean has been declining gradually since 2000 (Figure 3.13). Tourism has fluctuated over time, with major decreases in air and cruise passengers 2017 and 2020, but recovery to normal or above-normal levels since (Figure 3.14). A similar decline in hotel registrations in 2020 is apparent in the Puerto Rico data, following a general recovery. The total hotel guest count in USVI however declined in 2018 and has not recovered, though this is likely driven in part by a rise in vacation property rentals (Figure 3.15).



Figure 3.13: Population change in Puerto Rico (top) and USVI (bottom) according to census data.

3 Risks to meeting fishery management objectives



Figure 3.14: Annual tourism activity in Puerto Rico (left) and USVI (right) as indicated by the number of cruise and air passengers visiting the islands.

3 Risks to meeting fishery management objectives



Figure 3.15: Annual tourism activity in Puerto Rico and USVI as indicated by the number of hotel registrations (guests). Note that Puerto Rico data only include non-resident hotel registrations while for USVI data were available for all hotel registrations, so may include residents and non-residents.

4 Integrated ecosystem perspectives

For the purpose of synthesizing the information contained in the full suite of indicators presented in this report, we analyze the full indicator suite using multivariate methods. Principal components analysis (PCA) is a statistical method that distills a large number of potentially related indicators into a smaller number of indices representing most of the variability in the data set. We analyze the indicator suite separately by category: 1) risks to meeting management objectives, 2) management objective indicators based on fishery-independent data, 3) management objective indicators based on fishery-dependent data, and 4) other management objective indicators. A traffic light plot of the indicator suite is presented for the purpose of comprehensively viewing changes in the different parts of the ecosystem over time (Figure 4.1). A biplot of the principal components analysis is presented to convey temporal patterns in the progression of ecosystem status (Figure 4.2). PCA was carried out on a scaled matrix for all indicators with at least 12 years of data; any missing values were imputed with means of the time series. In the biplot, the labels represent time (years 2011 – 2023), the rainbow line represents chronology between adjacent years, and the distance between points conveys how different the indicator values were in those years.

Many indicators are based on time series of limited extent or contain data gaps, which makes it challenging to elucidate overall trends. However, the traffic plot conveys that many indicator values undergo rapid change in the period 2017-2021, and the PCA biplots confirm these patterns as there are larger two-dimensional shifts between these years. These shifts are most likely driven by several major stressor events in this time period, including the major hurricanes Maria and Irma (2017) and the COVID pandemic (2020-2021). Together, the multivariate analyses suggest that these events have had some destabilizing impacts on the U.S. Caribbean fishery ecosystem.

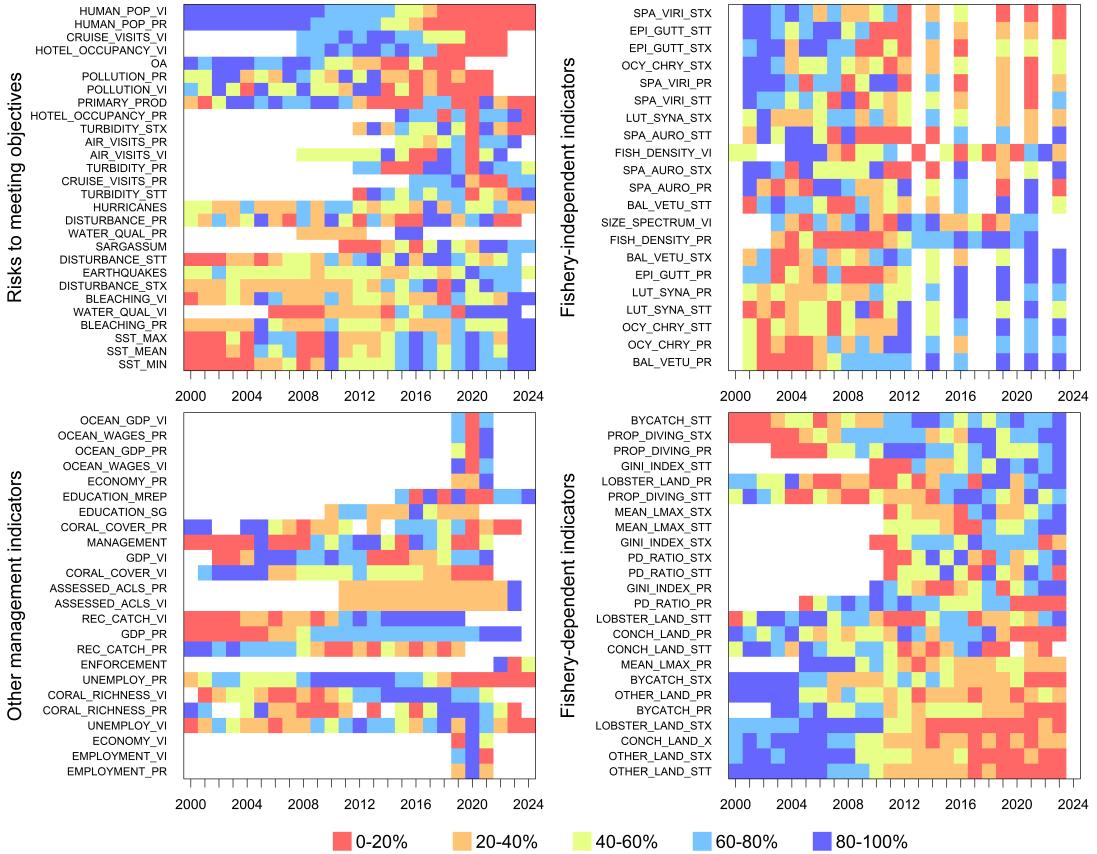


Figure 4.1: Traffic light plot representing the value of the indicator each year according to quintiles; colors show that the indicator moving between well below average (red, bottom quintile), below average (orange, 20-40% quintile), average (yellow, 40-60% quintile), above average (light blue, 60-80% quintile), and well above average (dark blue, top quintile), respectively (see legend). Indicators are grouped by category, and appear on the plot sorted by their loading (i.e., their influence) from a principal components analysis. In this way, indicators showing similar patterns across time are grouped more closely together.

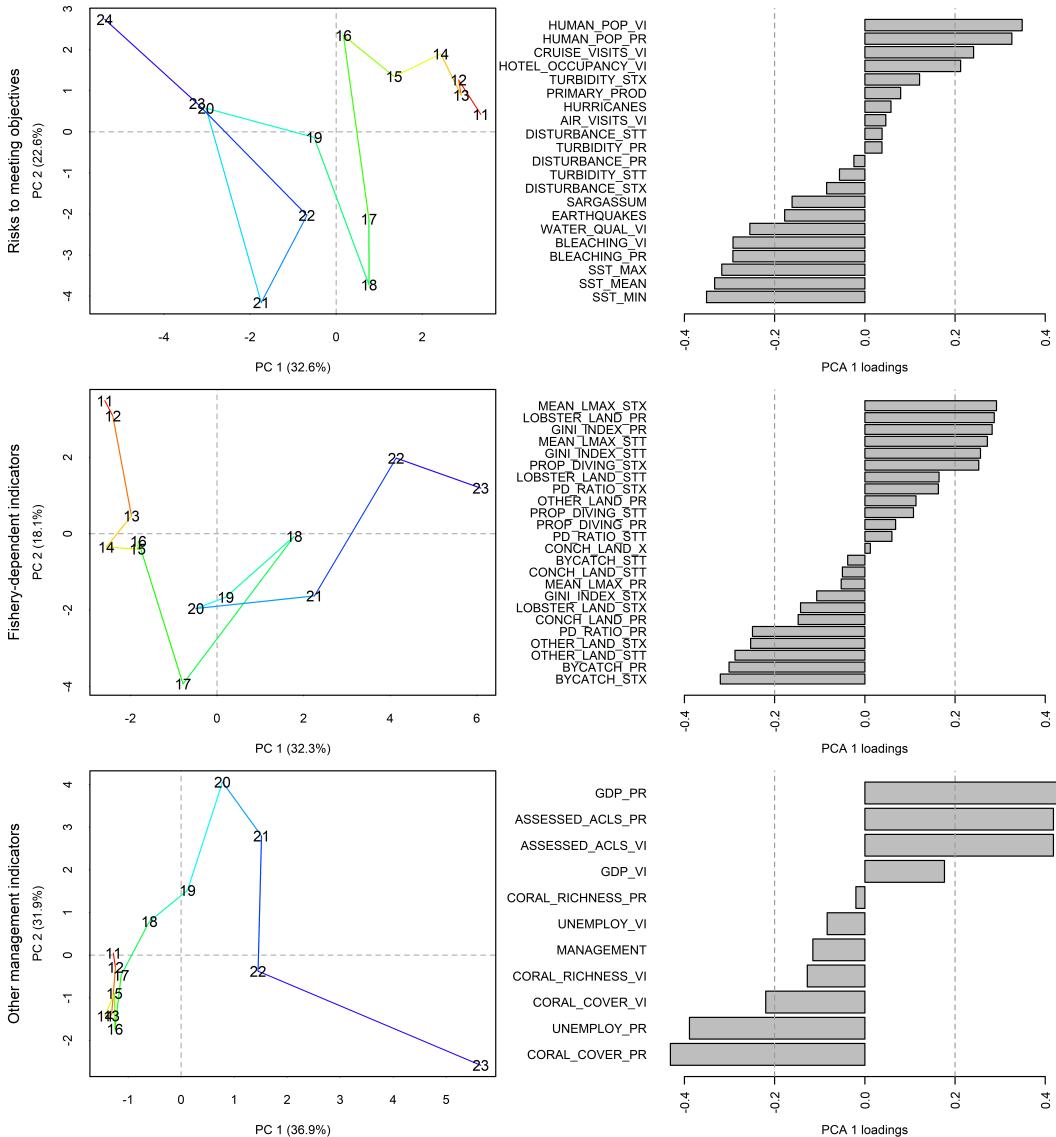


Figure 4.2: Left: Yearly scores of the first two components of a principal components analysis (PCA) for three groups of indicators, based on indicator values from 2011 – 2023. Right: Loadings plots show the relative influence of each indicator in driving the temporal trends observed on the left panel. Loadings with an absolute value greater than 0.2 are considered to be significant.

5 Research recommendations

5.1 Risks to meeting management objectives

A number of stressors were identified throughout the conceptual modeling stage (Seara et al. 2024) and indicator vetting process (Montenero, Kelble, and Broughton 2021); however, consistent monitoring efforts are lacking with which to capture some of these potential impacts. For example, marine debris was identified as a major concern, but we could not find any databases reporting standardized long-term trends in marine debris. Point source pollution, derelict vessels, and other impacts to water quality are also concerns that are not well documented in quantitative terms. Coastal development, beach erosion and their impacts on habitat loss were also a concern, particularly with respect to nursery habitats such as mangroves and seagrasses. The NOAA Office for Coastal Management's Coastal Change Analysis Program is currently in the process of updating its remotely-sensed imagery of land cover for the U.S. Caribbean; this data set will allow quantification of habitat and land use changes and can be included in future iterations of the report.

5.2 Fishery-dependent and fishery-independent data sources

Many of the indicators in this report are based on the self-reported logbook data known as the Caribbean Commercial Logbook (CCL). Logbook reporting began in 1974; however, reporting forms have changed throughout the years and catches have been reported at different taxonomic resolution, typically at family levels in the earlier years and at the species level only in the last decade. This makes it challenging to disentangle true signals in the indicators from changing fishing behavior from artifacts due to changes in reporting. The recent addition of an electronic reporting option in Puerto Rico is potentially particularly problematic, as the number of species being reported in the e-reporting has decreased dramatically relative to paper logbook reporting, likely due to fatigue in repeating reporting steps for each new species caught. Further work needs to be conducted to understand how the various

5 Research recommendations

changes in reporting forms have affected landings reports, and the influence of these reporting artifacts on the trends represented by indicators.

Additionally, there is high uncertainty surrounding some of the landings estimates, and underreporting is suspected. A significant decline in commercial landings occurred in many species around 2010, aligned with the period when many annual catch limits were initially put into place in the U.S. Caribbean, and it is thought that reporting may have been reduced in response to the catch limits out of concern that further restrictions might be put into place. In Puerto Rico, expansion factors are used and were applied to the indicators in this report, to account for known underestimates of commercial landings based on the incoming reports. These expansion factors, however, are not intended to correct for the absence of reporting across the island. Because of the issues and potential biases surrounding the self-reported commercial landings data, some of the indicators may not accurately reflect true changes in the fisheries. The indicators based on ratios or percentages (e.g., pelagic to demersal ratio, percentage of trips using a certain gear type) will be less subject to biases related to under-reporting, assuming that the trips that are reported are representative of the overall fishery. There is currently no regular reporting system for recreational landings, and this also remains a major source of uncertainty in the total landings estimates.

Due to the inherent uncertainties and potential biases in self-reported landings data, interpretation of fishery-dependent data is facilitated by comparison of trends from standardized fishery-independent data sources. The Puerto Rico Long-Term Coral Reef Monitoring Program (PRCRMP) and the USVI Territorial Coral Reef Monitoring Program (TCRMP) have conducted annual surveys of fish and benthic organisms since the late 1990s, providing a relatively long-term data set with which to analyze trends. However, these surveys are conducted at fixed sites at known locations with good habitat conditions, so may not be representative of wider regional trends in the populations. The National Coral Reef Monitoring Program (NCRMP), on the other hand, employs a stratified random sampling design, which better accounts for the variety of habitat types in the region; however, sampling is conducted every other year. Some preliminary explorations of these data sets were explored in this report, but could be mined for more signals. In particular, community-level and/or length-based indicators could be informative for understanding the response of populations and fish communities to fishing and other drivers.

5.3 Human dimensions

From the perspective of human well-being as it relates to marine resource management, there remain gaps in understanding human dimensions and resilience to dis-

5 Research recommendations

turbances. Indicators alone may not fully capture the nuanced knowledge about habitats, seasonal patterns and fish behavior that are critical for fishers and important in planning; local ecological knowledge has proven helpful for filling these gaps (see García-Quijano 2007; García-Quijano et al. 2023). Indicators or information on social cohesion and community identity are important in highlighting the importance of fishing for local communities in ways that goes beyond monetary benefits and speaks to the cultural significance (Valdés-Pizzini 2020; Griffith et al. 2007). Fishers in the U.S. Caribbean region engage in multiple occupations as a way to increase their resilience in times of crisis (García-Quijano et al. 2023; Yandle, Sweeney Tookes, and Grace-McCaskey 2020), and capturing the multiple economic activities in fishing communities would provide a more nuanced understanding of the economic diversity and vulnerability in fishing communities in the U.S. Caribbean region. Finally, indicators alone do not address the systemic barriers in accessing fishing governance (Grace-Mccaskey 2012; Valdés-Pizzini 1990).

6 Acknowledgments

6.1 Contributions

This report would like to acknowledge the efforts and contributions of: The National Coral Reef Monitoring Program funded by the NOAA Coral Reef Conservation Program, project number 743, as well as the Caribbean Fishery Management Council's District Advisory Panels for their conceptual model work, the Caribbean Fishery Management Council's Technical Advisory Panel, the Caribbean Fishery Management Council's Science and Statistical Committee, the Caribbean Fishery Management Council staff, and the NOAA Southeast Fisheries Science Center Social Science team and the Caribbean Branch staff as well as the NOAA Fisheries Southeast Regional Office. This report was supported in part by the Cooperative Institute for Marine and Atmospheric Studies (CIMAS), a Cooperative Institute of the University of Miami and the National Oceanic and Atmospheric Administration, cooperative agreement # NA20OAR4320472.

6.2 Resources

This repo and GitHub Action associated with generating this report was based on the Openscapes tutorial quarto-website-tutorial by Julia Lowndes and Stefanie Butland.

7 Contributors

7.1 Editors

Mandy Karnauskas, Carissa Gervasi

7.2 Contributors

Kelly Montenero, Seann Regan, Amy Freitag, Andrea Chan, Chuanmin Hu, Erica K. Towle, Laura Jay Grove, Jeremiah Blondeau, Sarah Groves, Shay Viehman, Nicole Besemer, Juan Agar, Kevin McCarthy, Manoj Shivlani, Mike Jepson, Adyan Rios, Matt McPherson, Miguel Figuerola, Nicole Angeli, Sennai Habtes, Dione Swanson, Liajay Rivera, Leigh Fletcher, Tarsila Seara, Suzana Blake, Carolyn Sramek, Matthew Walia, Fabian Gomez, Silene Prentice

References

- Agar, J., B. Stoffle, M. Shivilani, D. Matos-Caraballo, A. Mastitski, and F. Martin. 2022. "One-Year COVID-19 Pandemic Impacts on U.S. Caribbean Small-Scale Fisheries with a Note on the Puerto Rican Earthquake Swarm of 2020 and 2021." *NOAA Technical Memorandum NMFS-SEFSC-759*. <https://repository.library.noaa.gov/view/noaa/47711>.
- Andersson, A. J., I. B. Kuffner, F. T. Mackenzie, P. L. Jokiel, K. S. Rodgers, and A. Tan. 2009. "Net Loss of CaCO₃ from a Subtropical Calcifying Community Due to Seawater Acidification: Mesocosm-Scale Experimental Evidence." *Biogeosciences* 6 (8): 1811–23. <https://doi.org/10.5194/bg-6-1811-2009>.
- Brinson, Ayeisha A., and Eric M. Thunberg. 2016. "Performance of Federally Managed Catch Share Fisheries in the United States." *Fisheries Research* 179: 213–23. <https://doi.org/https://doi.org/10.1016/j.fishres.2016.03.008>.
- Clements, Janet, Vicente Feliciano, and Charles Colgan. 2016. "Describing the Ocean Economies of the U.S. Virgin Islands and Puerto Rico." *Report by Abt Associates to NOAA Office of Coastal Management*. <https://repository.library.noaa.gov/view/noaa/20724>.
- de Leiva Moreno, J. I., V. N. Agostini, J. F. Caddy, and F. Carocci. 2000. "Is the Pelagic-Demersal Ratio from Fishery Landings a Useful Proxy for Nutrient Availability? A Preliminary Data Exploration for the Semi-Enclosed Seas Around Europe." *ICES Journal of Marine Science* 57 (4): 1091–1102. <https://doi.org/10.1006/jmsc.2000.0705>.
- Froese, R, and D Pauly. 2024. "FishBase." www.fishbase.org.
- García-Quijano, Carlos G. 2007. "Fishers' Knowledge of Marine Species Assemblages: Bridging Between Scientific and Local Ecological Knowledge in Southeastern Puerto Rico." *American Anthropologist* 109 (3): 529–36. <https://www.jstor.org/stable/4496726>.
- García-Quijano, Carlos G., Hilda Lloréns, David C. Griffith, Miguel H. Del Pozo, and John J. Poggie. 2023. "Coastal Forest Fisheries, Estuarine Livelihoods, and Human Well-Being in Southern Puerto Rico." *Human Ecology* 51 (5): 861–76. <https://doi.org/10.1007/s10745-023-00449-2>.
- Gini, C. 1936. "On the Measure of Concentration with Special Reference to Income and Statistics." *Colorado College Publication, General Series* 208: 73–79. <https://cir.nii.ac.jp/crid/1370861704783841681>.

References

- Gomez, Fabian A., and Sang-Ki Lee. 2023. "Surface North Atlantic MOM5-TOPAZ Outputs Derived from a Regular Hindcast and a Robust Diagnostic Simulation Experiment from 1980-01-01 to 2017-12-31 (NCEI Accession 0283628)." *NOAA National Centers for Environmental Information. Dataset.* Accessed: 2023-02-19. <https://www.ncei.noaa.gov/archive/accession/0283628>.
- Grace-Mccaskey, Cynthia. 2012. "Fishermen, Politics, and Participation: An Ethnographic Examination of Commercial Fisheries Management in St. Croix, US Virgin Islands." *USF Tampa Graduate Theses and Dissertations*, April. <https://digitalcommons.usf.edu/etd/4054>.
- Griffith, David A., Manuel Valdés-Pizzini, Carlos García-Quijano, Juan J. Agar, and Brent William Stoffle. 2007. "Entangled Communities: Socioeconomic Profiles of Fishers, Their Communities and Their Responses to Marine Protective Measures in Puerto Rico (Volume 1: Overview). NOAA Series on U.S. Caribbean Fishing Communities." *NOAA Technical Memorandum NMFS-SEFSC-556*. <https://repository.library.noaa.gov/view/noaa/4395>.
- Hu, Chuanmin, Zhongping Lee, and Bryan Franz. 2012. "Chlorophyll Algorithms for Oligotrophic Oceans: A Novel Approach Based on Three-Band Reflectance Difference." *Journal of Geophysical Research: Oceans* 117: C01011. <https://doi.org/10.1029/2011JC007395>.
- Hu, Chuanmin, Brock Murch, Brian Barnes, Mengqiu Wang, Jean-Philippe Maréchal, James Franks, Brian Lapointe, Deb Goodwin, Jeffrey Schell, and Amy Siuda. 2016. "Sargassum Watch Warns of Incoming Seaweed." *Eos* 97 (September). <https://doi.org/10.1029/2016EO058355>.
- Knapp, Kenneth R., Michael C. Kruk, David H. Levinson, Howard J. Diamond, and Charles J. Neumann. 2010. "The International Best Track Archive for Climate Stewardship (IBTrACS)." <https://doi.org/10.1175/2009BAMS2755.1>.
- Montenero, Kelly, Chris Kelble, and Kathy Broughton. 2021. "A Quantitative and Qualitative Decision-Making Process for Selecting Indicators to Track Ecosystem Condition." *Marine Policy* 129: 104489. <https://doi.org/https://doi.org/10.1016/j.marpol.2021.104489>.
- NOAA Coral Reef Watch. 2019. "NOAA Coral Reef Watch 5km Regional Virtual Stations Degree Heating Weeks V3.1 Jan 1, 1985 - Dec 31, 2023." *Data Set Accessed 2024-10-31. Silver Spring, MD. USA.* <https://coralreefwatch.noaa.gov/product/vs/data.php>.
- NOAA Fisheries. 2024. "Social Indicators Supporting Information." <https://www.fisheries.noaa.gov/national/socioeconomics/social-indicators-supporting-information>.
- Pauly, D, and D Zeller. 2015. *Sea Around Us Concepts, Design and Data*. Sea Around Us, Institute for the Oceans; Fisheries, University of British Columbia, Vancouver, Canada. www.seaaroundus.org.
- Puerto Rico Department of Natural and Environmental Resources. 2019. "Puerto Rico Long-Term Coral Reef Monitoring Program Database Compilation: Substrate

References

- Cover Percent, Octocoral Colony Counts, Macro Invertebrate Densities, Fish Densities, and Fish Biomass from 1999 to 2023." *NOAA National Centers for Environmental Information. Dataset. NCEI Accession 0204647.* Accessed 2024-02-06. <https://www.ncei.noaa.gov/archive/acquisition/0204647>.
- Reynolds, Richard W., Thomas M. Smith, Chunying Liu, Dudley B. Chelton, Kenneth S. Casey, and Michael G. Schlax. 2007. "Daily High-Resolution-Blended Analyses for Sea Surface Temperature." <https://doi.org/10.1175/2007JCLI1824.1>.
- Rochet, Marie-Joëlle, and Verena M Trenkel. 2003. "Which Community Indicators Can Measure the Impact of Fishing? A Review and Proposals." *Canadian Journal of Fisheries and Aquatic Sciences* 60 (1): 86–99. <https://doi.org/10.1139/f02-164>.
- Seara, Tarsila, Stacey M. Williams, Kiara Acevedo, Graciela Garcia-Molliner, Orian Tzadik, Michelle Duval, and Juan J. Cruz-Motta. 2024. "Development and Analyses of Stakeholder Driven Conceptual Models to Support the Implementation of Ecosystem-Based Fisheries Management in the U.S. Caribbean." *PLOS ONE* 19 (5): e0304101. <https://doi.org/10.1371/journal.pone.0304101>.
- Smith, Steven G., Jerald S. Ault, James A. Bohnsack, Douglas E. Harper, Jiangang Luo, and David B. McClellan. 2011. "Multispecies Survey Design for Assessing Reef-Fish Stocks, Spatially Explicit Management Performance, and Ecosystem Condition." *Fisheries Research* 109 (1): 25–41. <https://doi.org/10.1016/j.fishres.2011.01.012>.
- Sumy, Danielle F., Russ Welti, and Michael Hubenthal. 2020. "Applications and Evaluation of the IRIS Earthquake Browser: A Web-Based Tool That Enables Multidimensional Earthquake Visualization." *Seismological Research Letters* 91 (5): 2922–35. <https://doi.org/10.1785/0220190386>.
- Towle, Erica K., Mary E. Allen, Hannah Barkley, and Nicole Besemer. 2021. "National Coral Reef Monitoring Plan. Coral Reef Conservation Program (United States)." <https://doi.org/10.25923/fqkq-w497>.
- U. S. Bureau of Labor Statistics. 2024. "U.s. Bureau of Labor Statistics, Unemployment Rate in Puerto Rico [PRUR], Retrieved from FRED, Federal Reserve Bank of St. Louis; <Https://Fred.stlouisfed.org/Series/PRUR>, May 16, 2024."
- United States Environmental Protection Agency. 2024. "Indicators: Enterococci." <https://www.epa.gov/national-aquatic-resource-surveys/indicators-enterococci>.
- U.S. Employment and Training Administration. 2024. "United States Employment and Training Administration, Insured Unemployment Rate in the US Virgin Islands [VIRINSUREDUR]." *Retrieved from FRED, Federal Reserve Bank of St. Louis, May 16, 2024.* <https://fred.stlouisfed.org/series/VIRINSUREDUR>.
- Valdés-Pizzini, Manuel. 1990. "Fishermen Associations in Puerto Rico: Praxis and Discourse in the Politics of Fishing." *Human Organization* 49 (2): 164–73. <https://www.jstor.org/stable/44126448>.
- . 2020. "Making Sense Out of Coastal Peoples and Fishers' Responses to Extreme Natural Events in the Caribbean." *Coastal Management* 48 (5): 349–53. <https://doi.org/10.1080/00928855.2020.1718111>.

References

- //doi.org/10.1080/08920753.2020.1802197.
- Wang, Menghua, Chuanmin Hu, Brian B. Barnes, Gary Mitchum, Brian Lapointe, and Joseph P. Montoya. 2019. "The Great Atlantic *Sargassum* Belt." *Science* 365: 83–87. <https://www.science.org/doi/10.1126/science.aaw7912>.
- Wang, Menghua, SeungHyun Son, and Lawrence W. Harding Jr. 2009. "Retrieval of Diffuse Attenuation Coefficient in the Chesapeake Bay and Turbid Ocean Regions for Satellite Ocean Color Applications." *Journal of Geophysical Research: Oceans* 114: C10011. <https://doi.org/10.1029/2009JC005286>.
- World Bank. 2024a. "Gross Domestic Product for Puerto Rico [NYGDPMKTPCDPRI]." *Retrieved from FRED, Federal Reserve Bank of St. Louis, May 16, 2024.* <https://fred.stlouisfed.org/series/NYGDPMKTPCDPRI>.
- . 2024b. "Gross Domestic Product for u.s. Virgin Islands [MKTGDPVIA646NWDB]." *Retrieved from FRED, Federal Reserve Bank of St. Louis, May 16, 2024.* <https://fred.stlouisfed.org/series/MKTGDPVIA646NWDB>.
- Yandle, Tracy, Jennifer Sweeney Tookes, and Cynthia A. Grace-McCaskey. 2020. "US Virgin Islands Fishing Community Resilience: Informing a Research Agenda." *Coastal Management* 48 (5): 481–504. <https://doi.org/10.1080/08920753.2020.1796191>.